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The seismic performance of stone masonry buildings in Faial island and the relevance of implementing effective seismic strengthening policies

Rui Maio [a,*], João M.C. Estêvão [b], Tiago M. Ferreira [c], Romeu Vicente [a]

[a] Department of Civil Engineering of the University of Aveiro, RISCO – Aveiro Research Centre of Risks and Sustainability in Construction, Portugal
[b] Department of Civil Engineering of the University of Algarve, Portugal
[c] Department of Civil Engineering, University of Minho, ISISE – Institute for Sustainability and Innovation in Structural Engineering, Portugal

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ABSTRACT

Enhancing the seismic performance of traditional stone masonry buildings is considered a crucial measure towards the preservation and safeguarding of our built heritage, particularly in seismic prone areas such as the Azores archipelago, in Portugal. In this context, the present paper is focused on the seismic vulnerability assessment of two traditional stone masonry building located in the Faial Island, taken as typologically representative of the rural Azorean building stock.

The case study buildings were modelled based on the equivalent frame model approach and non-linear static (pushover) analyses were performed to assess their seismic performance. Firstly, results were compared in terms of capacity curves, and secondly, two different seismic performance-based assessment methods (N2 and CSM) were used to determine the respective performance points and assess the seismic safety of both structures. The seismic demand was defined by a set of real ground motion records, which the authors assumed as representative of the 1998 Azores earthquake, both in terms of magnitude and epicentral distance.

Additionally, a set of traditional retrofitting solutions were implemented to the original models in order to analyse and compare their influence over the building's global seismic performance. These solutions were adopted in the aftermath of the 1980 and 1998 Azores earthquakes by different design offices and engineering consultants, based on the designing recommendations specifically prepared by the Regional Laboratory of Civil Engineering (LREC) under the scope of the Faial rehabilitation process. Finally, fragility curves were derived based on the spectral response approach, and the results were critically discussed.

1. Introduction

1.1. Seismic risk in Portugal

Earthquakes are one of the most frightening, destructive and deadliest natural disasters. In the European context, Portugal represents an important seismic prone area, as the latest estimations indicate that within the next 50 years this country incurs the risk of being severely hit by a strong earthquake similar to the historical 1755 Lisbon earthquake, in which more than 50% of the building stock is expected to undergo heavy levels of damage or even destruction, and about 10% of the population of Lisbon is expected to perish [1]. On the one hand, mainland Portugal is located in the southwest part of the Eurasian plate, near the southern border of the African and North-American plates, being subjected to both offshore and onshore seismic activity with large to very large and moderate to large magnitudes, respectively [2]. On the other hand, the Azores Archipelago, located at the triple intersection of the Eurasian, North-American and African (Nubian) plates, allies its volcanic origin with important tectonic activity, being therefore considered the most hazardous region of Portugal [3].

The seismic background of Portugal is beyond doubt remarkable. Among other minor events and apart from the well-known 1755 Lisbon earthquake, in 1909, a moderate event of magnitude 6.0 M_w struck the village of Benavente [4], causing 46 fatalities and damaging more than 3000 buildings [5]. More recently, in 1998, an offshore event of magnitude 5.8 M_L [6] struck the Islands of Faial, Pico and São Jorge, destroying roughly 70% of the building stock and causing 8 fatalities, over than 100 injured, and many thousands of homeless [7]. This earthquake has made possible to gather an unprecedented amount of data concerning the

* Corresponding author.
E-mail address: ruiamaio@ua.pt (R. Maio).

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characterisation of the building stock and respective damage mechanisms [8,9]. It is worth referring that both case studies herein analysed were identified and selected by accessing this database.

One of the most widely used definitions of risk was given by Cardona and Barbat in [10], and defines risk $R_{ie|_T}$, as the probability of loss in an exposed element e as a consequence of the occurrence of an event with intensity larger than or equal to i during an exposition period T. According to these authors, it can be represented by the Eq. (1), where the function, f, is the mathematical convolution between hazard, H_i, and vulnerability, V_e, during an exposition period, T.

$$R_{ie|_T} = f(H_i \otimes V_e)|_T \quad (1)$$

Several studies have been developed during last decades, either addressing the evaluation of the seismic risk in Portugal or focusing on a particular aspect of its definition. In Silva et al. [1,11] for example, the authors revisited most of the hazard-related methods that have contributed to the understanding of the Portuguese seismic hazard and risk. In Maio et al. [12,13] instead, the review of some of the most widely used vulnerability-related methods was carried out. As discussed in these noteworthy references and highlighted in Santos et al. [14], such seismic risk analyses must be necessarily based on an in-deep knowledge of the seismic response of samples of buildings considered to be representative of a particular structural system or a given class of buildings and, in this sense, the analysis of typologically representative buildings that can serve as basis for large-scale assessment methodologies is a clear and continuing need.

1.2. Existing masonry building stock

Despite all the huge technological advances, innovative materials and building systems that we have been recently witnessing, load-bearing masonry construction still represent one of the most widely used building systems worldwide. Furthermore, the representativeness of such building system when assessing old urban centres is even more relevant. It is estimated that this building system, typically more vulnerable to earthquakes and therefore at significant risk even when only subjected to moderate events, still represents more than half of the Portuguese building stock [15]. Nonetheless, the seismic performance of such structures differs substantially as a function of multiple factors such as architectural configuration, structural details, quality of materials and execution works, the presence of inappropriate or weakening interventions, or even the boundary conditions and interaction between adjacent buildings [13].

At a time when the crisis in the Portuguese construction sector seems to have been overcome as a result of a paradigmatic shift towards the renovation and rehabilitation of existing building stock, large-scale investments have been gradually made in focal historical centres across the nation. However, two major issues of great concern for the scientific community in general have arisen. Firstly, as the economic attractiveness seems to be the main if not the only interest behind the preservation of urban cultural heritage, the authors fear for the risk of excessive "façadism", a phenomenon that together with low-cost renovation strategies is threatening the adequate preservation of both tangible and intangible values of our cultural heritage. Secondly, the approval of the Decree-Law No. 53/2014 that rules the renovation of existing buildings [16] is indeed the most worrisome aspect because it calls into question the sustainability of such interventions, as they usually do not respect basic recommendations for seismic design neither consider the adoption of traditional and cost-effective strengthening techniques [17]. In seismic-prone areas such as the Tagus Valley and Algarve regions in mainland Portugal, this is seen as an utterly lack of sense of opportunity, knowing moreover that the cost associated with most of these traditional seismic strengthening techniques have little impact over the total cost of renovation when integrated in the structural project design.

Against this drawback, the development of a reliable and accurate methodology for the seismic vulnerability assessment of the existing old masonry building stock is seen as a crucial step towards the seismic risk mitigation in historical urban areas. According to Silva et al. [11], such a methodology should include the prioritisation of regions where both retrofitting and strengthening campaigns should take place, the creation of insurance and reinsurance schemes to transfer and share the consequent financial burden between governments and private sector, planning and managing emergency response at an urban or regional scale and the definition of regulations to endorse seismic-resistant construction practices. The seismic risk mitigation of the building stock inserted in these particular areas will not only allow us to guarantee an appropriate safety level for local communities but also to pass on our built heritage to future generations.

Nevertheless, it is outside urban areas' boundaries that higher levels of destruction are often found, not only due to poorer quality of construction materials and detailing, but also to poorer soil and foundation quality, as observed in recent earthquakes such as July 1998 earthquake in Azores, the April 2009 earthquake in L'Aquila or more recently, the April 2015 earthquake in Nepal [18–20]. Bearing in mind this framework, the authors also aimed to balance the attention given in the past few years to the conservation of our built heritage within seismic prone areas, by focusing on the seismic assessment of traditional stone masonry buildings located in a rural environment.

2. Traditional basalt stone masonry buildings from the Island of Faial

The earthquake that struck the Island of Faial, Pico and S. Jorge on the 9th of July 1998 allowed the collection of an unprecedented quantity of good quality data on damage in constructions. The information collected during the 10-year reconstruction process of Faial Island, conducted by the Society of Promotion for Housing and Infrastructures Rehabilitation (SPRHI), was gathered over an 8-month period in 2007 by the Regional Secretariat for Housing and Equipment (SRHE) of Faial and assembled in the book "*Sismo 1998 Açores – uma década depois*" edited by Oliveira et al. [7]. The quality and uniqueness of this database in both national and international context have encouraged the development of several advanced studies throughout the following years. Even though the full access to the mentioned database was made available, complementary field work, prospected in the scope of the FCT URBSIS project – Assessing Vulnerability and Managing Earthquake Risk at the Urban Scale - was carried out by the respective research team in order to understand the evolution and diachronic process resulting from rehabilitation interventions implemented since 1998.

More recently, Neves et al. [9] carried out a comprehensive characterisation of the building stock of the Faial Island, describing the most common structural typologies, contributing for the development of the referred database. According to the authors, at the time of the earthquake, stone masonry buildings represented about 60% of Faial's building stock (estimated from a total sample of 2305 buildings). Despite several factors that have been previously pointed out as influencing the seismic response of masonry buildings, with this study, the authors aimed to draw attention to the seismic response and vulnerability of traditional stone masonry buildings within rural areas of Faial Island, a topic discussed in the first place by Costa in [21]. Throughout research