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Efficiency of strengthening techniques assessed for existing masonry buildings

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ABSTRACT

The Azores archipelago is a zone with a vast cultural heritage, presenting a building stock mainly constructed in traditional stone masonry. It is known that this type of construction exhibits poor behaviour under seismic excitations; however it is extensively used in seismic prone areas, such as this case. The 9th of July of 1998 earthquake was the last seismic event in the islands, leaving many traditional stone constructions severely damaged or totally destroyed. This scenario led to an effort by the local government of improving the seismic resistance of these constructions, with the application of several reinforcement techniques.

This work aims to study some of the most used reinforcement schemes after the 1998 earthquake, and to assess their effectiveness in the mitigation of the construction's seismic vulnerability. A brief evaluation of the cost *versus* benefit of these retrofitting techniques is also made, seeking to identify those that are most suitable for each building typology. Thus, it was sought to analyze the case of real structures with different geometrical and physical characteristics, by establishing a comparison between the seismic performance of reinforced and non-reinforced structures. The first section contains the analysis of a total of six reinforcement scenarios for each building chosen. Using the recorded 1998 earthquake accelerograms, a linear time-history analysis was performed for each reinforcement scenario. A comparison was then established between the maximum displacements, inter-storey drift and maximum stress obtained, in order to evaluate the global seismic response of each reinforced structure. In the second part of the work, the examination of the performance obtained in the previous section, in relation to the cost of implementing each reinforcement technique, allowed to draw conclusions concerning the viability of implementing each reinforcement method, based on the book value of the buildings in study.

1. Introduction

The central group of Azores, in particular the island of Faial, is characterized for being a zone of high seismic intensity. On the 9th of July 1998 earthquake, the last seismic event in the islands, many examples of different types of failure were observed, with several masonry constructions behaving very badly, leading to a significant number of total or partial collapses. In a total of 8720 constructions, 2100 buildings were destroyed and 2900 were seriously damaged [1]. This scenario revealed the importance of the preservation of traditional stone masonry buildings and their inherent cultural heritage, constituting one of the essential principles of rehabilitation and adaptation to seismic activity on the island after the 1998 earthquake. This reinforcement campaign is a great source of data for the improvement of future interventions. By taking into account what has already been done in terms of seismic reinforcement, it is possible to increase the knowledge of this type of construction and the most suitable retrofitting methods.

In this context, a study was developed covering six construction typologies most used in the island. Different techniques for seismic strengthening were analyzed, seeking to identify those that offer the best seismic performance.

The addressed case studies were part of a post-earthquake survey that provided some information regarding the damages suffered by the structures. The data from observed damages were compared with numerical simulations, using the real earthquake records that hit the constructions under analysis. The numerical analysis was performed with a finite element method, which is one of the most powerful and accurate approaches to simulate

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masonry structures. Depending on the objectives set for the analyses, this method can be applied to different detailing levels, from micro to macro elements. Works like the one presented in [2] follow a detailed micro modelling for masonry, dividing the material into its basic components. This kind of modelling is only adequate for studying local effects because it requires detailed knowledge of the masonry structure, geometrical characteristics, and has high computation demands.

To analyze the structures' dynamic response, a simplified numerical strategy using macro-modelling was adopted. This approach does not distinguish between individual units and joints; instead it treats masonry as a homogeneous anisotropic continuum with an equivalent elastic modulus. Macro-models are applicable when the structure is composed of solid walls with sufficiently large dimensions that the stresses across or along a macro-length will be essentially uniform. Clearly, macro-modelling is more practice-oriented, owing to the reduced time and memory requirements as well as a user-friendly mesh generation. This type of modelling is more valuable when a compromise between accuracy and efficiency is needed [3]. Good examples of application of this type of models are presented in works such as [4,5].

Another important aspect to account in an accurate modelling is the idealization chosen to simulate the structural behaviour, keeping in mind that a complex analysis is not always synonym of a better result, and the choice of a method over the other depends mostly on the purpose of the analysis. Nonlinear analysis is able to trace the complete response of a structure from the elastic range, through cracking and crushing, up to complete failure, being, for this reason, the most powerful method [3]. Works like the one presented in [6], aims at evaluating the capacity of a nonlinear continuum damage model to simulate the behaviour of stone masonry construction. Linear elastic analysis assumes that the material obeys Hooke's law. This is hardly the case for masonry under tension, which cracks at very low stress levels. Nevertheless, this type of analysis allows an identification of the most susceptible zones to crack when solicited to an earthquake action. Moreover, it is possible to choose the most likely collapse mechanisms and the subsequent definition of adequate rehabilitation and strengthening procedures. Neves et al. [7] followed a similar process in the seismic evaluation of a building block, with good results.

In order to correctly simulate the response of a given structure, the characteristics must be well known. The knowledge of traditional stone masonry behaviour and mechanical characteristics is not as developed as other types of construction, such as reinforced concrete, although it accounts for a quite significant part of the built stock. This is due to the fact that masonry construction (and traditional stone masonry in particular) still remains with important lack of experimental characterization because it is strongly dependent on its constitution, materials, constructive process and actual connection conditions between different structural elements [8]. However, several experimental studies [2,8–10] have been developed, in which was sought to characterize the out-of-plane and in-plane behaviour, as well as the mechanical properties of traditional masonry walls. In [9], a presentation has been made of simple testing techniques developed for the physical and mechanical characterization of stone masonry walls traditionally used in dwellings of the Faial Island. These tests also allowed assessing the efficiency of two strengthening techniques applied to the dwellings. Nine years later, a test setup based on a self-equilibrated action-reaction scheme was presented, applied to a single-storey [10] and to a two-storey building [8]. In addition, the influence of strengthening techniques used after the 1998 Azores earthquake was also tested making use of the existing walls which were strengthened and retrofitted. On the other hand, [2] addresses the in-plane behaviour characterization of a stone masonry wall, proceeding with a complex numerical modelling of the tested specimen and, finally, assessing the efficiency of a retrofit/strengthening technique.

These studies provide a better insight of the dynamic behaviour of masonry elements and allow a better calibration of numerical models used to simulate stone masonry constructions.

The current paper seeks to continue the work developed, making use of the information previously gathered to develop an analytical study of the performance of real buildings impacted by the 1988 Azores earthquake, subjected to different retrofitting methods. Thus, six study cases were chosen to assess the influence of reinforcement solutions used in the rehabilitation of the building stock of the Faial Island after the 1998 earthquake, as reported by Arêde et al. [12]. The selection of the techniques sought mainly the reinforcement of the structure to the global level, by strengthening the connections between structural elements and also the connection of the superstructure to the foundation, but also a local intervention on the masonry material.

To study the interaction of these reinforcement schemes and their effects on the original structures, linear time-history analyses were used, seeking to identify the improvement in terms of dynamic response of the buildings. This was achieved by establishing a comparison between their seismic indicators such as maximum displacements, inter-storey drift and maximum stress. Using the data obtained from this analysis, it was possible to evaluate the applicability of each reinforcement method, based on a cost *versus*. benefit confrontation. This methodology was applied to all the study cases, which allowed drawing conclusions regarding the choice of the most suitable solution for each building typology.

The following sections provide an overview of the assumptions made in the numerical modelling of the structures, as well as the strengthening scenarios considered in the analysis. Next, a presentation of the adopted analysis methodology is made, identifying the main results obtained for one of the case studies. The work concludes with the evaluation of the cost/benefit ratio of each strengthening strategy, for each structure considered, presenting also the results obtained for one of the case studies.

2. Presentation of the study cases

2.1. Building description and structural typology

Six houses were chosen with the objective of analyzing the effect of an earthquake on stone masonry buildings with different geometric characteristics. Thus, it was sought to select houses with different configurations, both in plan or height. Priority was given to isolated buildings, so that the results found were not compromised by adjacent structures.

Houses one to four are isolated buildings of rural locations and all have very similar structural characteristics. The exterior walls are the main structural elements; these are made of stone masonry with a total thickness of 70 cm. These support the horizontal wooden structures of the roof and floor. This connection is made mostly by friction, given by the materials self-weight. The partition walls – wooden panelling – were not considered in the numerical modelling, because their reduced stiffness does not influence the overall response of structures. This evidence was also numerically stated by Ramos et al. [5] making use of even stiffer internal walls.

The first house has only one floor and is rectangular in plan, with a small adjacent outbuilding (1). The second house has two stories. On the ground floor there is a shopping area, separated from the residential area by a stone masonry wall. The main façade has a stone staircase leading to the second floor. It also has a traditional stone oven inside, which supports floor beams and roof joists