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Assessment of the efficiency of traditional earthquake resistant techniques for vernacular architecture

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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 practices, resulting from a local seismic culture, is a relevant and positive approach, since it focuses on the strength of the system rather than on its weaknesses. Its integration into current vernacular building practices can help to preserve and retrofit surviving in-use examples while respecting their authenticity. The main goal of the present work is to assess numerically the efficiency of traditional earthquake resistant solutions to mitigate the seismic vulnerability of vernacular architecture. The paper thus presents the results of a detailed numerical study based on finite element modeling and nonlinear static (pushover) analysis intended to quantitatively evaluate the influence of each technique on the seismic behavior of vernacular constructions and to better understand their structural role under seismic loading.

1. Introduction

Earthquakes are naturally occurring events that affect negatively people and their environment by causing loss of life, injury, property damage, social and economic disruptions or environmental damage. Since they seriously disrupt the functioning of a community, local builders have thus often integrated seismic risk as a determinant for construction, adopting different strategies to protect the population from these natural disasters. They have developed rich and varied knowledge resulting in singular construction techniques, building details and temporary technical devices aimed at reducing the vulnerability of structures. The existence of a local seismic culture (LSC) was recognized and firstly investigated by Ferrigni [12]. From that moment on, a LSC has been identified in many countries throughout the world frequently exposed to earthquakes, such as Italy [43], Greece [49], Turkey [18], Algeria [13], Iran [36], India [24], Nepal [15], Japan [40], Haiti [2], Colombia [34]and Portugal [41].

LSC thus emerges from the need of local population to react to earthquakes and from the efforts made for the physical community to survive. 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 [6]. In any case, traditional earthquake 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, giving rise to the development of a LSC, can become a key element for the preservation of cultural identity and vernacular construction practices. They can eventually help to preserve existing vernacular buildings while respecting their authenticity. However, since these traditional techniques are typically the result of empirical knowledge transmitted along generations, a numerical evaluation and analytical comprehension of their possible beneficial effect in the seismic resistance of vernacular buildings is necessary.

Therefore, the present paper addresses the gap in knowledge about the real efficiency of the most common measures adopted by local communities to repair and restore their dwellings. A better awareness of traditional earthquake resistant measures and a better understanding of their structural role when subjected to earthquake loading is considered 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. For that matter, the paper firstly outlines briefly some of the most

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common techniques traditionally used throughout the world, focusing on those that will be later further evaluated numerically. Secondly, the paper introduces the numerical strategy adopted for the evaluation of the efficiency of the different techniques in improving the seismic behavior of vernacular buildings. Thereafter, the paper presents and discusses the numerical assessment of each technique independently, following the same organization: (a) description of the numerical models prepared for the simulation of the different strengthening solutions; and (b) discussion of the results showing a comparative analysis of the seismic performance of the buildings with and without the different techniques in terms of damage patterns, failure mechanisms and strength capacity. Finally, the paper will present a summary of the different traditional earthquake resistant techniques particularly addressing their effect on the seismic behavior of vernacular buildings in terms of the particular construction and structural aspects that are improved with the use of the different techniques. This summary is provided as a conclusion and can be helpful as a criterion for decision-making on the seismic strengthening of vernacular constructions.

2. Traditional earthquake resistant techniques for vernacular architecture

The numerical study presented is based on previous research on traditional earthquake resistant solutions resulting from a local seismic culture carried out by Ortega et al. [41], who presented a comprehensive overview of the use of the different techniques around the world and particularly elaborated on their structural role and earthquake resisting concept. As a continuation of the abovementioned work, the present paper will delve further into this specific subject with the help of finite element (FE) modeling and nonlinear analysis. The traditional earthquake resistant techniques previously identified that will be now further evaluated using numerical analysis are summarized in Table 1.

Since traditional earthquake resistant techniques mainly follow similar earthquake resisting principles, the table is arranged according to them and makes reference to the type of damage that can be avoided with the application of each technique. One of the most common earthquake damage patterns observed is the separation between structural elements, which is typically led by a lack of structural integrity, i.e. deficient wall-to-wall connections or inadequate wall-to-roof and wall-to-floor connections. That is why many traditional techniques are intended to improve these connections, 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. A proper transfer of forces also ensures the 'box-behavior' of the building by enhancing the development of in-plane resisting mechanisms in the walls, which are typically the main structural elements in vernacular buildings. The first group thus includes techniques that are mainly aimed at improving the connections between the different structural elements, such as ring beams, corner braces, quoins and ties.

Table 1
Summary of traditional earthquake resistant techniques numerically evaluated, classified according to the main earthquake resisting principle and highlighting the type of damage avoided.

Technique	Damage prevention				Section
	Separation	Out-of-plane	Delamination	In-plane	
1. Techniques improving the connection between structural elements					
Ring beams	X	X	X	X	4.1
Corner braces	X				4.2
Quoins	X				4.3
Ties	X	X			4.4
2. Techniques stabilizing structural elements and buildings					
Timber elements within the masonry	X	X	X	X	4.5
Wall subdivision		X	X	X	4.6
3. Techniques counteracting horizontal loads					
Buttresses	X	X			4.7
Walls thickening		X		X	4.8

The second set of techniques includes those aimed at stabilizing structural elements and buildings by imparting resistance and deformation capacity to the typically brittle stone masonry or earthen walls. This added strength to the main resisting structural elements can result in preventing common out-of-plane failure patterns associated to the bending of the masonry walls or in-plane failure associated to the typically low shear strength of earthen and stone masonry materials. Additionally, by enhancing the quality of the masonry with the use of new elements that ensure an adequate bracing between the wall leaves, these techniques can also prevent the common delamination or bulging of the external wall leaf commonly observed in stone masonry walls. The use of timber elements within the masonry and the wall subdivision by means of brick horizontal courses are common techniques that follow this principle.

Finally, the last group of traditional earthquake resistant techniques corresponds to those that are meant to counteract horizontal loads exerted by the buildings during the shaking by adding extra resistance to the lateral thrust with the addition of new structural elements. The most common and widespread technique belonging to this group is the construction of buttresses or counterforts. They are typically 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. Another efficient technique of this kind is thickening the walls, which adds extra in-plane resistance because of increasing the resisting area. Moreover, it can also help to prevent common out-of-plane mechanisms and reduces the possibility of the walls to overturn because it reduces their height-to-thickness ratio.

3. Numerical strategy

The numerical study proposed to evaluate the influence of the traditional seismic strengthening techniques shown in Table 1 was performed using detailed FE modeling following a common macro-model approach together with nonlinear static (pushover) analysis. The strategy consists of first constructing a reference FE model based on representative vernacular rammed earth constructions commonly found in the South Portuguese region of Alentejo. The different strengthening solutions considered will be then simulated and applied to the reference model. Several numerical models will be prepared for each technique, reproducing different construction characteristics that can typically vary. Therefore, the numerical study also comprises individual parametric analyses for the different solutions in order to assess how the variations influence the seismic response of the structure by means of comparison with the response of a reference numerical model. This will provide a better understanding of the seismic behavior of these traditional earthquake resistant solutions and their particular structural role showing different characteristics in terms of construction, geometry and materials.

Despite being a simplified procedure because of simulating the earthquake loading as a set of equivalent static forces, pushover analysis is a widespread and generally accepted tool for the seismic assessment of existing buildings, due to the relatively low computation demand in comparison with other methods, such as nonlinear dynamic analysis. Similarly, the macro-modeling strategy also simplifies the heterogeneity of the masonry into a single material with average material properties. However, their combined use represents a good compromise between efficiency and accuracy, and has provided successful results for the analysis of the seismic behavior of complex historical masonry and rammed earth structures [25,30,3,27,45,29]. Since the planned numerical campaign comprised a significant number of