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Review

Traditional earthquake resistant techniques for vernacular architecture and local seismic cultures: A literature review



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ABSTRACT

Specific architectural elements can be identified in constructions located in regions frequently exposed to earthquakes. These earthquake resistant features were developed empirically by local communities to protect their built-up environment. Research in these traditional earthquake resistant practices, resulting from a local seismic culture, is a relevant and positive approach, since it focuses on the strengths of a system rather than on its weaknesses. Its integration into current vernacular building practices can help to preserve and retrofit surviving in-use examples without prejudice to their identity. This paper presents an overview of the most common techniques traditionally used around the world, based on literature review. Additionally, it identifies the use of these techniques in the Portuguese vernacular heritage in order to contribute for the awareness and strength of the local seismic culture in Portugal.

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1. Introduction

Vernacular architecture located in earthquake prone areas is particularly vulnerable because of the generalized use of poor materials, the scarcity of resources in poor communities, and the poor maintenance, associated at times with lack of a good construction. Nevertheless, due to the long-term exposure to earthquake hazard, local communities are eventually forced to adapt to this risk and protect their built-up environment. People can either undertake preventive measures, repairing and refurbishing their personal properties in order to minimize future losses in the following earthquakes, or they can respond to earthquakes just in the immediate aftermath of the event, with no future orientation, developing a reactive response behavior [1]. In any case, traditional seismic resistant construction techniques arise from this need to repair earthquake damage to both personal and public buildings. These efforts made by local populations as a reaction to earthquakes gave rise to the development of a local seismic culture, which is a key element for the preservation of cultural identity and vernacular construction practices. The use of technological and standardized materials in a globalized world created a tendency to unify the

way of building, jeopardizing local building cultures and vernacular architecture. For this reason, the valorization and preservation of the vernacular heritage is crucial, not only as a witness of the past, but also as a key factor for local development, boosting local economies [2,3].

Ferruccio Ferrigni, Centro Universitativo Europeo per i Beni Culturali (CUEBC), recognized the existence of local seismic cultures and carried out the first research project aimed at reducing the seismic vulnerability of the traditional housing stock based on the rediscovery and development of local know-how [4,5]. Local seismic cultures and traditional earthquake resistant techniques have been identified in many regions around the world frequently exposed to earthquakes, such as Italy [6], Greece [7], Turkey [8], Algeria [9], Iran [10], India [11], Nepal [12], Japan [13], Haiti [14], and Colombia [15]. Other organizations such as CRATerre have developed risk management programs including the construction of traditional seismic resistant housing in El Salvador and the development of guidelines for reconstruction based on the local seismic resistant building culture in Kashmir [16]. The World Housing Encyclopedia [17] is another project of the Earthquake engineering research institute (EERI) and the International association for earthquake engineering (IAEE) that collects existing construction practices in earthquake regions, with a focus on vernacular building typologies. Its main objectives are to understand the seismic vulnerability of these construction systems and the reasons for their good or poor seismic performance, as well as to provide recommendations for strengthening [18,19].

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Research in vernacular architecture has predominantly been focused on building typologies and spatial organization, while research in seismic strengthening solutions has for a long time been addressing monumental architecture instead of the vernacular heritage, which has traditionally been ignored and underestimated. However, in the last years, there has been a growing interest on the experimental characterization of the seismic behavior of representative vernacular construction systems [20–23], as well as on seismic strengthening solutions for vernacular constructions based on modern techniques and materials [24–26]. Still, little research has focused on traditional strengthening solutions emerging from vernacular architecture [27]. Therefore, the present paper addresses this critical gap in knowledge regarding vernacular architecture earthquake preparedness and the most common measures adopted by local communities to repair and restore their dwellings. For this purpose, this paper presents a comprehensive overview of earthquake resistant techniques and practices identified in regions frequently exposed to earthquakes based on a review of the literature, aiming in particular at a better understanding of their structural role.

It is considered that a better awareness of traditional earthquake resistant measures is important to protect and reduce the seismic vulnerability of the built vernacular heritage by encouraging local communities to recognize and readopt techniques emerging from a local seismic culture. Unfortunately, local communities are gradually abandoning the local seismic culture because they rely less and less on it [28]. Traditional construction techniques are being replaced with new modern techniques and technologies which enable structures to be erected quickly and cheaply, but not necessarily safely [29]. The overview presented in this paper on the local seismic culture and traditional earthquake resistant techniques is based on the research that has been developed under the framework of the research project “SEISMIC-V—vernacular seismic culture in Portugal” [30], which specifically focuses on the study of local seismic cultures and on the identification of adequate seismic retrofitting techniques for vernacular buildings in Portugal. Therefore, the paper also elaborates on the Portuguese context by indicating which techniques can also be recognized within Portuguese vernacular architecture, so that it can additionally contribute to the reflection on the existence of a local seismic culture in Portugal.

2. Basic concepts

2.1. Vernacular architecture and local seismic cultures

The object of this overview is the vernacular architectural heritage, which comprises dwellings and other buildings built by the people. Vernacular buildings are usually owner or community built. They are not designed by specialists but, on the contrary, are part of a process that involves many people over many generations and are based on empirical knowledge. This is why vernacular architecture is often called communal, popular or folk architecture and even “architecture without architects” [31]. Following the same reasoning, vernacular architecture has often been defined as the opposite of high or monumental architecture. Still, vernacular is the most common term used by academics [32,33] and professionals [34].

Earthquakes striking cities and devastating communities have been reported since ancient times. However, in spite of the constant threat that earthquakes represent, far from abandoning these seismic prone regions, people have proven to be exceedingly attached to the places where they have always lived and have remained living under these dangerous circumstances. Consequently, it seems reasonable that people coexisting with earthquakes are forced to learn how to protect themselves from them and have developed

preventive measures for earthquake mitigation. This is the origin of a local seismic culture. Considering that the built up environment is the most vulnerable element to earthquake forces and the major cause for the economic and human toll, most of the efforts have been dedicated to improve the seismic resistance of constructions, aiming at minimizing the earthquake catastrophic effects.

As part of the vernacular practice, local seismic cultures make use of locally available materials, skills and resources but, more importantly, they are culturally sensitive to the local building tradition and effective in resisting earthquakes. This type of knowledge derives from centuries of trial and error and generally uses low-level technology. However, it is frequently disregarded and rarely documented or scientifically explained. For this reason, research in hazard mitigation through vernacular building practices resulting from a local seismic culture is relevant.

The main factor that leads to the development of a seismic culture is earthquake hazard awareness, which is strictly correlated with the seismic hazard of the region or the probability of occurrence of an earthquake in a given area. In addition to the seismic hazard, the impact of the earthquake on the built-up environment is of great importance. In this way, methods and construction solutions proved as dangerous after an earthquake are either abandoned or modified, while reconstruction works will copy those construction techniques that have withstood the event, as a sort of natural selection.

There is a close correlation between the development of seismic resistant building practices and the earthquake frequency [7]. Earthquakes must be frequent in a region so the people can remember the seismic behavior of the empirically devised techniques. At least one important earthquake during the life period of a generation is needed to keep the local seismic culture level high, resulting in a “culture of prevention”, and enhancing the quality of aseismic construction (Fig. 1). If earthquakes are not frequent and there are long periods of time between the seismic events, larger than the average generation life time, the function of different techniques implemented after an earthquake will be forgotten and gradually abandoned, developing a “culture of repairs”. This loss of the collective memory of past events eventually leads to the abandonment and erosion of seismic cultures.

The development of a seismic culture is not only related with the frequency of the earthquakes but also with their intensity. As an example, Portugal has a moderate seismicity characterized by small events, but several devastating earthquakes have sporadically struck the country throughout its history. This has led to the development of important reactive responses in which seismic resistant constructions were devised and implemented after earthquakes, such as the well-known “Pombalino” buildings after the 1755 Lisbon earthquake. However, due to a progressive loss of seismic awareness, “Pombalino” buildings were replaced by the “Gaioleiro” buildings, with a much worse construction quality and where the initially devised seismic resistant measures were neglected, increasing their vulnerability [35]. A similar example can be found in India, where the seismicity of some regions is also characterized by a relative high frequency of large earthquakes and low frequency of moderate earthquakes. According to Jain [36], this has led to the development of seismic resistant construction typologies, such as the “Assam-type” timber-frame houses developed after the 1897 Assam Earthquake. They showed an excellent performance in subsequent earthquakes but were again abandoned because of the lack of seismic concern.

2.2. Earthquake performance of vernacular constructions

The serious aftermaths of earthquakes, such as human fatalities, are caused mainly by the collapse of poorly constructed or unsafe buildings and other man-made structures. Therefore, the

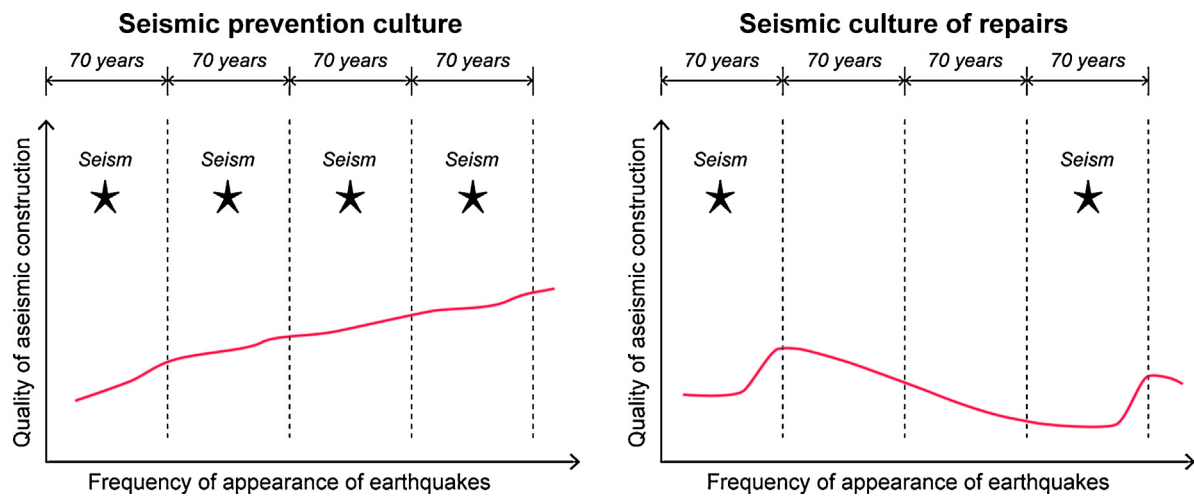


Fig. 1. Evolution of the quality of aseismic construction in relation with the earthquake frequency (adapted from [7]).

seismic risk directly depends on the seismic vulnerability of the constructions, which can be defined as their intrinsic proneness to suffer damage as a result of a seismic event of a given intensity. Other factors, such as the level of exposure (e.g. density of population or time of the day of the earthquake occurrence) and the seismic hazard of the region can also reduce or increase the risk. However, since the earthquake action cannot be reduced, efforts should be made on identifying the building fragilities and on repairing and strengthening the building stock, addressing an essential aspect in which the engineering research can intervene. For that purpose, understanding the earthquake effects on buildings is of major importance.

Vernacular buildings are mainly constructed with traditional materials using low cost and simple construction technology. Thus, they respond very poorly to earthquake ground shakings, even to moderate ones. The seismic deficiencies of vernacular constructions are mainly caused by the poor quality of building materials, workmanship and maintenance, generally resulting from economic constraints and lack of proper training of local masons. Examples of the poor performance of vernacular architecture that led to significant human and economic losses include: the 2005 Kashmir and 2001 Bhuj earthquakes, where most of the deaths were attributed to the collapse of stone masonry dwellings [18]; and the 2001 El Salvador, 2003 Bam and 2007 Pisco earthquakes, where many people died and were left without shelter after the collapse of earthen dwellings [19]. Vernacular stone masonry buildings can show insufficient construction quality to withstand seismic loads because of the use of round, unshaped stones, the absence of connection between leaves, the lack of adhesion and cohesion of the mortar, or the presence of voids. Earthen buildings seismic failure is mainly due to its own characteristics as a building material, such as its low strength and brittleness. In this section, a brief overview of common earthquake damages patterns associated to poor building practices will be provided.

2.2.1. Poor connection between structural elements

The lack of structural integrity due to poor connection between structural elements is one of the main causes of earthquake damage in vernacular buildings. Proper connections are required to ensure the “box-behavior” of the building so that inertial forces can be transferred between the structural elements and in-plane resisting mechanisms can develop in the masonry walls, which are typically the main structural elements in masonry buildings. This is one of the main earthquake resistant construction concepts, since the in-plane stiffness of the masonry is significantly higher than its

out-of-plane stiffness [37]. However, a full multi-connected box is often very far from reality in vernacular architecture given the absence of rigid floors, causing the single walls to work separately.

Deficient walls connections lead to out-of-plane failures due to the separation of walls at the corners. When seismic forces are transferred between perpendicular walls, there is a concentration of tensile and shear stresses at the connection that instigates vertical cracking and ultimately the global overturning of external walls (Fig. 2a). Additionally, if the anchorage between horizontal diaphragms (floors and roofs) and walls is not adequate, walls are free to vibrate independently and are more susceptible to top-ple (Fig. 2b). Inadequate wall-to-roof and wall-to-floor connections also lead to the separation of roofs and floors from walls. The loss of support often causes the partial and sometimes even the complete collapse of the roof and floors (Fig. 2c), which is one of the major causes of fatalities during earthquakes.

2.2.2. Out-of-plane wall collapse

Other out-of-plane failure patterns associated to the bending of the masonry walls can also develop. The damage pattern varies according to the geometry and boundary conditions of the walls. It can consist of vertical cracks at the wall intersections preceding the tilting and collapse of big portions of the walls, sometimes even the entire wall. If the free length of the wall is significant (i.e. the distance between intermediate transversal supports), the out-of-plane mechanism typically consists of horizontal cracking in the base or intermediate height, together with vertical cracks (Fig. 3a). Failure mechanisms in shorter walls are usually formed by vertical cracks in the center of the wall and diagonal cracking, coupled with the separation of the walls at the corners (Fig. 3b). Other out-of-plane mechanisms can also involve specific structural elements of the buildings, such as the out-of-plane collapse of corners (Fig. 3c). Buildings with gable walls tend to vibrate as freestanding cantilevers and are susceptible to their out-of-plane partial collapse (Fig. 3d). These failures are facilitated at top floors in multi-story buildings, where earthquake accelerations are intensified and there are lower axial loads.

2.2.3. Delamination of wall leaves

Another common damage concerning multiple-leaf stone masonry walls is the bulging of the external leaf or delamination (Fig. 4a). This type of failure is typically caused by poor quality of the masonry because of the lack of through-stones or “diatons”, which are larger stones that cross the entire thickness of the wall and allow the adequate bracing between leaves. Moreover, the space between

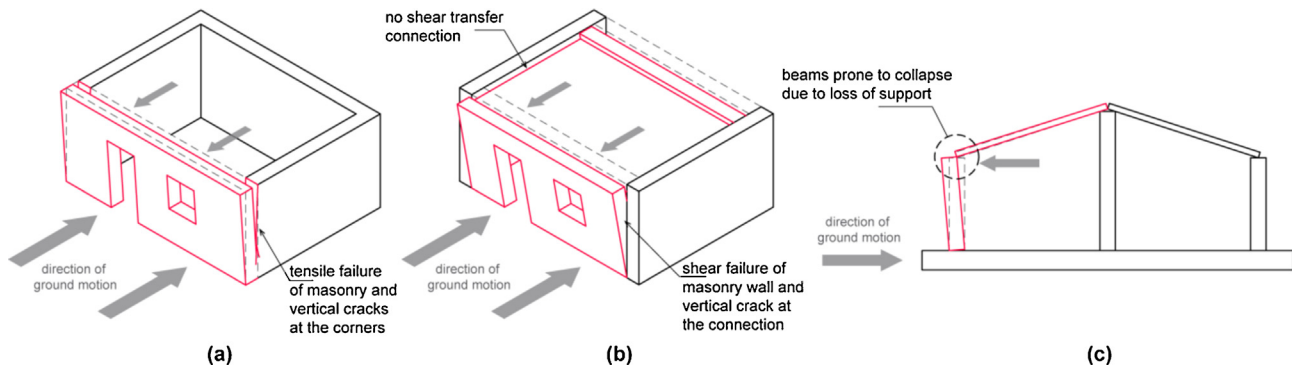


Fig. 2. (a) Global overturning of the external walls; (b) lack of anchorage between walls and horizontal diaphragms leading to the toppling of walls; and (c) separation of floors and roofs from the walls.

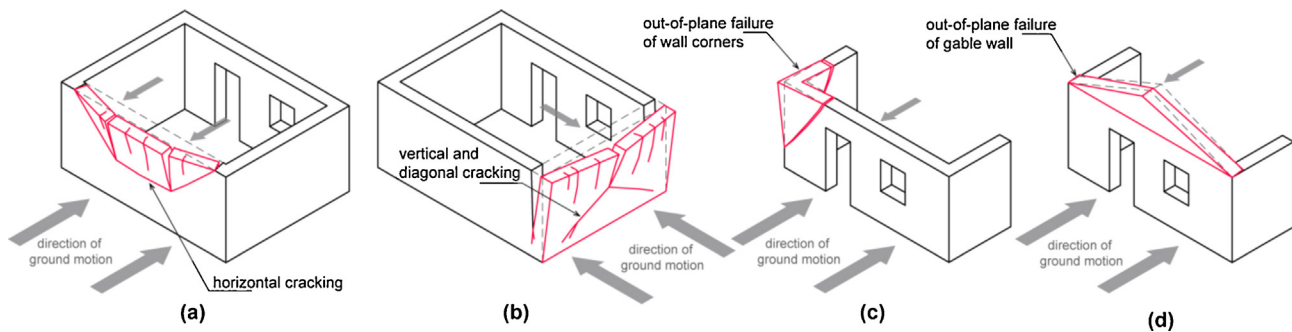


Fig. 3. (a) Out-of-plane mechanism in long walls (adapted from [74]); (b) out-of-plane mechanism in short walls (adapted from [74]); (c) out-of-plane collapse of the corner; and (d) out-of-plane collapse of the gable.

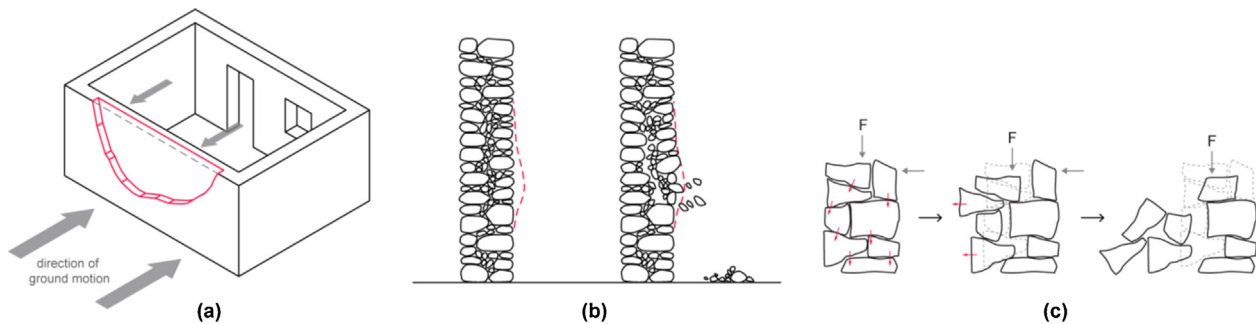


Fig. 4. (a) Delamination of the wall leaf; (b) inner leaf causing the bulging of the exterior wall leaf (adapted from [75]); and (c) wall failure caused by the irregularity of stones (adapted from [76]).

the wall leaves is usually filled with small stones and rubble, which can exert thrust from inside and push the leaves outward, causing the bulging and either partial or total collapse of the wall (Fig. 4b). This usually occurs at the upper parts of the wall, where the lack of weight allows the masonry to vibrate more independently [18]. The use of low quality building materials such as poorly placed irregular stones also tends to induce localized damage and partial collapses (Fig. 4c).

2.2.4. In-plane shear failure

Seismic events may also cause in-plane shear failure, which is mainly characterized by diagonal or X-cracking in the direction of the wall length (Fig. 5a). This failure is due to excessive shear efforts and low material shear strength, which is the case of earthen constructions and poorly constructed stone masonry buildings. In-plane failures also highly depend on the geometry of the walls, such as the length to height ratio and the wall thickness. The presence of openings facilitates in-plane cracking, which typically arises from the opening edges, where a greater concentration of stress is

present (Fig. 5b). In the case of slender piers, rocking may occur, which consists of the rotation of the piers and results in the crushing of the pier end zones [18] (Fig. 5c).

2.2.5. Poor workmanship and maintenance

Poor construction practices commonly observed in vernacular architecture increase the earthquake damage previously described. For example, openings that are too large or bad positioned (e.g. very close to each other or to the edges of the building) lead to excessively slender piers in the wall, enabling in-plane damage. Additionally, an irregular distribution of openings leads to an uneven distribution of stiffness and shear capacity among the piers so that some might be more vulnerable than others [38]. The thrust exerted by heavy roofs also greatly facilitates out-of-plane and in-plane mechanisms to take place. Parapets and other free-standing nonstructural elements prone to out-of-plane collapse are also potential seismic deficiencies of vernacular buildings.

Moreover, vernacular architecture has a distinctly open-ended and spontaneous nature so it is strongly characterized by its

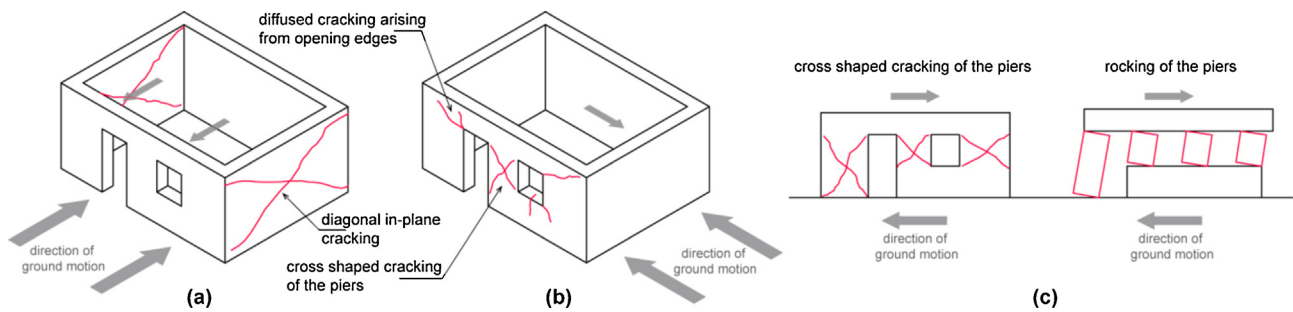


Fig. 5. (a) In-plane shear failure in the direction of the wall length; (b) shear cracking around the openings; and (c) shear cracking versus rocking of the piers (adapted from [18]).

transformation process. Vernacular buildings are thus subjected to continuous modifications that are a normal consequence of the changes in the use of the buildings and of the new needs of the users. These alterations on the original structures are a common source of vulnerability because they usually compromise the seismic performance of the buildings. The most common structural alterations include the addition of new floors, the opening of new windows and doors, the enlargement of the original openings, and the replacement of structural elements, such as floors and roofs.

3. Traditional seismic resistant building practices

Many different seismic resilient local building practices and constructive traditions can be recognized throughout the world and history, involving just some basic structural members of the building or consisting of an entire building structural system. The most successful ones have lasted for centuries and have survived numerous seismic events, proving their validity. Indeed, they were actually efficient in enhancing the structural performance of buildings during earthquakes and they have become recognized as evidences of a local seismic culture. Given the unchangeable nature of earthquakes, similar techniques following the same earthquake resistant principles can be observed in different seismic prone regions of the world, despite the use of different materials and techniques more adapted to each local situation and practice (Fig. 6).

Traditionally, the best and costliest materials, as well as the most advanced techniques, were traditionally reserved for temples and monumental buildings, as they were the buildings conceived to last over time. The sturdiest types of masonry were used to build bulky constructions that were able to resist very large earthquakes based solely on the strength, stiffness and good quality of the materials. The well-known Inca cyclopean masonry walls composed by large stones very precisely cut to fit perfectly one another are a good example. Another example is Roman monumental architecture whose massive walls and foundations work as rigid monolithic constructions thanks to the use of pozzolanic materials. However, these techniques required a high consumption of materials and massive labor force, which limited their use only for monuments and great buildings.

Ordinary constructions and dwellings belonging to vernacular architecture could not replicate the technologies used in monumental architecture because they had to make use of more affordable and locally available materials. The basic seismic resistant concepts that eventually took root in the vernacular building culture of a seismic prone region had to be necessarily different. Local populations acknowledged and accepted that it is not economically viable to construct every building to resist earthquakes without suffering deformation and damage but the collapse of the structure must always be avoided. Thus, the main construction efforts traditionally made by vernacular builders consist of improving the capacity of the structures to undergo deformation

and damage but maintaining enough load-carrying capacity to prevent global collapse. Traditional earthquake resistant techniques mainly follow four main resisting principles:

- improving the connections between the structural elements and enhancing the global behavior of the structure by forming closed contours in vertical and horizontal planes so that stress concentrations are avoided and forces are transmitted from one component to another even through large deformations;
- stabilizing structural elements and buildings by imparting resistance and deformation capacity to the brittle stone masonry or earthen walls, and by improving the diaphragm action of floors and roofs;
- allowing partial collapse by means of redundancy of structural elements so that the failure of certain members is tolerated;
- counteracting horizontal loads exerted by the buildings during the shaking by adding extra resistance to the lateral thrust with the help of new structural elements.

This section presents different traditional construction solutions and detailing that improve the seismic performance of vernacular architecture and can be considered as examples of local seismic cultures throughout the world. Additionally, an effort is carried out in order to identify signs of earthquake resistant traditional construction in Portugal that supports the existence of a true Portuguese local seismic culture.

3.1. Techniques improving the connections between structural elements

As previously mentioned, the lack of connection between structural elements is one of the main causes of earthquake induced damage in buildings and, as shown by past earthquakes, this can be significantly reduced when building components are properly connected and the construction behaves like a monolithic box [18]. Therefore, many traditional earthquake resistant construction techniques are aimed at improving the connections between the different structural elements: wall-to-wall, wall-to-floor and wall-to-roof.

One of the most effective and widespread traditional techniques used to ensure the structural integrity of stone masonry and earthen buildings is the construction of timber ring beams, also known as bond or collar beams. Traditionally, ring beams are built using a pair of longitudinal parallel planks joined together with small transversal members in a ladder-like configuration (Fig. 7), but sometimes they simply consist of a rough timber grid of horizontal timber trunks or tree branches lying longitudinally and transversally. They are usually placed continuously at the lintel level, at the roof level or, in the case of multi-story buildings, at the floor levels. The introduction of this type of beams at different levels within the height of the walls improves the connections between

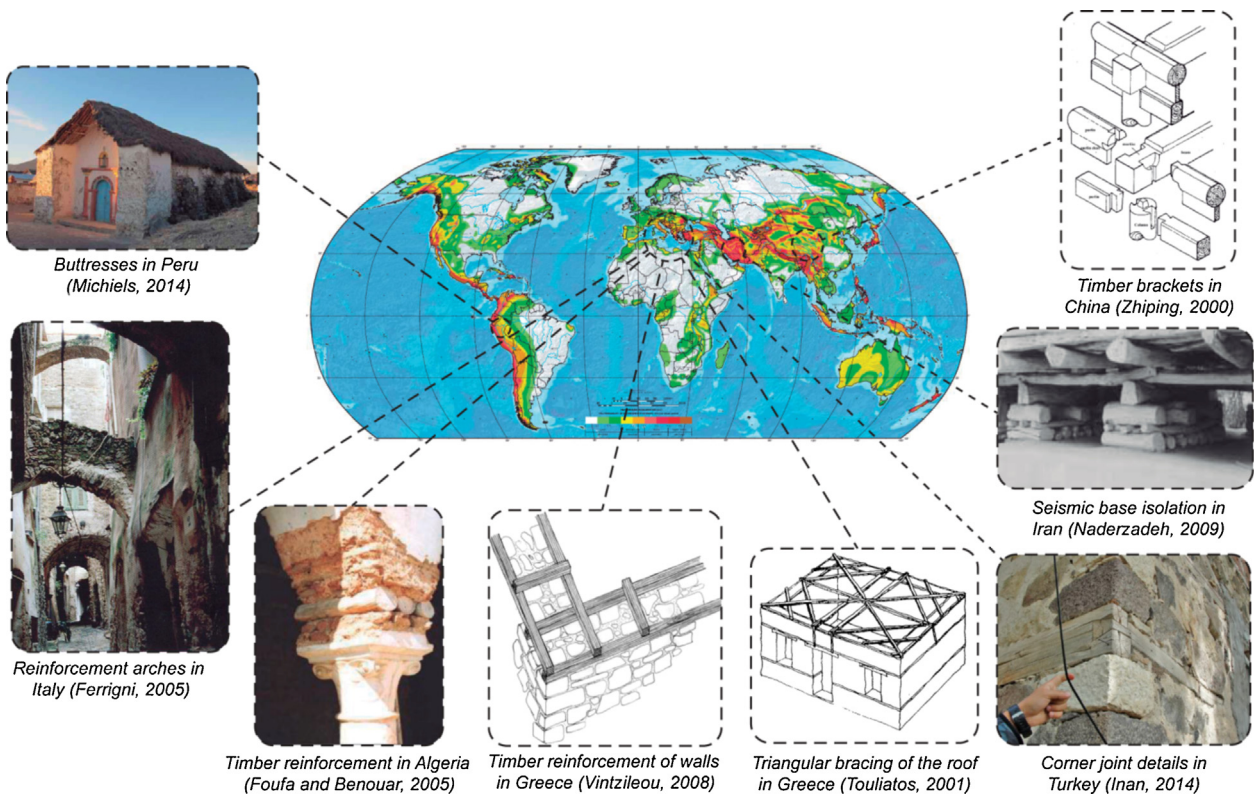


Fig. 6. Examples of earthquake resistant techniques and traces of local seismic culture throughout the world in relation to the global seismic hazard map [77].

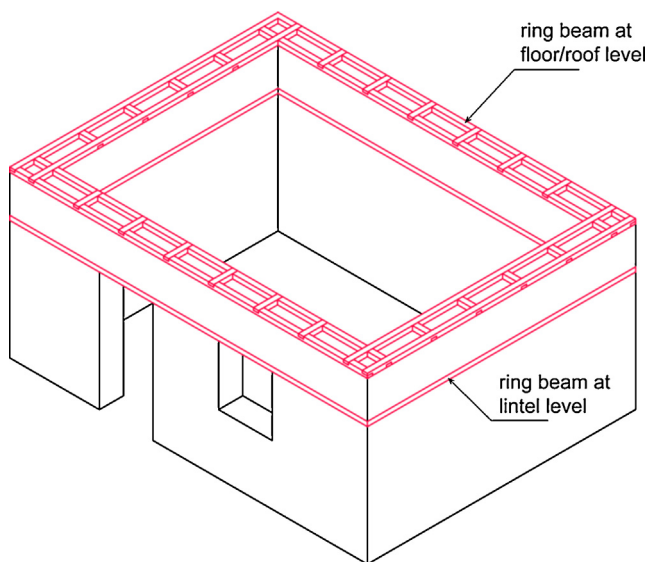


Fig. 7. Traditional timber ring beam reinforcement.

the different structural elements, tying the building and improving its “box-behavior”. In order to be more effective, ring beams should be continuous around the entire building. A proper connection between timber elements at the wall intersections should be ensured, by means of different timber joint details or even steel dowels or straps. The connection between the beam and the wall should also be ensured but it has been traditionally achieved solely by friction.

Ring beams can prevent the overturning of the wall by providing out-of-plane strength and stiffness. In addition, since they are usually built running across the entire thickness of the wall,

they can also help to tie the leaves of multiple-leaf masonry walls and prevent their separation. This technique does not avoid the formation of cracks, which still initiates for a loading similar to that observed in unreinforced structures [39]. However, it can greatly improve the seismic performance of the building in its inelastic range, maintaining its load-carrying capacity and being able to undergo larger deformations without collapsing. The use of ring beams as a strengthening technique in existing buildings is quite difficult, since their installation might require the raising and removal of the roof.

Timber ring beams can be observed in many highly seismic regions of the world and have been used for a long time in both monumental and vernacular architecture. For example, they have been used in Greece during the last 35 centuries and have nowadays become endemic of vernacular constructions in many regions of the country, being part of their local seismic culture [40]. It is also a common practice in other countries, such as Turkey, Nepal, Pakistan and India. Moreover, in recognition of this ancient traditional wisdom, their use has been recently included in the present-day codes of some of these countries as a way of improving the earthquake resistance of low strength masonry and earthen buildings, see the Indian Standards [41,42] and the Nepalese code [43,44].

The connection between the ring beams at the wall intersections has also been typically ensured by means of *corner braces* or *corner keys*. Traditional braces are timber-stiffening elements placed usually diagonally at the corners that help to reinforce the wall-to-wall connections of the building (Fig. 8a). Nevertheless, these braces are not always necessarily attached to ring beams but are also used independently, particularly in earth buildings (Fig. 8b). If they are applied independently, timber wedges are usually used to attach the diagonal struts to the walls in order to limit their movement [45]. Corner braces can simply consist of longitudinal timber beams embedded within the walls at the corners, properly connected (Fig. 8c). This technique also improves the post-elastic

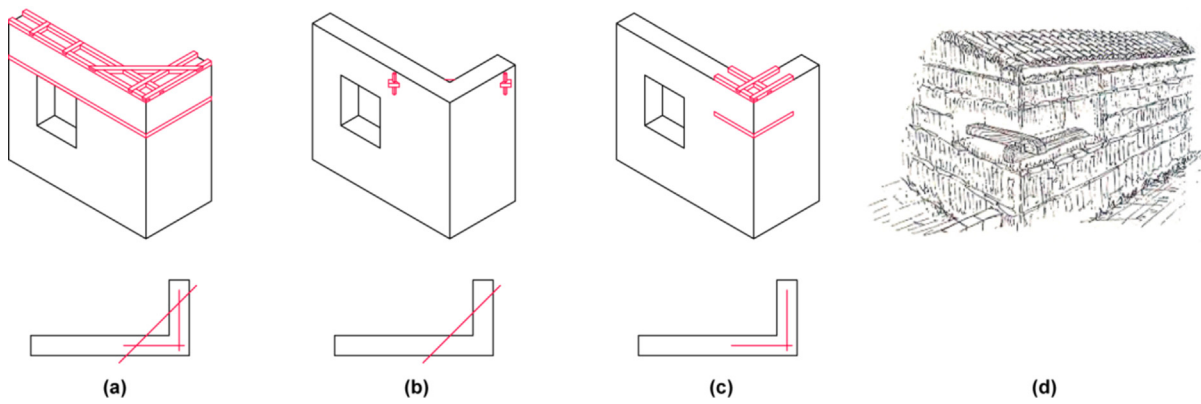


Fig. 8. Different types of corner braces: (a) stiffening ring beams; (b) independent corner brace attached to the wall with wedges; (c) partial ring beam at the corner; and (d) timber corner brace in rammed earth building in Alentejo, Portugal [47].

performance of the walls because it will keep the walls working together even when the joints between perpendicular walls crack during an earthquake. Given the ease of application of this technique as a strengthening solution, it has been traditionally applied in many seismic prone countries, such as Chile, Morocco and Peru [45]. Timber corner braces can also be found in some regions of Portugal (Fig. 8d), but its use is scarce.

The need of strengthening buildings at the corners was already emphasized by Leon Battista Alberti (1404–1472) in his treatise “*De re aedificatoria*”. He recommended thickening the walls at the corners by adding pilasters to reinforce the area [46]. Another common and efficient traditional technique of reinforcing wall-to-wall connections, mainly at the façades, is the construction of *quoins*. This technique consists of using the best quality large squared stone blocks at the corners, carefully bonded to the orthogonal walls by creating an efficient overlapping of the ashlers with the rest of the wall (Fig. 9a). However, the efficacy of quoins is limited when coupled with poor fabric or internally unconnected masonry which tends to become loose [38]. Quoins can be made of other materials, such as brick masonry, when used together with earthen walls. This technique is practically impossible to be implemented other than at the time of construction or during partial reconstruction. Quoins can be commonly found in many stone masonry vernacular buildings composing the historic city centers of many seismic prone regions, such as Italy, Greece and Algeria. There are many examples in Portugal as well, whose old city centers are also mainly constructed with stone masonry (Fig. 9b, c). Moreover, quoins can also be recognized in earthen buildings in some cases in Portugal, where pieces of schist or brick are introduced at the corners as reinforcement [47].

Many technical construction manuals that arose during the nineteenth and early twentieth century in Italy described detailed methods on how to properly connect the floors to the vertical resisting walls [48]. They acknowledged the importance of this aspect in seismic resistant construction in order to prevent the global overturning of the walls. Eventually, these technical solutions were also widely applied in vernacular architecture. Reinforced floor-to-wall and roof-to-wall connections are traditionally achieved using wooden wedges to ensure a tight connection between the walls and the floor or roof joists. Transition elements, such as timber resting plates and stone brackets, are also applied to improve these connections (Fig. 10a–d). Metallic anchoring devices, such as metal brackets, steel straps and ties are typically implemented as strengthening solutions. Reinforced connections can be commonly found in vernacular architecture in many seismic countries, including Portugal (Fig. 10e).

The use of ties for making effective links to hold together the different structural elements of the building is another ancient

practice. Traditionally, ties might be the most often adopted technique to ensure the “box-behavior” of the building and improve its structural integrity. Steel tie rods and wooden tie beams can be systematically observed in highly seismic regions as a reinforcement measure to connect perpendicular load bearing walls, load bearing walls to interior walls, parallel load bearing walls, walls to floors, and walls to roofs (Fig. 11). Ties connecting parallel walls are intended to avoid their out-of-plane collapse but can also constrain the floors and facilitate a better load redistribution among the different walls, improving the overall performance of the system. They are usually placed at the floor and roof levels. Actually, a common vernacular practice is the use of the floor timber joists as ties connecting parallel walls by means of using solutions such as the ones previously described to reinforce their connection with the walls.

Ties have to be well fastened at the ends typically using steel anchor plates in the case of steel tie rods and timber wedges in the case of wooden tie beams. If not properly connected, they can actually be counterproductive and induce significant stress concentrations, causing cracking [49]. Given the fact that ties are easy to implement in existing structures before or after earthquake damage, they have been widely used for many centuries. Wooden tie beams are more frequently used in earthen buildings due to the compatibility of materials, and they can be commonly observed in many seismic prone regions, such as Peru [39]. Steel tie rods are very commonly used to strengthen stone masonry buildings across the Mediterranean region. Their use is also widespread in Portuguese vernacular architecture (Fig. 12).

3.2. Techniques stabilizing structural elements and buildings

3.2.1. Masonry walls

Besides the widespread use of timber ring beams at the top of the loadbearing walls aiming at improving the global behavior of masonry buildings, the insertion of timber elements within the masonry can also be clearly seen as a strengthening method (Fig. 13a). Timber elements are applied due to their excellent tensile properties, becoming successful slip planes in the horizontal direction and helping to dissipate great amounts of energy. This horizontal reinforcement usually runs continuously around the entire building, holding the walls together. Furthermore, it improves the out-of-plane bending and in-plane shear resistance because, by confining portions of masonry walls, it enhances their compressive strength, shear strength and deformability properties [50]. Since timber bands are typically inserted within the entire thickness of the walls, they can also avoid the separation of the leaves in multiple-leaf stone masonry walls and prevent crack propagation.



Fig. 9. (a) Traditional ashlar stone masonry quoin; (b) stone masonry quoin in Lagos, Portugal; and (c) ashlar stone masonry quoin in Vila Real de Santo António, Portugal.

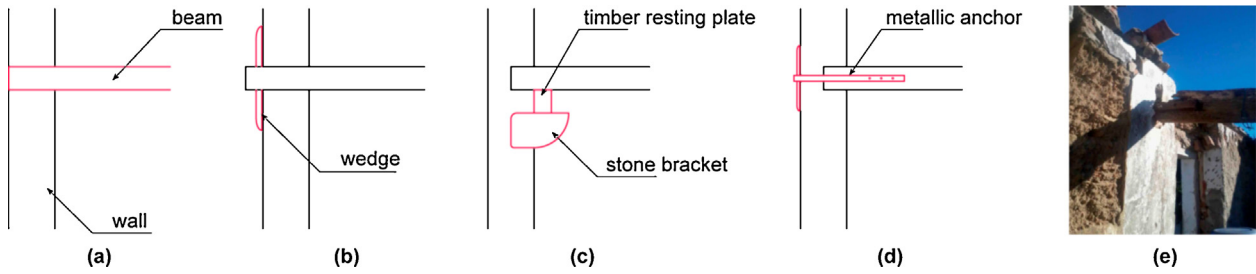


Fig. 10. Different types of reinforced floor/roof-to-wall connections: (a) timber beam resting on the whole width of the wall; (b) timber wedges; (c) timber resting plates and stone brackets; (d) metallic anchoring devices; and (e) roof timber beam strengthened with metal bracket in Melides, Portugal (photo by CI-ESG, 2013).

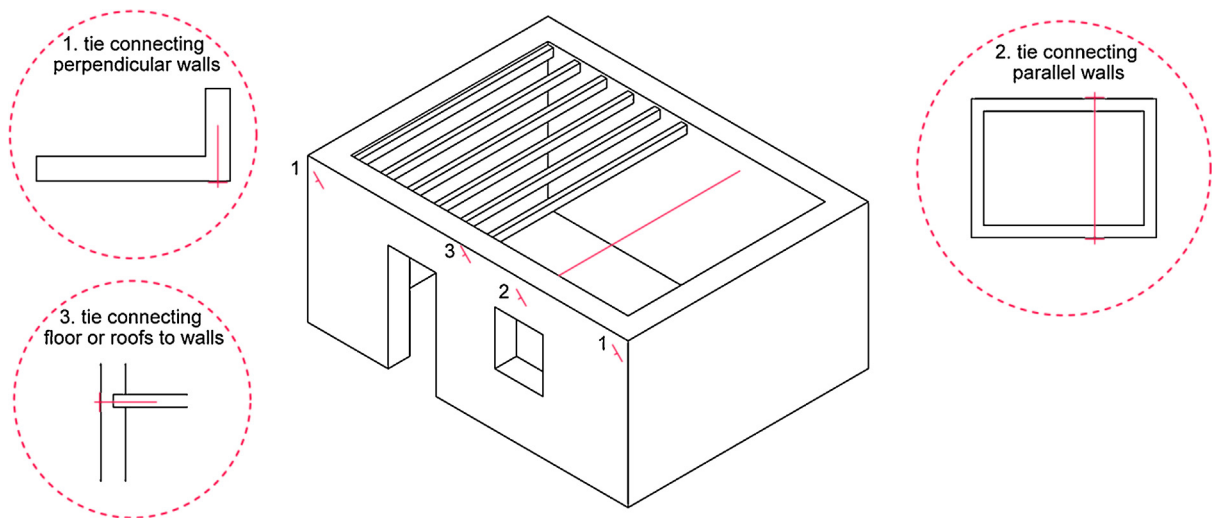


Fig. 11. Different possible locations of ties.



Fig. 12. Ties in Portuguese vernacular architecture: (a) Alcácer do Sal (photo by Mariana Correia, 1997); (b) Melides (photo by CI-ESG, 2013); and (c) Vila Real de Santo António.

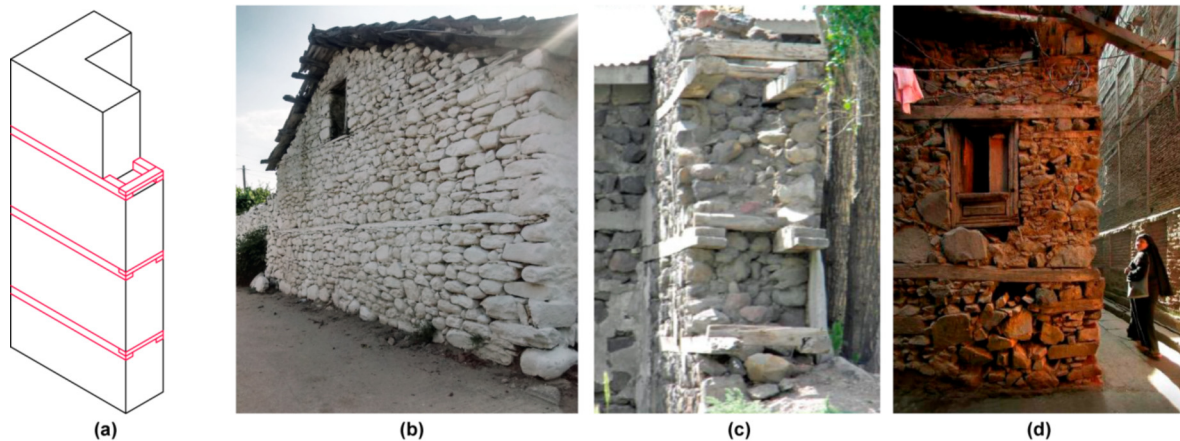


Fig. 13. (a) Traditional way of inserting horizontal timber elements within the masonry walls; (b) timber-laced wall in Greece; (c) timber-laced wall or “hatil” in Turkey [78]; and (d) timber-laced wall or “taq” in India [11].

This is a very common vernacular construction practice in many seismic prone areas such as in Greece, in Turkey, where the resulting timber-laced masonry is generally known as “hatil”, and in India, where it is known as “taq” (Fig. 13b–d). In the case of earthen buildings, bamboo or reed elements can be placed inside the walls as internal reinforcement instead of timber. Timber elements can sometimes be inserted as reinforcement of structural elements other than walls. As an example, logs are inserted on top of the column capital, working as imposts from which the arches are built, in some buildings in the Casbah of Algiers, in Algeria. The presence of the logs allows some slip movement or rolling, providing ductility and energy dissipation in the occurrence of an earthquake [51].

Vernacular builders used other ways of providing ductility to the structural walls without timber. Most of them are based on the same concept of subdivision of the wall, interrupting its structural homogeneity in order to allow relative displacements of the subdivided elements and thus absorb large amounts of energy (Fig. 14). The subdivision of the wall is also beneficial because it arrests crack development. Among the techniques and materials applied for this subdivision, the use of brick horizontal courses that extend through the thickness of the wall is the most common. Rush mats or layers of reed in-between the masonry or between lifts of rammed earth constructions have also been historically used for the same purpose of creating slip planes [52]. Horizontal courses of brick masonry can sometimes be recognized in the Portuguese vernacular practice [47]. This common traditional technique is only practically applicable at the time of construction or during partial reconstruction.

One of the most common earthquake resistant provisions for masonry walls in vernacular buildings is the use of through-stones, also known as bond stones or “diatons” (Fig. 15a). As previously defined, through-stones are long stones placed across the full wall thickness. They help to prevent the separation of the wall leaves, and they provide the walls with greater stability by improving its monolithic behavior due to a better distribution of efforts through the whole section. They can also be placed at wall intersections to improve the connections between walls. The morphology of the wall cross section has a pronounced influence on the stability and bending resistance of the wall. Particularly, the number and position of through-stones can greatly improve the wall structural behavior for both in-plane and out-of-plane seismic action [53]. Through-stones can usually only be implemented at the moment of the construction or during partial reconstruction (Fig. 15b). Timber or metal elements can also be used as transversal ties to connect the masonry leaves and are usable as a strengthening technique.

Post-earthquake repairs such as mended cracks intend to restore the wall integrity and stabilize it. Many techniques can be traditionally applied to repair cracks. Partial reconstructions are used to recover heavily damaged parts of the masonry and fill cracks. However, they are labor-intensive and not very widespread as a traditional repairing technique. In the case of rammed earth structures, an ancient repair technique is soft stitching (Fig. 16a), which mainly consists of cutting chases both internally and externally around the cracks and re-filling them with rammed earth [54]. A common vernacular solution that can be found also in Portugal is the application of metallic staples at the cracks (Fig. 16b, c).

The presence of openings in load bearing walls always indicates a potential seismic vulnerability of the building. A bad positioning, such as openings near the edges, causes stress concentration and cracks to arise, while too many openings or openings with oversized dimensions can greatly reduce the shear capacity of the walls. In order to reduce this seismic vulnerability, vernacular constructions usually present a reduced number of openings and symmetry in their layout. Closed openings can be commonly identified in seismic prone areas, showing the inhabitants awareness of the vulnerability of these elements.

Nevertheless, several traditional ways of reinforcing openings exist, such as the insertion of relieving or discharging arches within the walls, over the openings lintels. They are intended to lighten the load on the lintels and better distribute the load path. Windows and door frames are also traditionally reinforced with big stones or timber lintels, aimed at promoting enough resistance to bending stresses. Double timber window frames used at both sides of the thick walls and adequately linked with the help of cross ties can contribute to a safer dissipation of energy. They have been identified in Italian [48] and Nepalese architecture [55,56]. Brackets are useful reducing the free span of the lintel, and jambs are necessary because of the strong compression forces that concentrate on the bearing area of the lintel. With the exception of the closing of the openings, most of these reinforcement techniques have to be implemented at the time of construction or during partial reconstruction. Portuguese vernacular architecture presents many of these practices (Fig. 17).

3.2.2. Floors and roofs

Concerning the stabilization of roofs and floors, the main idea consists of improving their diaphragmatic behavior by reducing their excessive deformability and adding in-plane and flexural stiffness. In this way, they are able to maintain their integrity during an earthquake and can transfer the lateral loads to the shear masonry walls. Stiffening floors and roofs has been traditionally achieved

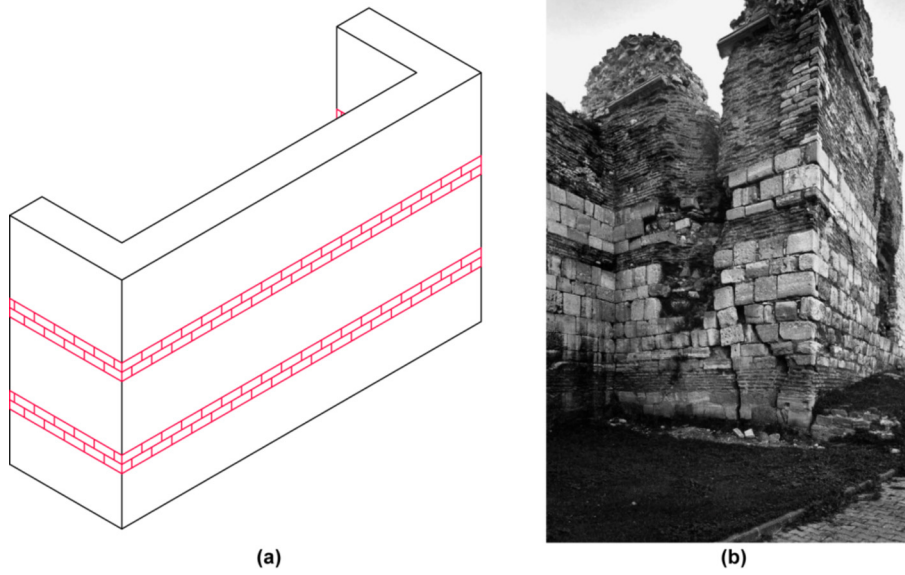


Fig. 14. (a) Subdivision of the wall with brick horizontal courses; and (b) original city wall constructed using horizontal brick masonry bands in Istanbul, Turkey [79].

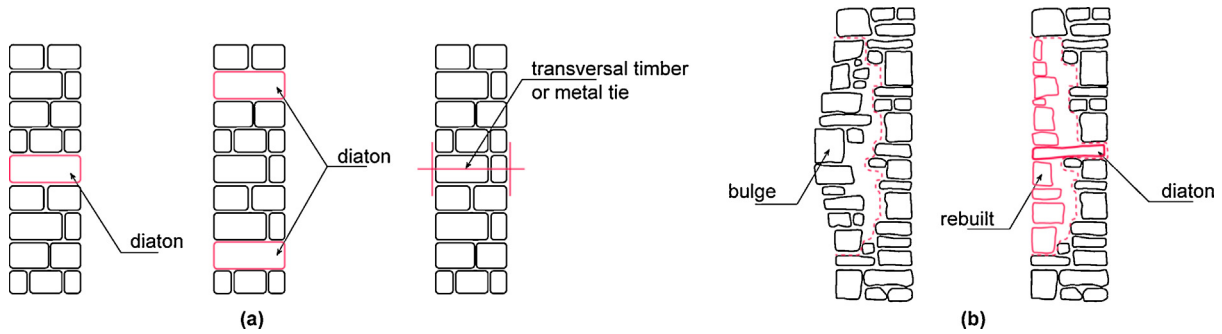


Fig. 15. (a) Use of through-stones or “diatons” and transversal elements; and (b) partial reconstruction of masonry wall using through-stones (adapted from [24]).

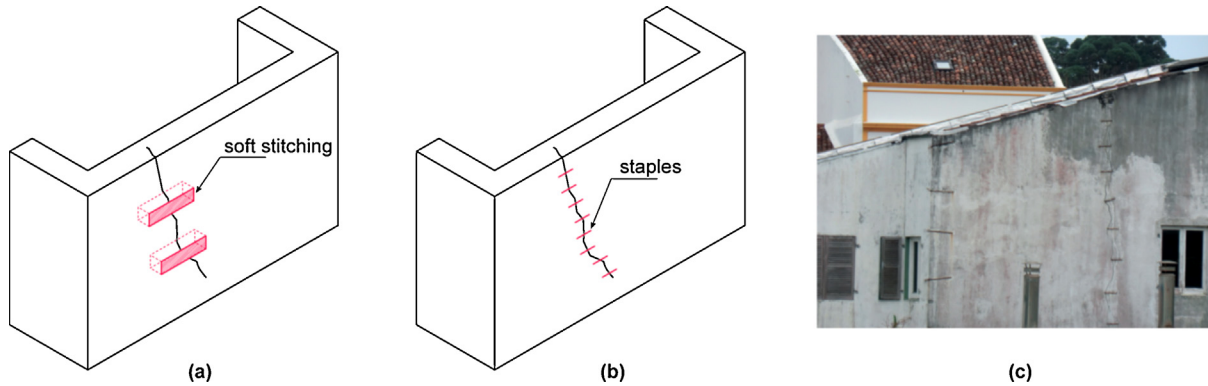


Fig. 16. Mended cracks: (a) soft stitching, characteristic of rammed earth constructions; (b) staples, characteristic of stone masonry construction; and (c) example of mended cracks in Azores, Portugal (photo by Mariana Correia, 2013).

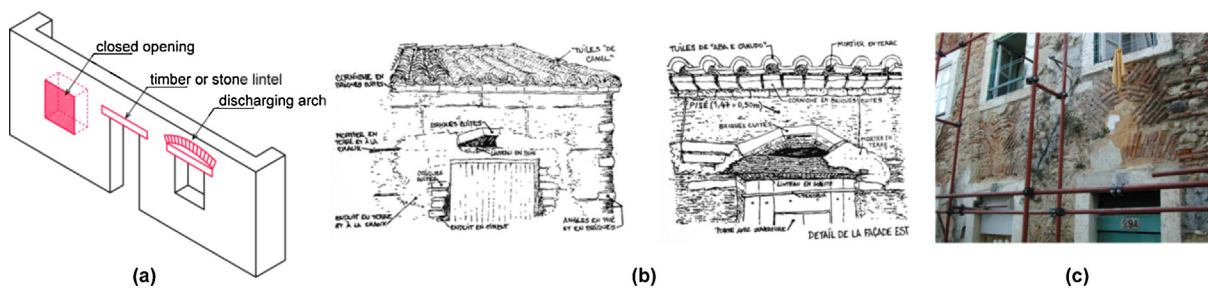


Fig. 17. (a) Traditional ways of reinforcing the openings; (b) brick masonry discharging arches and timber lintels used in rammed earth constructions in Alentejo, Portugal [47]; and (c) discharging arch in Lisbon, Portugal [1].

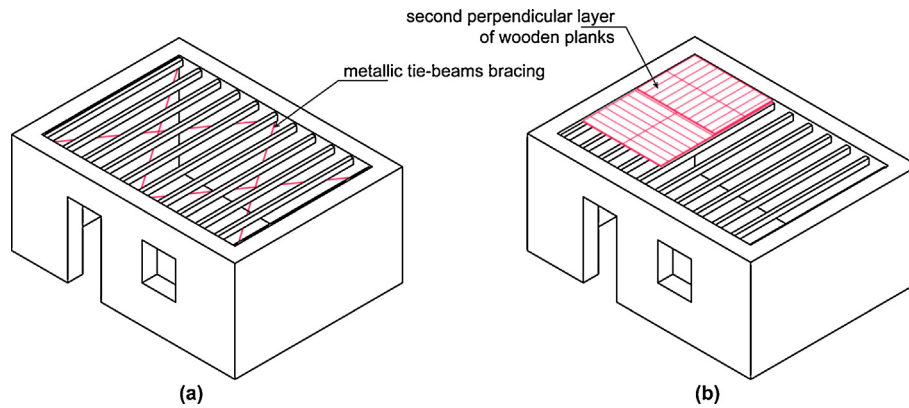


Fig. 18. (a) Traditional way of stiffening floors and roofs by diagonal bracing; and (b) floor stiffening by adding an extra floor layer consisting of wooden planks placed perpendicular to the existing ones.

through diagonal bracing, triangulation, or by providing a further layer of sheathing boards or wooden planks placed perpendicular to the existing one (Fig. 18). All these practices can be implemented as strengthening techniques. An illustrative example of a local seismic culture exists in Galaxidi, on the seismically hazardous Corinthian Bay in Greece. In this case, the typical structural system includes stiffening the ceiling by means of triangulation and proper coupling with the timber reinforcing components located on top of the masonry walls [57].

3.2.3. Timber frames as earthquake resistant systems

The use of structural timber frames in vernacular architecture can be observed in many places around the world, where they are acknowledged as earthquake resistant construction systems. They can be found in Greece, in Turkey, where they are known as “*himis*”, in Northern Pakistan, known as “*cator and cribbage*” [58], or in Kashmir, known as “*dhajji-dewari*” [11]. Even in Central and South America, timber or bamboo frame constructions have been used since Pre-Hispanic times in rural houses and are known as “*bahareque*” in Colombia, Ecuador and El Salvador, “*quincha*” in Peru, or “*taquezal*” in Nicaragua. The good seismic performance of timber frame traditional structures has been reported in many past earthquakes, such as the 1988 Armenian earthquake [59], the 1999 Marmara earthquake in Turkey [60], the 2005 Kashmir earthquake [11], or the 2010 Haiti earthquake [61]. In all these cases, they performed overall better than many new reinforced concrete buildings.

In Portugal, there is a particular case of timber frame construction known as “*Pombalino*”, which can be highlighted as the most representative example of a Portuguese seismic culture. A complex reconstruction process introducing new urban, architectural and structural concepts was devised by the government and mandatorily introduced after the 1755 Lisbon destructive earthquake. It introduced what can be considered the first technical prescriptions regarding seismic resistance [62]. This process has been widely studied [63,64], and the most relevant seismic resistant provision was the inclusion of a three-dimensional braced timber structure named “*gaiola pombalina*” as the internal structure of the building.

The “*gaiola*” is a resistant and flexible cage, whose walls are composed by horizontal, vertical and diagonal timber elements usually filled with rubble or brick masonry and plastered. The external walls of “*Pombalino*” buildings are made of stone masonry and the walls composing the “*gaiola*”, which are known as “*frontal*” walls, act as the shear walls of the building. They are supposed to resist horizontal loads by providing a bracing function, avoiding an out-of-plane premature collapse of the exterior masonry walls while dissipating substantial amounts of energy (Fig. 19a). A minimal

timber skeleton is occasionally also present in the inner face of the exterior masonry walls, facilitating the connection with the floors and the inner shear walls.

This constructive system was adopted by local communities as a model of earthquake resistant construction. Its use spread around the country, eventually taking root in the vernacular way of building and becoming part of the Portuguese local seismic culture [65]. Nowadays, “*frontal*” walls can be identified in many vernacular constructions scattered across the country (Fig. 19b–d). A relevant example is the case of the town of Benavente, where this seismic resistant construction system was chosen for the reconstruction works of the city after the 1909 devastating earthquake, based on the Lisbon experience. According to Vieira (2009) [66], all the rebuilt districts of the town have buildings with a timber skeleton. A similar experience took place in Calabria (Italy), where the government developed another similar timber frame earthquake resistant system, known as “*casa baraccata*”, after the 1783 earthquake [67,68]. Again, the imposed reconstruction solution with timber frame buildings was eventually adopted by vernacular builders and several buildings testify to its widespread application in the region.

3.3. Techniques allowing partial collapse of structural elements

A key aspect for a building to sustain damage without total collapse is the redundancy of structural elements so that the failure of certain members does not mean the failure of the building. Structural redundancy is a very efficient seismic resistant technique that was traditionally achieved by the simultaneous use of timber and masonry structural elements (Fig. 20). The most representative example of this technique and illustrative of the development of a local seismic culture can be observed in the island of Lefkas, in Greece. The periodic recurrence of earthquake in the island led the inhabitants to improve the seismic resistance of their constructions and to work out an indigenous structural system that effectively resisted earthquake loading. This system is thus a consequence of the practical need of inhabitants to respond to the local conditions, and it emerged from a long traditional practice [69]. Additionally, after the 1825 destructive earthquake, its use was also imposed by the English government, which occupied the island at the time [7].

The structural system includes a highly perfected timber frame but the most significant resistant characteristic is the structural redundancy. The ground floor of the buildings is constructed with load bearing thick masonry walls but timber structural columns are also present as a secondary structure, independent from the first one. In this way, the masonry walls can collapse in the event of an earthquake and tend to be thrown towards the exterior due



Fig. 19. (a) Traditional structural timber frame “frontal” wall; (b) “frontal” wall in Benavente, Portugal [80]; (c) “frontal” wall in Alcácer do Sal, Portugal [1]; and (d) “frontal” wall in Vila Real de Santo António, Portugal [66].

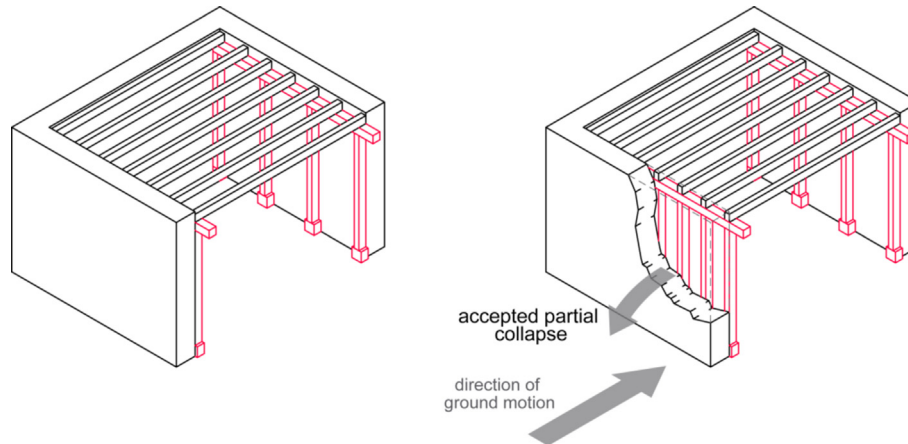


Fig. 20. Structural redundancy: the use of a dual load bearing structure allows the partial collapse of some elements while keeping the construction standing.

to the presence of the timber structure in the interior. The timber structure does not collapse because it is supported by the timber columns and keeps the building standing with the timber frame second floor and the roof intact. As a result, the people inside the building are more protected and the masonry walls can be easily and rapidly repaired. Today, this system is still common and widespread in the island and has proven to behave well against earthquakes. In the 2003 earthquake, none of these traditional buildings suffered total collapse, even though some three-story reinforced concrete buildings did, and just several of them suffered partial collapse of the timber frame masonry infill or the ground floor masonry walls [70].

The redundancy of structural elements is also a characteristic feature of some Chinese traditional buildings, in which timber beams and columns are the main structural elements, but heavy masonry walls made of adobe or brick are also commonly built in between columns. These walls highly increase the stiffness of the building but, due to their poor shear strength, are vulnerable to earthquakes. According to Zhiping [71], their collapse during an earthquake reduces the earthquake action and therefore it is accepted and expected. In addition, as there is no link between the walls and the columns, it does not endanger the timber frame, keeping the building standing. It should be mentioned that this is also a characteristic feature of the previously discussed “*pombalino*” buildings. During a seismic event, the heavy masonry façade can fall, together with the roof tiles and the plaster of the inner walls, but the inner timber skeleton is supposed to keep standing, avoiding the complete collapse of the building. Nevertheless, all these construction typologies were conceived at the time of the construction of the building. Therefore, they can only be implemented as a strengthening technique by introducing new structural elements in the building, which can be rather invasive and unacceptable.

3.4. Techniques counteracting horizontal loads

Techniques based on providing a counteracting effect against the buckling tendency of a wall are very common in most seismic prone regions [6]. The most common and widespread traditional strengthening technique used for resisting and counterbalancing seismic horizontal forces is the construction of *buttresses* or counterforts. They can also be known as pilasters if they are embedded within the walls in rammed earth buildings. They can be built at the same time as the building, as a deliberate feature, or they can be added as a reinforcement measure. They consist of pier-like, massive local additions typically of masonry, whose working principle is to counter the rotation of the façade thanks to their shear mass (Fig. 21).

When adding a buttress as reinforcement, special attention should be put at its connection with the original walls. If they are not properly connected, they add little or no stability to the building, acting independently and only when the wall moves towards the buttress. They can even be prone to rock against the wall if the movement is the opposite, imposing an extra load. Therefore, it is recommended to tie the buttresses to the walls using, for example, cross ties [39]. Buttresses should be placed at critical locations, such as the mid-span of long walls, which are the most vulnerable elements to the effects of out-of-plane earthquake vibrations, and at the corners, in order to avoid the separation of the walls. They can be found in most seismic prone regions, such as Peru and Italy, but are also very common in Portugal (Fig. 22). Buttresses are also very common in an urban environment, and are distinctly a reinforcement measure because, when added to the buildings, they invade the public space, sacrificing the comfort of the inhabitants in pursuit of the seismic safety (Fig. 22a). Sometimes, other urban structures, such as external stairs, can also achieve a similar role of counteracting the rotation of the walls (Fig. 22c).

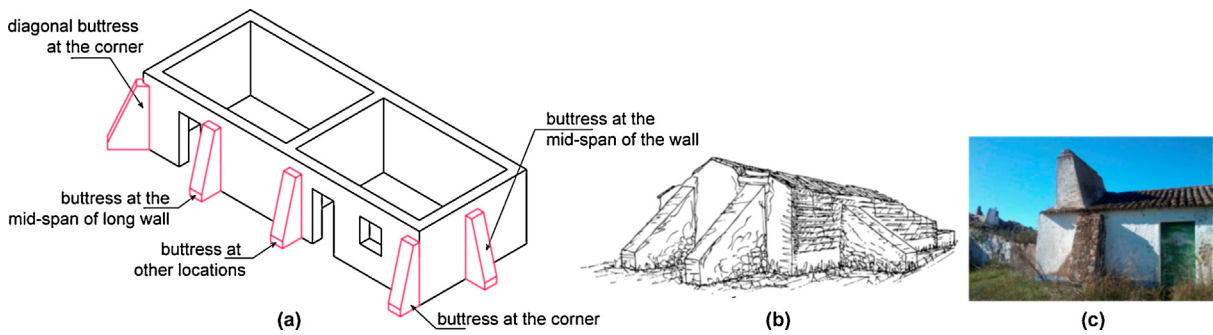


Fig. 21. (a) Different possible locations of butters; (b) butters in Redondo, Portugal [47]; and (c) butters in the region of Évora, Portugal (Photo by CI-ESG, 2013).



Fig. 22. (a) Butters invading the side walk in Samora Correia [1]; (b) two-floor butters in Évora [1]; and (c) external staircase in Benavente [1].

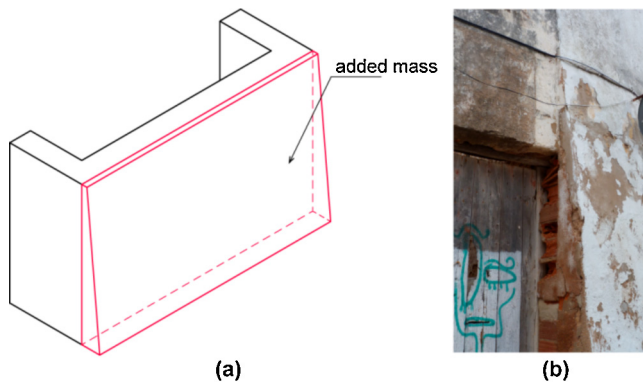


Fig. 23. (a) Traditional thickening of the wall by adding mass and increasing the resisting cross section; (b) example of thickened wall in Lagos, Portugal.

Another traditional seismic resistant concept is to lower the center of gravity of the buildings. This has been traditionally achieved by using scarp walls, decreasing the thickness of the upper floors walls, and using light timber floors and roofs. The combination of two different structural systems, using the lighter one on the upper floors, is also common. Usually, the ground floor is built with stone masonry and a timber frame system is used in the upper floors. This is a common practice in Turkey and Greece, but also in Portugal [72]. A traditional strengthening technique aimed at lowering the center of gravity of the building consists of thickening the walls by means of adding mass to the ground floor walls (Fig. 23). This technique increases the resisting area of the walls and reduces their height-to-thickness ratio, which improves their out-of-plane resistance and reduces the possibility of overturning.

In urban environments, other common reinforcement elements are urban reinforcing arches, also known as butters arches. They are usually made of masonry and span the streets, joining facing buildings at the level of their floors (Fig. 24a). These alterations of the historical built-up areas effectively lead to the collaborative action of neighboring constructions, enabling the horizontal

movements to be redistributed among their structural elements. In order to perform an effective reinforcing function, reinforcing arches should be properly connected with the old structures, and they should avoid differences in the level of the floors or ceilings, which may lead to dangerous eccentricities. Similarly to the butters, these arches work as propping structures and do not have an influence under static conditions. They are the typical historical solution to avoid the development of out-of-plane mechanisms at an urban level in villages built mainly of stone masonry, such as Italians, and have become part of their historical fabric. They can also be recognized in many Portuguese cities, such as Lisbon, Évora and Lagos (Fig. 24b–d).

Urban reinforcement arches and butters can eventually transform into other urban elements that accommodate new uses, since their construction can result in an increase in volume and in new space available for the building. In this way, these added structures can eventually become habitable and turn into loggias, vaulted passageways or arcades, fulfilling simultaneously a structural and a functional role, with the addition of new paths and rooms. The use of these elements can be counterproductive if the reinforced buildings have insufficient thick walls and thus are not able to produce counterthrust that centers the new horizontal forces exerted by the arcades and habitable butters [73].

3.5. Summary

Aiming at providing a general overview of the earthquake resistant techniques observed in vernacular architecture, a summary is presented in Table 1, arranged following the typologies previously defined.

The table highlights the type of damage that can be avoided applying each technique, as well as the applicability of the different techniques as strengthening solutions. The applicability as strengthening technique refers to the ease of use of the technique for strengthening existing buildings, where “difficult” indicates that the technique should be better implemented at the time of the construction or during partial reconstruction, and ‘practical’ indicates

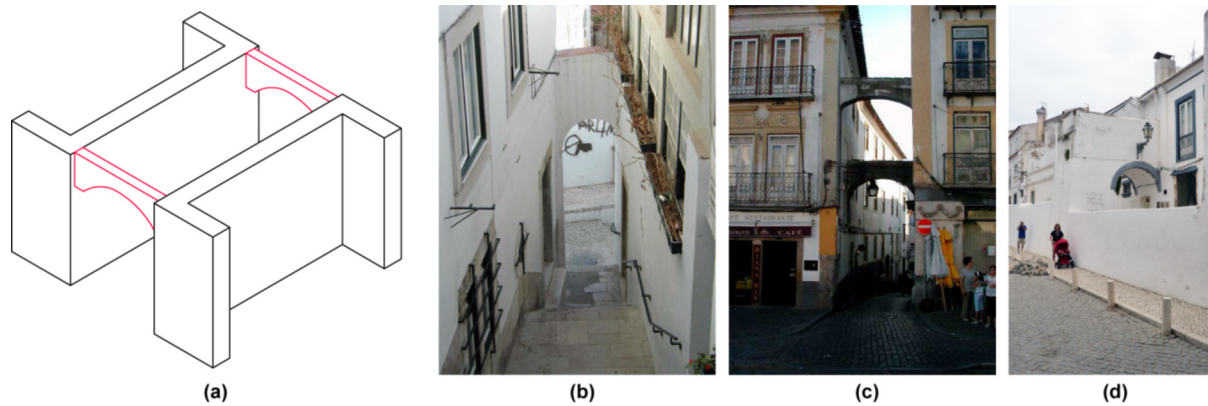


Fig. 24. (a) Traditional urban masonry reinforcing arches; (b) reinforcement arch in Alfama, Lisbon [1]; (c) reinforcement arches in Évora [1]; and (d) vaulted passage in Lagos, Portugal.

Table 1
Summary of traditional earthquake resistant techniques classified according to the typologies defined and highlighting: (a) type of damage avoided; and (b) applicability or ease of use as a strengthening technique.

| Technique | Damage prevention | | | Applicability as strengthening technique ^a | | |
|---|-------------------|--------------|--------------|---|-----------|-----------|
| | Separation | Out-of-plane | Delamination | In-plane | Difficult | Practical |
| <i>1. Techniques improving the connection between structural elements</i> | | | | | | |
| Ring beam | X | X | X | X | X | |
| Corner braces | X | | | | | X |
| Quoins | X | | | | X | |
| Reinforced floor-to-wall and roof-to-wall connections | | X | | | | X |
| Ties | X | X | | | | X |
| <i>2. Techniques stabilizing structural elements and buildings</i> | | | | | | |
| Timber elements within the masonry | X | X | X | X | X | |
| Wall subdivision | | X | X | X | X | |
| Through-stones | X | X | X | X | | X |
| Mended cracks | | X | | X | | X |
| Reinforcing openings | | X | | X | X | |
| Stiffening floors and roofs | | X | | X | | X |
| Wall structural timber frame | X | X | X | X | X | |
| <i>3. Techniques allowing partial collapse of structural elements</i> | | | | | | |
| Redundancy of structural elements ^b | | | | | X | |
| <i>4. Techniques counteracting horizontal loads</i> | | | | | | |
| Buttresses | X | X | | | | X |
| Walls thickening | | X | | X | | X |
| Urban reinforcing arches | | X | | | | X |

^a The applicability as strengthening technique refers to the ease of use of the technique for retrofitting existing buildings, where “difficult” indicates that the technique should be better implemented at the time of the construction or during partial reconstruction, and “practical” indicates that the technique can be and have been successfully applied for strengthening.

^b Damage of certain structural elements is tolerated, such as the out-of-plane collapse of the walls.

that the technique can be and have been successfully applied for strengthening.

4. Conclusions

This paper provides an overview of the most common seismic resistant provisions traditionally used in vernacular architecture associated with local seismic cultures, and classifies them according to the damage prevention and their possible applicability as strengthening measures. Sometimes, it can be difficult to associate changes or innovations in the construction techniques to the existence of a seismic culture. However, even if they were or not consciously developed to minimize damages produced by an earthquake, a sort of natural selection of the successful designs that have continually proven to withstand earthquakes have most likely occurred. If something has become traditional is because it has been 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.

Most of the reviewed techniques can also be identified in Portugal, particularly where past earthquakes took place in the past, namely in Lisbon and other cities located in the south region of Portugal, which is also considered as a moderate seismic hazard region. However, signs of seismic culture in these regions seem to become scarcer and essentially abandoned. Portugal seismicity is distinguished by large periods of time without seismic events and this has led to the development of a reactive response behavior in which local communities usually just respond to earthquakes in the immediate aftermath of the event. This means that there has been a seismic concern and awareness at particular times in the past. Important measures and seismic resistant construction techniques, such as the “Pombalino” construction system, were devised and implemented after the infrequent destructive earthquakes, and they eventually became part of the indigenous knowledge. Nevertheless, the large periods of time without earthquakes resulted in the removing and abandonment of these elements, particularly in rehabilitation processes or in the adaptation of the buildings to other uses. Therefore, Portugal is considered to belong to those cases where there has been an abandonment of a local seismic culture led by the loss of the seismic awareness of the population.

The appreciation and successful protection of the vernacular heritage is a demand of the modern societies, but it highly depends on the involvement and support of the community. Thus, the dissemination of local seismic cultures is a must in order to contribute to the reawakening of the risk awareness of local communities. Local communities should be encouraged to readopt some of the reviewed traditional techniques in order to reduce the seismic vulnerability of their constructions. Research in these traditional provisions and in its possible use as seismic strengthening for existing in-use vernacular architecture is, therefore, justified. Besides, the use of traditional solutions is in accordance with the modern principles of preservation of the vernacular heritage regarding compatibility and authenticity, since they use similar materials and techniques. This paper is a first step and consisted of the identification of earthquake resistant techniques traditionally used throughout the world, with a parallel analysis of the Portuguese context. Future work must include the validation and update of the most adequate solutions for its eventual application for the strengthening of vernacular architecture.

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