Earthq Eng & Eng Vib (2017) 16: 329-348 **DOI**: 10.1007/s11803-017-0385-x

Analysis of the impact of large scale seismic retrofitting strategies through the application of a vulnerability-based approach on traditional masonry buildings

Tiago Miguel Ferreira[1†], Rui Maio[2‡] and Romeu Vicente[2§]

1. *ISISE, Department of Civil Engineering, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal*

2. *RISCO, Department of Civil Engineering, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal*

Abstract: The buildings' capacity to maintain minimum structural safety levels during natural disasters, such as earthquakes, is recognisably one of the aspects that most influence urban resilience. Moreover, the public investment in risk mitigation strategies is fundamental, not only to promote social and urban and resilience, but also to limit consequent material, human and environmental losses. Despite the growing awareness of this issue, there is still a vast number of traditional masonry buildings spread throughout many European old city centres that lacks of adequate seismic resistance, requiring therefore urgent retrofitting interventions in order to both reduce their seismic vulnerability and to cope with the increased seismic requirements of recent code standards. Thus, this paper aims at contributing to mitigate the social and economic impacts of earthquake damage scenarios through the development of vulnerability-based comparative analysis of some of the most popular retrofitting techniques applied after the 1998 Azores earthquake. The influence of each technique individually and globally studied resorting to a seismic vulnerability index methodology integrated into a GIS tool and damage and loss scenarios are constructed and critically discussed. Finally, the economic balance resulting from the implementation of that techniques are also examined.

Keywords: urban resilience; masonry buildings; retrofitting strategies; vulnerability-based approach; loss estimation

1 Introduction and scope

Risks are associated to dangerous events that have an estimable probability of occurring and some potentially severe consequences. In the case of earthquake risk, it is a compound concept determined by the combination of the local seismic hazard, exposure and intrinsic vulnerability of either a singular structure or a building stock. From an engineering point of view, risk mitigation is generally concerned in reducing the structural vulnerability through the implementation of seismic retrofitting strategies, within a cost-effectiveness framework. For management purposes, it is recognised that earthquake risk requires a multidisciplinary evaluation that must take into account the expected physical damage, the number of casualties and economic losses. These risk analyses outputs have to improve decisions in order to contribute to the effectiveness of risk management, concerning the action and identifying the weakness of the exposed element and their evaluation in time (Carreño *et al.*, 2007). Thus, the comprehensive seismic vulnerability assessment of an old urban centre, with the view to mitigate earthquake risk, assumes great importance due to the evident potential of physical, human, economical and patrimonial losses associated to such areas.

In this context, this paper addresses the topic of the seismic retrofitting of traditional masonry buildings in urban environment through a vulnerability-based approach from which a series of vulnerability, loss and economic outputs are critically discussed. In order to improve their interpretation, the results are mapped using a commercial GIS software, ArcGis® 10.2 (2012), wherein geo-referenced graphical information was combined and connected to a relational database containing the main structural characteristics of the assessed buildings. Various modules with different objectives were developed and integrated into the GIS, including vulnerability assessment, damage and loss estimation (number of collapsed buildings, casualty rate, number of unusable buildings and repair costs) for different macroseismic intensities, allowing for the construction of multiple physical damage and loss scenarios. With this discussion, the authors intend to demonstrate how vulnerability index methods can be used to analyse the impacts resulting from the implementation of large scale retrofitting programs and

Correspondence to: Tiago Miguel Ferreira, Department of Civil Engineering, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal
Tel: 00351 253 510 200, Fax: 00351 253 510 217
E-mail: tmferreira@civil.uminho.pt
[†]Postdoctoral Researcher; [‡]PhD Candidate; [§]Associate Professor
Supported by: URBSIS: Assessing Vulnerability and Managing Earthquake Risk at Urban Scale (PTDC/ECM-URB/2564/2012)
Received March 22, 2016; **Accepted** July 18, 2016

to give a contribution to clarify the common idea that seismic retrofitting interventions are not viable from an economic point of view, particularly in Portugal wherein these kind of interventions to reduce the seismic vulnerability of old building stock have been neglected as inherent to rehabilitation and retrofitting actions during the last decades.

2 Managing earthquake risk: urban resilience and emergency planning

According to Coaffee (2008), the concept of urban resilience is often defined as the ability of exposed communities to sustainably resist, support and recover from the effects of hazards and is directly connected to mitigation, preparedness, disaster, response, recovery and reconstruction disaster risk management phases. Several organisations such as GFDRR (Global Facility for Disaster Reduction and Recovery) are committed on helping governments and communities in vulnerable disaster-prone areas by increasing the perception, awareness and access to comprehensive information about physical and societal exposure to disaster risk (Arshad and Athar, 2013). This way, governments, communities, and private stakeholders are able to better quantify and predict potential impacts of natural hazards on both society and economy, and also to carry out risk-sensitive decision-making. Moreover, these global knowledge-sharing partnerships usually work together along with governments, civil society and the private sector to create and improve the policies and legislation needed for better land use planning, to drive investment aimed at risk mitigation and acting as a moderator over the often-difficult dialogue between stakeholders (Arshad and Athar, 2013).

There are several successful examples of the positive influence of disaster risk management and planning on communities' resilient capacity, as the case of the RHRP (Rural Housing Reconstruction Program) in the aftermath of the October 2005 earthquake in northern Pakistan, which roughly caused 73,000 deaths and more than 2.8 million homeless people (Arshad and Athar, 2013), the February 2010 Chile (Astroza *et al*., 2012) or the February 2011 Christchurch earthquakes (Mitchelson, 2011). Moreover, the March 2011 GEJE (Great East Japan Earthquake), the first ever recorded mega-disaster comprehending earthquake, tsunami, nuclear power plant accident, power supply failure and large-scale disruption of supply chains, caused 20,000 casualties, over than 130,000 collapsed buildings and 270,000 severely damaged, with a direct economic cost estimated in $210 billion (Ranghieri and Ishiwatari, 2014). Although Japan's community preparedness is internationally acclaimed and disaster risk management strategies had been developed and implemented for decades, no one could ever have foreseen this complexity derived from the 9.0 magnitude earthquake cascading effects.

In many countries, civil protection bodies are the agencies responsible for the general emergency response plan, which covers all types of hazards (natural and man-made), both before and after an event. So that they can fulfil this task, the agents involved in planning earthquake risk mitigation strategies should be able to define which zones are physically more vulnerable and to prepare logistic and field exercises to simulate situations that may arise in a real earthquake situation (Goula *et al*., 2006). However, as discussed by Ferreira *et al*. (2013), risk management of urban areas is frequently undertaken without the use of a general planning tool, which can seriously commit the effectiveness of potential rehabilitation strategies and risk mitigation measures. One of the most effective ways of tackling this issue is through the use of a multi-purpose tool connected to a relational database within a Geographic Information System (GIS) environment, from which it is possible to perform spatially integrated analysis of the building stock and manage different type of data, such as building features, survey information, seismic vulnerability and damage and loss scenarios. By allowing an integrated spatial analysis of the area under study, these are very valuable tools for the development of retrofitting strategies and cost-benefit analyses, as well as for supporting the development and implementation of civil protection and local emergency plans (Neves *et al*., 2012a).

3 Seismicity, earthquake risk and risk mitigation policies in Portugal

Mainland Portugal is located in the Southwest part of the Eurasian plate, near the southern border of the African and North American plates and is subjected to both onshore and offshore seismic activity, with moderate to large and large to very large magnitudes, respectively (Moreira, 1989). Additionally, the Azores Archipelago allies its volcanic origin with important tectonic activity, as it is located at the triple intersection of the Eurasian, North American and Nubian plates, being considered therefore, a very prone seismic area in Portugal, even though its seismicity is not evenly distributed over all the seven islands composing this Archipelago, either in terms of magnitude and frequency of earthquakes (Nunes, 2008). Hence, this tectonic and volcanic environment background of mainland Portugal and its associated islands induce low to moderate seismic hazard, which in countries similar to Portugal has caused considerable economic and human losses (Barata, 2005).

The great 1755 Lisbon earthquake, which was followed by tsunami and urban fire events, is still the major disaster ever occurred in Portugal and a crucial milestone in the building sector history. The Pombalino period, which has emerged following this disaster, was a great breakthrough in terms of building technology and quality, because for the first time this designing process was carried out taking into account some basic principles of seismic design, giving rise to the well-known Gaiola Pombalina anti-seismic technique (see for example Mendes and Lourenço (2010) and Simões *et al*. (2014)). At about 1930, when reinforced concrete was firstly introduced into the building sector, traditional stone masonry structures (including Gaioleiros buildings) were progressively replaced by reinforced concrete buildings as the dreadful memories of the earthquake and subsequently the compliance with seismic design principles were gradually forgotten, starting initially with the replacement of horizontal diaphragms and balconies, and after the 50's, with the entire replacement of original masonry typologies by reinforced concrete (Andrade, 2011). Presently, the built environment of several Portuguese cities is in a very poor conservation state, presenting serious structural issues, lack of maintenance and inadequate seismic design. A recent study carried out by Maio *et al*. (2015) in the Bairro Ribeirinho area, located within the historical centre of Faro (Algarve region), has pointed out that abandoned or dilapidated buildings comprise around 20% of the total number of buildings in this particular area. To face this background, a joint effort has been carried out in recent years by the national research community, media and civil protection, warning for both structural and seismic vulnerability of the building stock present in seismic-prone areas such as Lisbon and the Southwest coastal area of mainland Portugal, which has generated a positive boost in society's overall awareness and perception to earthquakes, although late surveys conducted in the city centre of Faro were revealing of the poor global awareness and perception regarding seismic risk and vulnerability of both local population and technicians in the building sector (see Vicente *et al*., 2014b), demonstrating that there is a lot yet to be done in this regard.

This scenario and background strengthens the need for a reliable and comprehensive assessment of the seismic risk in Portugal, as well as strategic development of risk mitigation measures to improve global resilience, through establishing intervention priorities for both retrofitting and strengthening campaigns over the building stock, insurance and reinsurance schemes to transfer the financial burden due to reconstruction from governments to the private sector, regulations to endorse seismic-resistant construction practices and developing emergency plans at a regional scale level (Silva *et al*., 2014). Notwithstanding, Portugal is simultaneously tackling serious economic problems, which are directly conditioning the previous mentioned measures and thus limiting resilience. The recent economic and financial crisis particularly and severely faced by the building sector has contributed to a globalised crisis of values and social mind-sets issues with multilateral implications, naturally reflected in this particular matter. Presently, the Portuguese society is still not acknowledging the absolute necessity of retrofitting and strengthening buildings aiming to reduce both its inherent vulnerability and thus the associated seismic risk. Planners, structural designers and builders, taking advantage both of the successive impasses concerning the approval of a design seismic code, and of the low-cost urban rehabilitation boost that has been strongly encouraged by the government and private investors, are carrying out intrusive or cosmetic rehabilitation works without considering the principles seismic design. Moreover, general population still does not perceive and acknowledge the investment associated with structural and seismic reinforcement design, being entirely unaware about the additional costs involved, thereby preferring cheaper solution. As a result, these inhabitants of seismic-prone areas are incurring in considerable risk arising from the seismic vulnerability of their own houses.

Following the outlines of the IDNDR Yokohama Strategy for Safer World (IDNDR, 1994), long-term mitigation policies ought to form part of national interest development programs that can significantly reduce loss of lives, property damage and socio-economic disruption. In order to move towards these objectives, the following earthquake risk mitigation actions have been promoted so far in Portugal:

Creating public awareness about safety from earthquakes: Through disseminating information, communication tools and organizing awareness campaigns as the event named "A terra treme" carried out in October 2013 by the National Civil Protection Authority (ANPC), which aimed to inform the population how to behave in case of an earthquake. Lately, under the current FCT URBSIS project, a questionnaire campaign was conducted among the inhabitants of the historical centre of the city of Faro, in order to explore the earthquake risk perception and communication level (Vicente *et al*., 2014c);

Amending legislation for seismic safety: Appropriate legislation for land use zoning of development areas, building codes and empowerment for implementation is needed on urgent basis. In this particular point the Portuguese Society of Earthquake Engineering (SPES) has been struggling against the late Decree-Law no. 53/2014, which regards the promotion for urban regeneration, advocating the legislative obligation for structural rehabilitation and verification of minimum seismic-resistant capacity when assessing existing buildings. Moreover, seismic safety certification of both new and existing buildings has been set as one of the main goals for the next years;

Planning development areas: All urban and rural habitat development should be planned to be safe from the impact of the probable earthquake hazard;

Protection from Hazard Impacts: The existing cities and villages are to be protected from the ravages of natural hazards. The supply line presented in this work is argued by the authors as of great importance not only on providing a privileged spatial overview of the built environment preliminary seismic vulnerability assessment, but also for the implementation of retrofitting and strengthening strategies, cost-benefit analyses and aid decision making of civil protection bodies (Vicente *et al*., 2014a);

Seismic Building Design: All buildings for various uses, bridges and infrastructures, in moderate to severe earthquake intensity zones, should be built according to earthquake resistant criteria and guidelines;

Retrofitting Existing Buildings for Improving Earthquake Resistance: Important and critical buildings, selected on the basis of criteria of safety and importance to economy, should be upgraded by retrofitting procedures to meet earthquake resistant criteria and guidelines. Once again, the supply line presented in this work, which has been used in other case studies (Vicente *et al*., 2011; Ferreira *et al*., 2013; Maio *et al*., 2015), is considered crucial towards the desired goals (Vicente *et al*., 2014a).

According to Anand (2000), the previous mentioned goals and strategies should adopt time-wise targets focusing on actions with higher benefit to cost ratios. It is believed that by organizing the various activities on scientific basis with appropriate financial and institutional support, preventive actions will begin showing good results starting with the very first year of their implementation. The strategy for prevention may be adopted differently for government buildings, public sector and public undertakings and finally to private buildings within municipal areas, to which the same author points out that the implementation of building codes containing earthquake-safety requirements would be the most appropriate method for ensuring safety (Anand, 2000).

4 Seismic vulnerability assessment of the old city centre of Horta, Portugal

The present case study concerns the seismic vulnerability assessment of the city centre of Horta, in Faial Island, Azores. This island was severely hit by the July 9, 1998 Azores earthquake, leaving a trail of destruction - roughly 70% of the built environment was damaged (see Fig. 1) -, affecting directly more than 5000 people and causing 8 deaths, 150 injured and 1500 homeless.

All data and information collected during the 10-year reconstruction process of Faial Island (hereinafter designated by Faial database), conducted by the Society of Promotion for Housing and Infrastructures Rehabilitation (SPRHI), was gathered over an 8-month-length period in 2007 by the Regional Secretariat for Housing and Equipment (SRHE) of the Faial Island, which funded this initiative (Neves *et al*., 2012a). The quality and uniqueness of this database in both national and international contexts have encouraged the development of several advanced studies throughout the years, part of them already included in a commemorative publication of the 10 years after the event, (Oliveira *et al*., 2008). It is worth noting that although the damage levels observed in the built environment of Horta were not as severe as in the remaining parishes of the Faial Island, classified with a macroseismic intensity IEMS-98 = V/VI (Zonno *et al*., 2010), this urban area was selected as case study due to its importance in both cultural and architectural heritage contexts. Moreover, taking into consideration the goal of the present work, the authors based their assessment on the existing building condition at the time of the earthquake that hit Faial Island in 1998, before likely late comprehensive retrofitting actions ever occurred, hereinafter designated as BR (Before Retrofitting).

4.1 Vulnerability index methodology

The seismic vulnerability of the old city centre of Horta was evaluated by using the vulnerability index methodology developed by Vicente (2008), based on the Italian GNDT II level approach (GNDT, 1994), which has been used in recent years for the seismic vulnerability assessment of several old city centres in Portugal, namely Coimbra, Seixal and Faro (Vicente *et al*., 2011; Ferreira *et al*., 2013; Maio *et al*., 2015). As is the above mentioned past surveying and assessment case studies, due to access and time constraint related issues, the vulnerability assessment was carried out considering two different assessment levels. To do that, 313 buildings that represent the total sample of buildings were divided into four different groups based on the detail level of the available information. The first group (Detailed assessment), is composed by 50 buildings that were thoroughly characterized resorting to architectural and structural plans, photographic and post-earthquake damage reports (gathered in the Faial database), and for which a full evaluation of the required input parameters of the vulnerability index methodology was possible to carry out. The second group was composed of

Fig. 1 Severe damage recorded in Faial island after the 1998 Azores earthquake

142 buildings for which only a non-detailed exterior inspection was possible (Non-detailed assessment). A third group composed of 93 reinforced concrete buildings was not included in this study as the used vulnerability index methodology is only suitable for masonry building typologies. Finally, a fourth group was created to include other 28 non-assessable buildings related to religious or governmental use, and also buildings in pre-ruin or buildings undergoing a retrofitting process. Thus, the outputs of mean vulnerability index values presented further on, were obtained through assembling both detailed and non-detailed assessment groups, hereinafter designated as Overall Assessment.

The seismic vulnerability index methodology used involves the calculation of a vulnerability index score, I_v^*, for each building as the weighted sum of 14 parameters, each one of them evaluating one aspect related to the building's seismic response, see Eq. (1). As can be seen in Table 1, they are distributed into four vulnerability classes (C_{vi}) of growing vulnerability - A, B, C and D - and a weight p_i, is assigned to each parameter, ranging from 0.50 up to 1.50 for the less and the most important ones (in terms of structural vulnerability), respectively. Also according to Table 1, the 14 parameters are further arranged into four groups to emphasize their differences and relative importance on the global seismic response of the building.

$$I_v^* = \sum_{i=1}^{14} C_{vi} \times p_i \tag{1}$$

It is worth noting that although the value of I_v^* resulting from Eq. (1) initially ranges between 0 and 650, for ease of use, it is then normalised to fall within the range between 0 and 100, assuming the designation of I_v. As discussed in Section 4.2.3, this vulnerability index was used in this work to estimate building's damage condition based on different macroseismic intensities (Grünthal, 1998) of the earthquake action.

Despite it is based on expert opinion, the definition of each parameter's weight can be a source of uncertainty. Nonetheless, if the inspection of buildings is performed in detail and accurate geometrical information is available, this method can be considered robust and the uncertainty in the assignment of vulnerability classes to each parameter can be considered low (Vicente *et al*., 2011; Maio *et al*., 2015).

According to the previous definition of the Detailed assessment group (first inspection phase), the evaluation of the vulnerability index was made for those buildings to which detailed information was available (50 buildings out of 313). Accordingly, a more expeditious approach for the Non-detailed assessment group of the remaining 142 buildings was conducted (second inspection phase), using the mean values obtained from the analysis of the first group of buildings, assuming that characteristics of the masonry buildings are homogeneous throughout the study area. Starting from this principle, it is then possible to use the mean vulnerability index value obtained from the first Detailed evaluation as a typological vulnerability index (mean value) that could be subsequently affected by modifiers of the mean vulnerability index (Ferreira

Table 1 Vulnerability index methodology (Vicente, 2008)

Parameters by group	Class C_{vi}				Weight p_i	Relative weight over I_v^*
	A	B	C	D		
1. Structural building system						
P1 Type of resisting system	0	5	20	50	0.75	46/100
P2 Quality of resisting system	0	5	20	50	1.00	
P3 Conventional strength	0	5	20	50	1.50	
P4 Maximum distance between walls	0	5	20	50	0.50	
P5 Number of floors	0	5	20	50	1.50	
P6 Location and soil conditions	0	5	20	50	0.75	
2. Irregularities and interactions						
P7 Aggregate position and interaction	0	5	20	50	1.50	27/100
P8 Plan configuration	0	5	20	50	0.75	
P9 Height regularity	0	5	20	50	0.75	
P10 Wall façade openings and alignments	0	5	20	50	0.50	
3. Floor slabs and roofs						
P11 Horizontal diaphragms	0	5	20	50	1.00	15/100
P12 Roofing system	0	5	20	50	1.00	
4. Conservation status and other elements						
P13 Fragilities and conservation status	0	5	20	50	1.00	12/100
P14 Non-structural elements	0	5	20	50	0.50	

et al., 2013). The classification of these modifiers influenced the final vulnerability index as a sum of the scores for all modifiers. Their scores in relation to the mean vulnerability value for each parameter are shown in the following Table 2.

The vulnerability index of each Non-detailed building, $\overline{\overline{I_\mathrm{v}}}$,is defined in the following Eq. (2):

$$\overline{\overline{I_\mathrm{v}}} = \overline{I_\mathrm{v}} + \sum \Delta I_\mathrm{v} \tag{2}$$

where $\overline{I_\mathrm{v}}$ is the mean vulnerability index resulting from the Detailed assessment, and $\sum \Delta I_\mathrm{v}$ is the sum of the modifier scores for the attributed class. It is important to note that this strategy is valid only if a reliable Detailed assessment of a large number of buildings in the study area is initially obtained and the strategy is applied to a single building typology. The following Eq. (3) shows how the scores of each modifier parameter class was estimated:

$$\frac{p_i}{\sum_{i=1}^{6} p_i} \times (C_{\mathrm{v}i} - \overline{C_{\mathrm{v}i}}) \tag{3}$$

where p_i is the weight assigned to parameter i, $\sum_{i=1}^{6} p_i$ is the sum of parameter's weights, $C_{\mathrm{v}i}$ is the modifier factor for a determined vulnerability class and $\overline{C_{\mathrm{v}i}}$ is the mean vulnerability class of parameter i, defined by the Detailed assessment.

From the application of the vulnerability index methodology to the 50 buildings assessed in a Detailed manner, corresponding to the first inspection phase, a mean value of the seismic vulnerability index, $\overline{I_\mathrm{v}}$, of 26.32 was obtained, to which was associated a standard deviation value, $\sigma_{\overline{I_\mathrm{v}}}$ of 9.73. Assembling the complementary approach, used in the Non-detailed assessment of the remaining 142 buildings to which the available information was somehow incomplete (second phase of assessment), an overall assessment seismic vulnerability index mean value, $\overline{I_{\mathrm{v\,OA}}}$, of 26.55 with a corresponding standard deviation value, $\sigma_{\overline{I_{\mathrm{v\,OA}}}}$, of 5.45, was estimated. The maximum and minimum I_v index values obtained from the detailed assessment were evaluated in 55.00 and 10.96, respectively. Histograms and the best-fit normal distribution curves resulting from both assessment phases are presented in Fig. 2. Moreover, the mapping of these vulnerability index values, I_v , is presented later in Section 3.1 in order to compare it with the considered retrofitting scenarios. It is important to note that the results obtained for the BR building condition are well adjusted to the building characteristics and fragilities the assessed buildings, an evidence of the method's robust nature.

4.2 Comparative analysis of different traditional seismic retrofitting strategies

Although the establishment of retrofit strategies for a specific building depends on socio-economic

Table 2 Vulnerability index modifier factors and scores

	Vulnerability modifiers	Class $C_{\mathrm{v}i}$			
		A	B	C	D
P4	Maximum distance between walls	-0.31	0.00	0.94	2.81
P5	Number of floors	-0.94	0.00	2.81	8.44
P7	Aggregate position and interaction	-0.94	0.00	2.81	8.44
P9	Height regularity	-0.47	0.00	1.41	4.22
P10	Wall façade openings and alignments	-0.31	0.00	0.94	2.81
P14	Non-structural elements	-1.25	-0.94	0.00	1.88

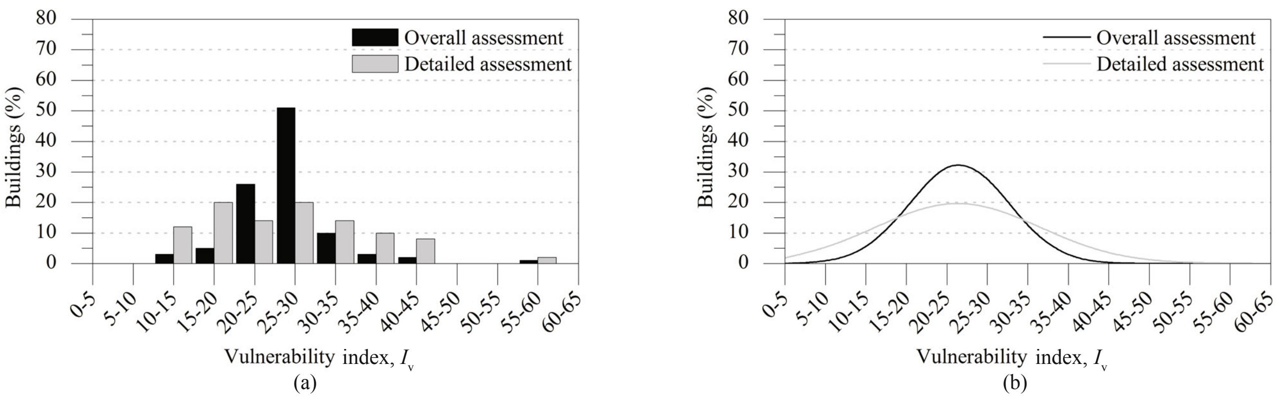


Fig. 2 Vulnerability index distributions: (a) histograms and (b) best-fit normal distributions

constraints, a number of technical issues, namely related with: structural system; building materials; quality of construction; building and site conditions; intensity of damage sustained by the building in past earthquakes; and the expected ground shaking in the area, always arise. The following strategies have been point out by several authors, such as Tomaževič (1999), Bothara and Brzev (2011) and Penna (2015), as the most effective for improving the seismic safety of unreinforced stone masonry buildings: i) enhancing integrity of the entire building by ensuring the box-like seismic behaviour; ii) enhancing the wall strength for in-plane and out-of-plane effects of seismic loads; improving floor and roof diaphragm action; and finally, iii) the strengthening of the existing foundation, which strategy is not considered practical and economically feasible in most cases.

As massive demolition and replacement of this vulnerable building typology seems neither affordable nor feasible due to historical, cultural, social and economic constraints, this section presents the retrofitting strategies adopted in this study, which are based on the reconstruction methodology defined shortly after the 1998 earthquake by the Regional government of Azores, aiming to enhance the seismic performance, and thus the vulnerability of existing stone masonry buildings, through retrofitting solutions that comply with the mentioned constraints.

4.2.1 Description of the seismic retrofitting techniques adopted

Bearing in mind the exposed, six retrofitting solutions of increasing intrusiveness and cost (from S1 to S6), grouped into three cumulative retrofitting packages (from RP1 to RP3), were herein addressed (see Fig. 3). These solutions were adopted in the aftermath of the 1980 and 1998 Azores earthquakes by different design offices based on the design recommendations specially prepared for the Faial rehabilitation process (Cansado *et al*., 1998), developed by the Civil Engineering Regional Laboratory of Azores (LREC) in partnership with several experienced technicians in this field (Oliveira *et al*., 1990; Costa *et al*., 2008). The costs associated to each one of the retrofitting packages considered (also included in Fig. 3), were defined from the analyses of an extensive database containing hundreds of detailed structural design projects developed during the rehabilitation process of the Faial island in 1998 and considered representative of the traditional Azorean construction, see Neves *et al*. (2012a) and Ferreira *et al*. (2015). As the adopted strategy pursues the cumulative implementation of retrofitting solutions and the authors have considered this set of retrofitting solutions effective on enhancing the box-like behaviour of stone masonry buildings, resorting to low-to-moderate intrusiveness and estimated costs, the following solutions S1 to S4 were grouped in RP1 package (shown in Fig. 4).

The retrofitting of wall-to-wall connections by means of effectively tying walls together with steel tie-rods, addressed in the retrofitting solution S1, is an ancient provision to enhance the building integrity, seen as a crucial requirement for survival during an earthquake, which has been used for many centuries in Mediterranean European countries, such as Italy. With diameters ranging normally from 16 to 20 mm (Bothara and Brzev, 2011), these threaded steel tie-rods are installed horizontally beneath floors (S1) or roofs (S4) on both sides of the wall, and are restrained at the ends by steel anchor plates, as depicted in Fig. 4(a), adapted from Cansado *et al*. (1998), D'Ayala and Speranza (2002). This solution is not only effective in increasing the stiffness of flexible floor diaphragms, a topic that is thoroughly discussed by Betti *et al*. (2014), but also in enhancing the connections with exterior load-bearing walls and frontal walls. Moreover, through the assessment of the stone masonry building stock under study, the authors have confirmed the predominance of flexible timber floors, many of which besides aging have been deteriorated over time.

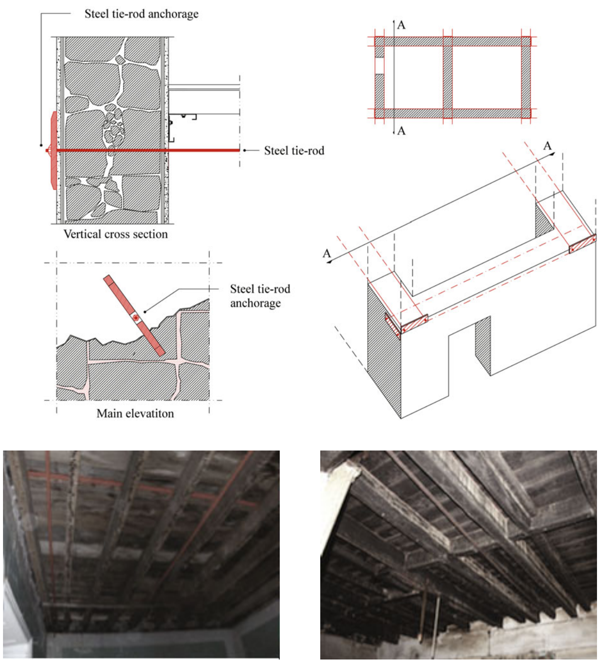
Furthermore replacing all deteriorated structural timber elements of floors diaphragms by new timber sections adequately connected, restoring their original

S1: Wall-to-wall connection improvement through tie-rods
S2: Floors stiffening with diagonal bracing and new timber planks
S3: Wall-to-floor connection improvement
S4: Wall-to-roof connection improvement through tie-rods
Estimated cost of RP1: 35€/m² **Retrofitting Package 1 (RP1)**

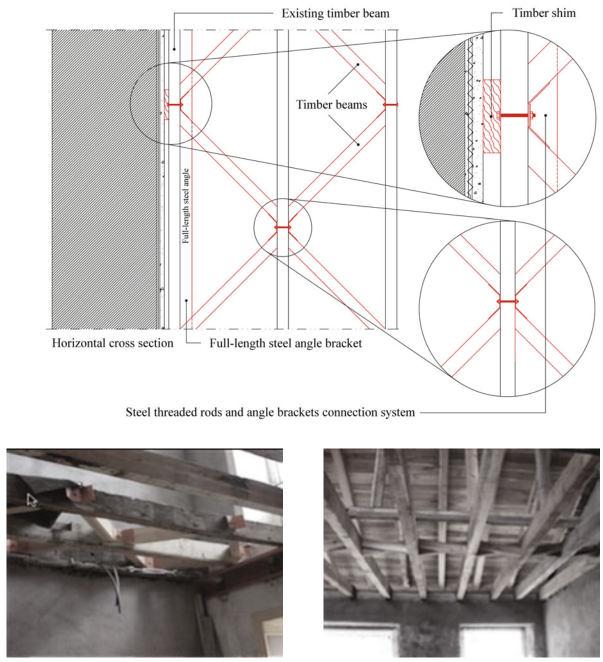
S5: Wall-to-roof connection improvement through concrete strapping beam
Estimated cost of RP2: 100€/m² **Retrofitting Package 2 (RP2) = RP1 + S5**

S6: Stone masonry consolidation through reinforced plasters
Estimated cost of RP3: 250€/m² **Retrofitting Package 3 (RP3) = RP2 + S6**

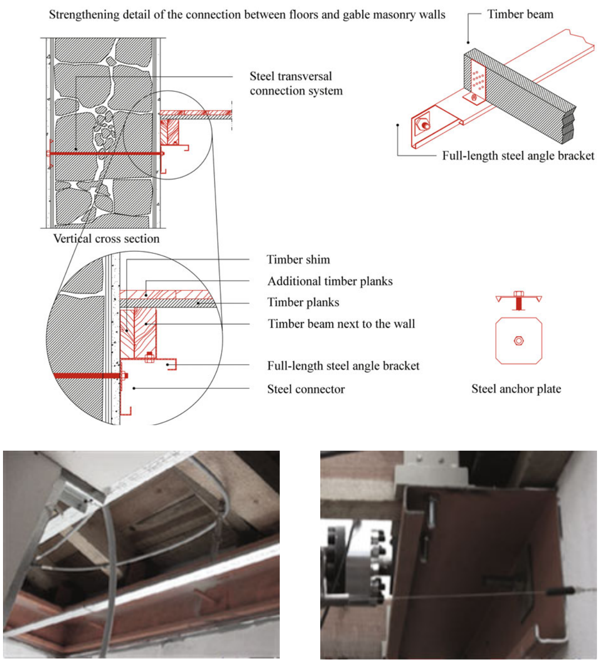
Fig. 3 Seismic retrofitting solutions adopted



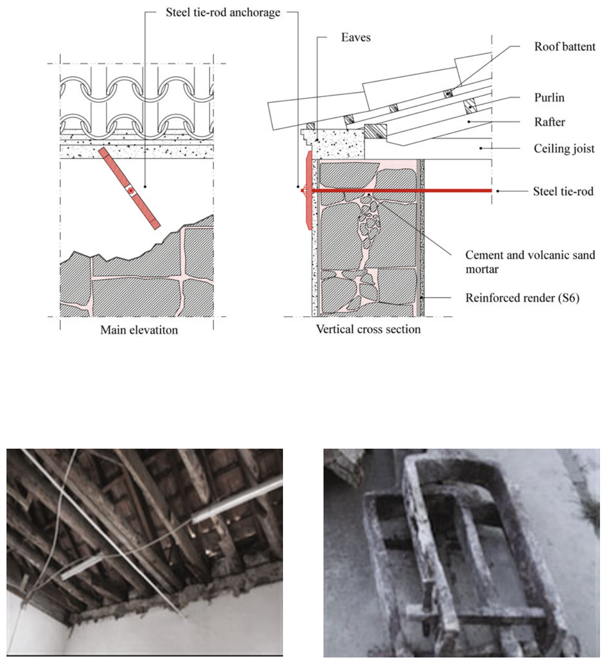
(a) Retrofitting Solution S1



(b) Retrofitting Solution S1



(c) Retrofitting Solution S3



(d) Retrofitting Solution S4

Fig. 4 Details of retrofitting actions of Package RP1

resistant capacity, the solution adopted in this study for retrofitting of floor connections (S2), joins two different stiffening provisions: the installation of 75 mm thick diagonal timber braces at the floor level between principal timber beams, anchored with ϕ10 galvanized steel threaded rods of and 3 mm thick galvanized steel angle brackets, and a new layer of timber planks, laid perpendicular to the existing planks and adequately nailed to the existent floor planks as shown in Fig. 4(b).

The retrofitting of wall-to-floor connections Solution (S3) was enhanced by introducing 3 mm thick full-length steel angle brackets adequately anchored to walls through steel connectors and anchor plates, as depicted in Fig. 4(c), complementing the previous Solution S2. Finally, Fig. 4(d) illustrates the retrofitting of wall-to-roof connections Solution (S4), ensured by applying the same technique as in Solution S1 but at the roof level, by introducing steel tie-rods underneath the ceiling joists, to sustain horizontal thrusts in the event of an earthquake.

The Retrofitting Package RP2 adds the Retrofitting Solution S5 to the previous Package RP1, comprehending the introduction of a reinforced concrete strapping beam (with 4 ϕ10 longitudinal steel bars and ϕ6//.20 stirrups) at the top of stone masonry walls, executed along the whole perimeter of the building, enhancing the connection between roof and load-bearing stone masonry (see Fig. 5). In the same figure it is also illustrated a strengthening detail of the connection between the roof and gable masonry walls.

Retrofitting Package RP3, comprises solution S6 (in Fig. 6), which involves the shear strengthening and confinement of masonry structural walls by the implementation of reinforced render, as specified in Costa (2002). Thus, after application of a first layer of filling mortar in the proportion of 1:3 (local sand extracted from Fajã Beach: Portland cement: water) for voids and surface regularisation, a 0.5 mm thick welded steel mesh made of Fe 430 steel and 10 cm spaced ribs, is then fixed on both sides of the masonry wall through a system composed of M20 galvanized screws, ϕ20 galvanized steel threaded rods and 4 mm thick anchor plates (20 mm × 20 mm), spaced of 150 cm. Finally, a 3 cm thick second layer of fine sand-blasted finishing mortar is applied for finishing (Costa, 2002).

4.2.2 Seismic vulnerability results

Following the previous subsection wherein the retrofitting solutions and packages were presented, the current point begins by explaining how exactly these retrofitting solutions were accounted on the seismic vulnerability index methodology herein used. According to the following Table 3, each retrofitting solution has directly contributed to the gradual enhancement of the vulnerability index value I_v, by upgrading the vulnerability classes C_{vi}, of Parameters P1, P2, P3, P11, P12 and P13. It is important to refer that these solutions were cumulatively implemented, from S1 to S6, with the exception of Retrofitting Solutions S4 and S6, which do not define directly the vulnerability class upgrade, the remaining vulnerability classes presented in Table 3 were directly attributed to all the evaluated buildings. Moreover, it should be noted that this approach assumes the ultimate case scenario, i.e., the retrofitting of the whole building stock regardless of the initial vulnerability index value. In practice, this means that, for buildings with low values of I_v, some of the following retrofitting solutions can be uneconomical for lower macroseismic intensities. This issue is further discussed within Section 6.

While Retrofitting Solution S4 the enhancement was simply guaranteed by improving in one class the original vulnerability class C_{vi} of Parameter P12, the explanation concerning retrofitting Solution S6, influencing over Parameter P3, requires deeper attention. Acknowledging the fact that in an urban context, as in the present case study, the observed masonry typology and fabric is quite distinct than in rural areas and in order to estimate reliable values for the stone masonry buildings within the city centre of Horta, the authors have matched the

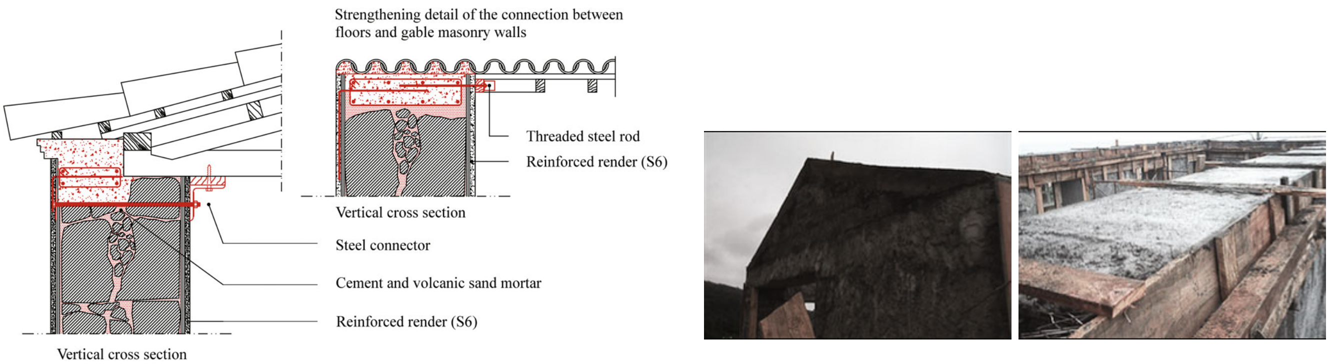


Fig. 5 Detail of Retrofitting Solution S5 (RP2)

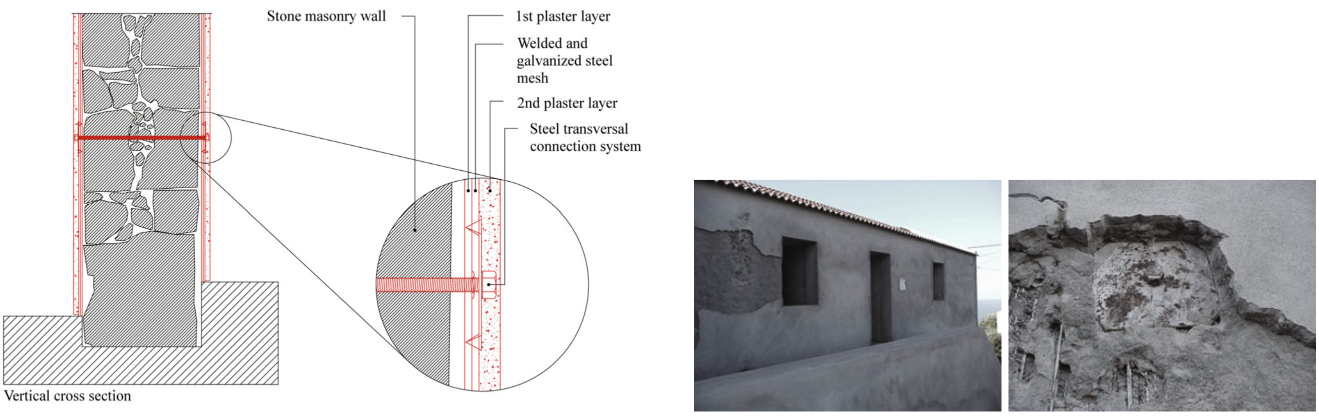


Fig. 6 Detail of Retrofitting Solution S6 (RP3)

Table 3 Influence of each retrofitting solution over the vulnerability index value, I_v

Retrofitting packages	Retrofitting solution	Description	Parameter	Vulnerability class, C_{vi}
RP1 = S1 + S2 + S3 + S4	S1	Wall-to-wall connection improvement through tie-rods	P1	B
	S2	Floors stiffening with diagonal bracing and new timber planks	P11	A
	S3	Wall-to-floor connection improvement	P1	A
	S4	Wall-to-roof connection improvement through tie-rods	P12	+1
RP2 = P1 + S5	S5	Wall-to-roof connection improvement through concrete strapping beam	P12	A
RP3 = P2 + S6	S6	Stone masonry consolidation through reinforced plasters	P2 P3 P13	A τ_0 A

masonry typological classification argued by Costa (2002) with the Italian Seismic Code (DM, 2008) classification and corresponding mechanical properties of those masonry typologies. Through observing the available information collected in the aftermath of the 1998 earthquake, it was possible to clearly differentiate the masonry typology Type A, commonly observed in the noblest and most magnificent buildings (see Fig. 7). Moreover, as described in Table 4, masonry Type B merges two different typological classifications and was attributed to the remaining buildings within the studied urban area.

In this sense, after a revision of the existent literature, the authors adopted the values of mechanical properties for masonry Type A, based on the corresponding lower limit of NTC 2008 guidelines (DM, 2008), which are similar to those adopted in literature for buildings with this masonry typology within the same urban area of the city of Horta (Neves *et al*., 2012b; Cunha, 2013). However, to masonry Type B, as it results from merging two different typological classes, those mean values were considered for those properties, which have resulted in accordance to the experimental work developed by Costa *et al*. (2012). Thus, by introducing Retrofitting Solution S6 (of RP3), ultimate shear strength value τ_0,required to estimate the conventional strength in Parameter P3, were enhanced for both masonry typologies (see Table 4).

As mentioned in Section 2.1, the seismic vulnerability index mean value, $\overline{I}_{v\,OA}$, of 26.55 was obtained for the BR building stock condition, reflecting the good general quality of these buildings within the current urban environment, namely features regarding building's


Fig. 7 Type A (a) and Type B (b) stone masonry walls fabric and arrangement

Table 4 Correspondence between Costa (2002) masonry typological classification and the masonry type description of Tabella C.8.A.2.1 of the Italian Seismic Code (DM, 2008)

	Costa masonry typological classification (2002)	NTC *Tabella* C.8.A.2.1 (DM, 2008)	τ_0 (kPa) (BR)	τ_0 (kPa) (RP3)
Type A	Masonry walls of good quality, built with regular size stones (basalt, cirenite, andesite, etc)	*Muratura a blocchi lapidei squadratti*	40	90
Type B	Masonry walls of irregular stones, interconnected using smaller fragments of stone or clay to fill in the small voids and to ensure adequate strength	*Muratura in pietrame disordinata (ciottoli, pietre erratiche e irregolari)*	90	110
	Double leaf masonry walls built with stones slightly larger than half of the wall width, complemented with small sized stone and clay fragments filling wall voids	*Muratura a conci sbozzati, con paramento di limitato spessore e nucleo interno*		

geometry and global alignments, as in P4, P5, P7, P8, P9 and P10. Figure 8 depicts the gradual evolution observed over the class vulnerability distribution, C_{vi}, for each building condition (BR, RP1, RP2 and RP3).

The application of the same vulnerability index methodology considering the Retrofitting Package RP1, led to a reduction of the seismic vulnerability index mean value, $\overline{I}_{v\,OA}$, of roughly 18.9%. Moreover, introducing the Retrofitting Package RP2, this reduction slightly increased to 23.1%, again when compared to the BR vulnerability index mean value. Finally, by considering the Retrofitting Package RP3 (which includes the previous Packages RP1 and RP2), the seismic vulnerability index mean value was reduced in 51.7%. Figure 9(a) depicts the vulnerability index mapping estimated to the BR building condition and Fig. 9(b) presents the obtained mapping through implementing all the mentioned retrofitting solutions (Package RP3) and Table 5 summarizes the vulnerability results in terms of seismic vulnerability index values, as well as the reductions achieved with each one of the Retrofitting Packages (RPi) with respect to the original building condition (BR).

4.2.3 Damage distribution and scenarios

As already discussed in Section 2, loss estimation plays a very important role over the implementation of urban planning and retrofitting strategies, enabling costs to be placed alongside beneficial measures such as reduced repair costs and life safety (D'Ayala *et al*., 1997). Thus, this section presents loss estimation obtained for different damage scenarios computed for several macroseismic intensities, $I_{EMS\text{-}98}$. According to Nunes (2008), ever since the second half of the 20th century, maximum intensities of $I_{EMS\text{-}98}$ = VII and VIII were observed in the Azorean archipelago, during the earthquakes of 1952 (São Miguel), 1964 (São Jorge), 1973 (Pico) and 1988 (São Miguel). Moreover, from Nunes (2008), one can also state that maximum intensities of $I_{EMS\text{-}98}$ = IX were recorded in 1958, 1980 and 1998.

Among the several methods described in the literature for estimating losses in function of the probability of occurrence of a certain damage grade, this task was herein carried out through the construction of damage scenarios based on global probabilistic distributions, using the seismic vulnerability index values, I_v, obtained to the different above-mentioned building conditions (BR, RP1, RP2 and RP3). The damage estimation models are inevitably dependent on the physical damage grades, including the definition of correlations between the probability of exceeding a certain level of damage and the probability of different loss phenomena (such as the probability of collapsing or becoming unusable due to the lack of structural safety conditions, the probability of death and severely injured, etc.). Thus, and based on the previously discussed seismic vulnerability assessment outputs, mean damage grades, μ_D, were estimated and

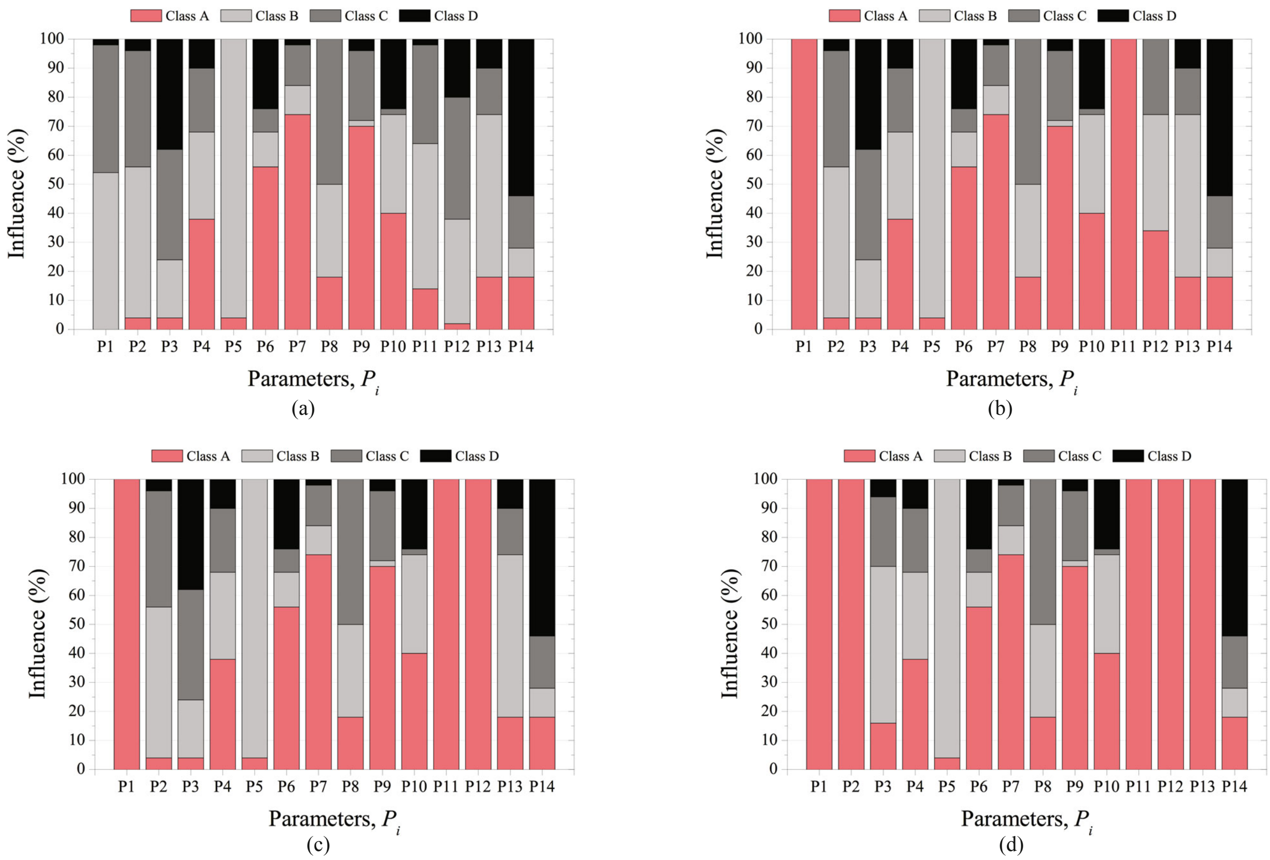


Fig. 8 Influence of each class over the $\overline{I}_{v\,OA}$ value for each building condition: (a) BR; (b) RP1; (c) RP2 and (d) RP3

(a) (b)

Fig. 9 Vulnerability index, I_v, obtained for: (a) BR condition and (b) RP3 retrofitting package

Table 5 Vulnerability index values and reduction values

Building condition	Detailed assessment		Overall assessment		Reduction
	$\overline{I_v}$	$\sigma_{\overline{I_v}}$	$\overline{I}_{vOA}$	$\sigma_{\overline{I}_{vOA}}$	(%)
BR	26.32	9.73	26.55	5.45	-
RP1	21.30	7.64	21.52	4.52	18.9
RP2	20.19	7.18	20.41	4.32	23.1
RP3	12.61	4.72	12.84	3.34	51.7

discussed next for different macroseismic intensities, based on each building vulnerability index, I_v. To this end, Bernardini *et al*. (2007) proposed an analytical expression that correlates hazard with the mean damage grade $(0 \le \mu_D \le 5)$ of the damage distribution in terms of vulnerability value, Eq. (4):

$$\mu_D = 2.5 \times \left[1 + \tanh\left(\frac{I + 6.25 \times V - 13.1}{Q}\right)\right]; \quad 0 \le \mu_D \le 5 \tag{4}$$

where I is the macroseismic intensity in accordance to the European Macroseismic Scale (EMS-98), V is the vulnerability index used in the macroseismic methodology, which can be related to the vulnerability index value I_v, through Eq. (5), and Q, which is a ductility factor that describes the ductility of the constructive typology under study (ranging from 1 to 4). In order to provide the best fit between the GNDT curves and the EMS-98 functions, a ductility factor, Q, of 3.0 was adopted in this work (see Vicente *et al*. (2011) and Ferreira *et al*. (2013)).

$$V = 0.592 + 0.0057 \times I_v \tag{5}$$

Figure 10(a) shows the vulnerability curves obtained from the mean value of the vulnerability index, $\overline{I}_{vOA}$, considering each of the evaluated building condition, for macroseismic intensities ranging between VI and XI. In addition, Figs. 10(b) and (c) present two examples of mean damage grade distributions obtained through a beta probability distribution for macroseismic intensities $I_{EMS\text{-}98}$ = IX and $I_{EMS\text{-}98}$ = X which correspond to the higher historical intensities observed for the city of Horta (Nunes, 2008). It is worth referring that the variance of the beta distribution was defined using 8, 0 and 5 for parameters t, a and b, respectively.

As already mentioned, the use of a GIS tool allows to spatially represent the global damage distribution, μ_D, of the building stock under analysis, enabling the identification of the most vulnerable areas and buildings, which can be very useful for urban management and planning protection strategies. Figures 11(a) and (b) present damage scenarios for earthquake intensities

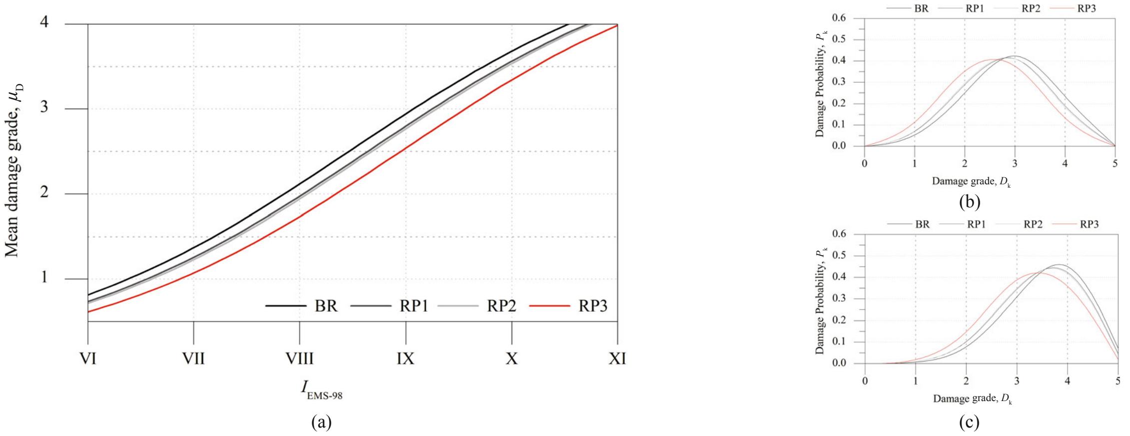
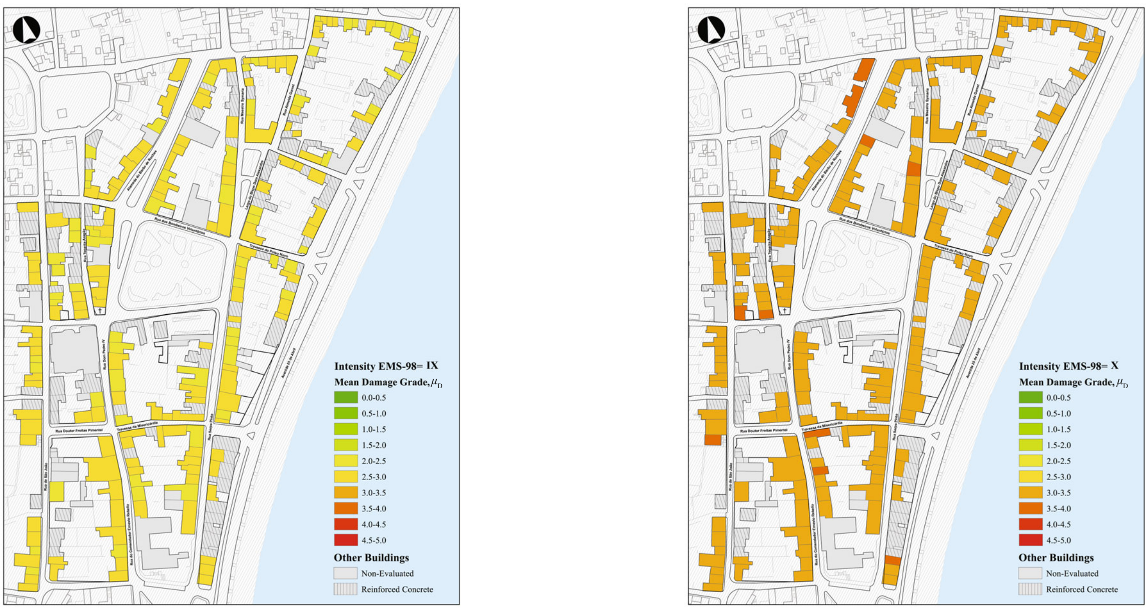


Fig. 10 Vulnerability curves for the considered building conditions (a) and the corresponding damage probabilities, P_k, obtained for each damage grade, D_k, for macroseismic intensities of I_{EMS-98} = IX (b) and I_{EMS-98} = X (c)

(a) BR building condition for macroseismic intensities I_{EMS-98} = IX and I_{EMS-98} = X



(b) RP3 building condition for macroseismic intensities I_{EMS-98} = IX and I_{EMS-98} = X

Fig. 11 Mapping of the mean damage grade, μ_D, for: (a) BR and (b) RP3 building conditions

$I_{\text{EMS-98}}$ = IX and $I_{\text{EMS-98}}$ = X, considering respectively the BR and the RP3 conditions.

Globally, the estimated damage for the original building condition (BR) ranged from 2.49 to 3.69 and 3.30 to 4.23 for earthquake scenarios corresponding to $I_{\text{EMS-98}}$ = IX and $I_{\text{EMS-98}}$ = X, respectively. As can be seen in Fig. 11(b), when the Retrofitting Package RP3 is applied to the building stock of Horta, the values obtained for the mean damage grade decrease substantially, ranging between 2.30 and 2.88 and from 3.12 to 3.63 (minimum and maximum) for macroseismic intensities of $I_{\text{EMS-98}}$ = IX and $I_{\text{EMS-98}}$ = X, respectively. In this sense it is pertinent to note that according to some authors (Pagnini *et al*., 2011; Vicente *et al*., 2011; Ferreira *et al*., 2013), buildings with a vulnerability index higher than 45, i.e. building for which severe damages $(3 \leq \mu_D \leq 4)$ and potential local collapse $(\mu_D > 4)$ are expected, should be subjected to a further assessment resorting to a more detailed approach.

5 Losses estimation

This section includes different loss estimation results, which are organised and discussed here by the construction of damage scenarios based on global probabilistic distributions, using representative values of the vulnerability index obtained considering the four building conditions addressed (BR to RP3).

The potential for manipulating and editing data allows for the construction of sensibility analyses, scenario modelling and simulation to foresee the impact of such retrofitting strategies in the reduction of losses. The damage estimation models are inevitably dependent on the physical damage grades, including the definition of correlations between the probability of exceeding a certain level of damage and the probability of different loss phenomena (such as the probability of collapsing or become unusable due to a lack of structural safety conditions, the probability of death and severe injuries, etc.) (Ferreira *et al*., 2014). It is important to highlight that due to the uncertainty associated with the evaluation of some of the parameters required to perform this kind of probabilistic analyses, all the results produced and discussed in the following sections should be interpreted statistically. In fact, further to the uncertainties associated with the formulation of the loss models themselves, the uncertainties in the assessment of the vulnerability index (already discussed in Section 4.1) and in the interpretation of the macroseismic intensities should be also taken into account.

5.1 Collapsed and unusable buildings

The loss estimation model adopted in this research is based on damage grades that relate the probability of exceeding a certain damage level with the probability of collapse and functional loss. Supported on observed damage data, the approach herein applied has been proposed by Servizio Sísmico Nazionale (SSN) based on the work of Bramerini *et al*. (1995), involving the analysis of data associated with the probability of buildings to be deemed unusable after minor and moderate seismic action.

As referred in Maio *et al*. (2015), although such events produce lower levels of structural and non-structural damage, higher mean damage grade values are associated with a higher probability of building collapse. The probabilities of exceeding a certain damage grade are used in the loss estimation and are affected by multiplier factors, which range from 0 to 1 according to different proposals. In Italy, data processing undertaken by Bramerini *et al*. (1995) has enabled the establishment of these weighted factors and respective expressions for their use in the estimation of building losses. The following Eqs. (6) and (7) were used for the determination of collapsed and unusable buildings:

$$P_{\text{collapse}} = P(D_5) \tag{6}$$

$$P_{\text{unusable buildings}} = P(D_3) \times W_{\text{ei},3} + P(D_4) \times W_{\text{ei},4} \tag{7}$$

where $P(D_i)$ is the probability of the occurrence of a certain damage grade (from D_1 to D_5) and $W_{\text{ei},j}$ are multiplier factors that indicate the percentage of buildings associated with the damage grades, D_i, that suffer collapse or are considered unusable. Following the work of Maio *et al*. (2015), these multiplier factors are assumed here as $W_{\text{ei},3}$ = 0.4 and $W_{\text{ei},4}$ = 0.6. Figure 12 presents the probability of building collapse and unusable buildings for the four building conditions studied in this work (BR, RP1, RP2 and RP3).

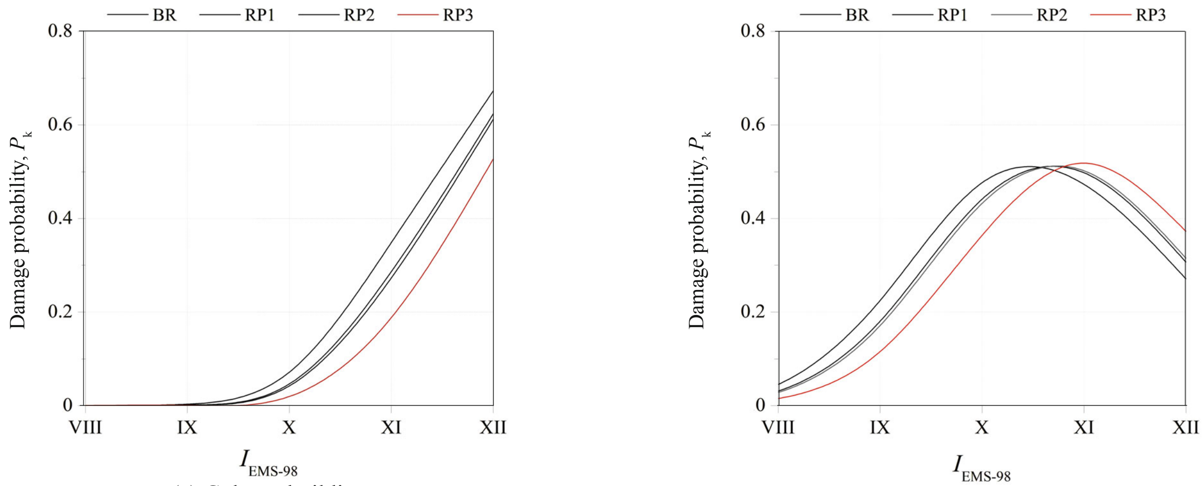
Moreover, Table 6 summarizes the overall results in terms of collapsed and unusable buildings, obtained for those building conditions by considering macroseismic intensities in the range of $I_{\text{EMS-98}}$ = VIII to $I_{\text{EMS-98}}$ = XII.

5.2 Human casualties and homelessness

Also here, a proposal of the Servizio Sismico Nazionalle (Bramerini *et al*., 1995) was used to estimate the casualties (deaths and severely injured) and homeless rates. Regarding the deaths and severely injured rate, it is defined as being 30% of the inhabitants living in collapsed and unusable buildings. In this case, the survivors assumed to require short-term shelters. Casualties and homeless rates were determined using Eqs. (8) and (9), respectively.

$$P_{\text{death and severely injured}} = 0.3 \times P(D_5) \tag{8}$$

$$P_{\text{homeless}} = P(D_3) \times W_{\text{ei},3} + P(D_4) \times W_{\text{ei},4} + 0.7 \times P(D_5) \tag{9}$$



(a) Colapse buildings (b) Unusable buildings

Fig. 12 Probability of collapsed (a) and unusable buildings (b) for the different building conditions analysed

Table 6 Estimation of the number of collapsed and unusable buildings, for a total of 192 buildings evaluated

Intensity	Collapsed buildings				Unusable buildings			
I_{EMS-98}	BR	RP1	RP2	RP3	BR	RP1	RP2	RP3
VIII	0	0	0	0	9 (4.5%)	6 (3.1%)	5 (2.8%)	3 (1.5%)
IX	1 (0.3%)	0	0	0	43 (22.4%)	35 (18.1%)	33 (17.1%)	22 (11.5%)
X	14 (7.2%)	9 (4.7%)	8 (4.2%)	4 (2.0%)	92 (47.7%)	85 (44.1%)	83 (43.2%)	70 (36.4%)
XI	67 (34.9%)	55 (28.6%)	52 (27.3%)	36 (18.8%)	91 (47.3%)	96 (49.8%)	96 (50.2%)	100 (51.8%)
XII	129 (67.3%)	120 (62.4%)	118 (61.2%)	101 (52.7%)	52 (27.1%)	59 (30.7%)	60 (31.5%)	72 (37.3%)

Figure 13 presents the probability of casualties and homeless obtained for each of the building conditions (BR to RP3) for the previous seismic intensity scenarios (from I_{EMS-98} = VIII to XII). In addition, the global frequencies computed from these two probabilistic outputs are given in Table 7, from which it is worth emphasizing the significant decrease of the homeless attained through the application of the retrofitting package solutions. As an example, a decrease of about 15% was observed in the number of homeless people (from 841 to 603 out of 1596 inhabitants) for an intensity I_{EMS-98} = X.

The earthquake that occurred in 2009 in the Italian city of L'Aquila caused about 300 deaths and rendered 40,000 homeless. This example should provide to other countries an important lesson about strategies that disbelieve the community engagement in post-disaster decision-making. Therefore, it is suggested that both communities and governments should put more emphasis on planning for post-disaster, valuing the community engagement and decision-making, especially planning for emergency response.

As a final note, it is worth referring that these outputs stress the importance of efficient logistical preparation by competent authorities for the temporary relocation of a potentially high number of residents (refer to Table 7). The Portuguese Civil Protection bodies and all the regional responsible authorities are aware of these outputs and examples to perform simulation exercises and prioritizing all logistical and financial resources that would be inevitably necessary if an earthquake occurs.

6 Economic balance

Anand (2000) have pointed out very useful statements regarding economic loss resulting from earthquake, supporting that from the cost-wise point of view, the building construction including the seismic resistance provisions in the first instance is the cheapest strategy in terms of building's structural safety, which is already a generalized common view shared among scientists. While retrofitting an existing building may involve two to three times the initial investment, repair and seismic strengthening cost of a damaged building may even be four to eight times as expensive. It is therefore more

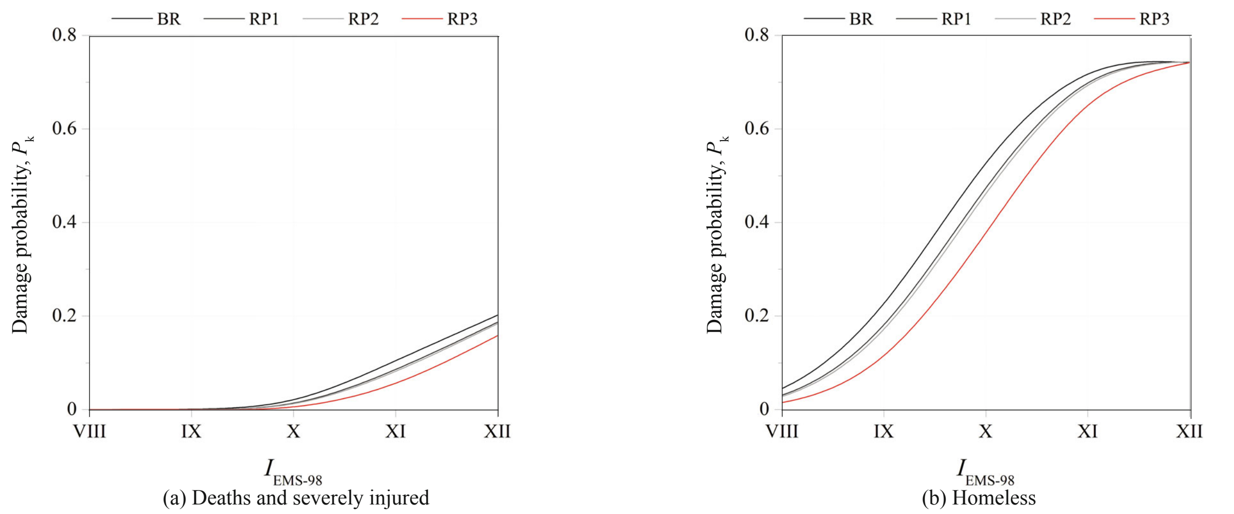


Fig. 13 Probability of deaths and severely injured (a) and homeless (b) for the evaluated building conditions (BR to RP3)

Table 7 Estimation of the number of deaths and severely injured, and homeless, for a total number of 1596 inhabitants

Intensity	Deaths and severely injured				Homeless			
I_{EMS-98}	BR	RP1	RP2	RP3	BR	RP1	RP2	RP3
VIII	0	0	0	0	73 (4.5%)	49 (3.1%)	45 (2.8%)	24 (1.5%)
IX	2 (0.1%)	1 (0.1%)	1 (0.1%)	0	363 (22.7%)	290 (18.2%)	275 (17.2%)	185 (11.6%)
X	34 (2.2%)	22 (1.4%)	20 (1.3%)	9 (0.6%)	841 (52.7%)	756 (47.4%)	737 (46.2%)	603 (37.8%)
XI	167 (10.5%)	137 (8.6%)	131 (8.2%)	90 (5.6%)	1144 (71.7%)	1114 (69.8%)	1106 (69.3%)	1037 (65.0%)
XII	322 (20.2%)	299 (18.7%)	293 (18.4%)	253 (15.8%)	1184 (74.2%)	1186 (74.3%)	1187 (74.4%)	1184 (74.2%)

viable from the cost-effective point of view to construct earthquake resistant buildings at the initial stage itself according to the relevant seismic codes. Moreover, the replacement of damaged buildings or existing unsafe buildings by reconstruction should generally be avoided due to the following issues: higher cost of reconstruction than that of strengthening or retrofitting actions; preservation and safeguarding of historical architecture and built heritage; and finally maintaining functional, social and cultural environment (Anand, 2000). For developed countries, such as Portugal, retrofitting the built environment through traditional and low-cost reinforcement techniques is of great advantage, as it will also require less workmanship and living disruption of the residents. This author argues that non-structural or architectural repairs like patching of cracks and plaster, repairing of joinery or electrical, water supply and sewerage systems, repairing and replacing of roofing elements, re-plastering and painting are superficial in nature and neither restore the loss structural strength nor seismic resistance, focusing a crucial issue (Anand, 2000).

Following the above preliminary reflection, the behavioral influence of the retrofitting packages are analyzed in this section, not only over the estimation of the seismic vulnerability index associated to each, but also how these actions contribute to mitigate the earthquake risk in general. As addressed by Benedetti and Petrini (1984), the mean damage grade, discussed in Section 3.2, can be interpreted either economically or by means of an economic damage index representing the ratio between repair and replacement costs (i.e. building value). The correlation between damage grades and these repair and replacement costs was proposed by Dolce *et al*. (2006) by processing and analysing post-earthquake damage data collected after the Umbria-Marche (1997) and Pollino (1998) earthquakes (Dolce *et al*., 2006), using the GNDT-SSN procedure (GNDT, 1994). From that extensive amount of data, these authors obtained statistical values based on the estimated cost of typical replacement actions applied to more than 50,000 buildings.

Thus, and according to Vicente *et al*. (2010), the repair cost probabilities for a certain seismic event characterized by an intensity I, $P[R|I]$, can be obtained from the product of the conditional probability of the repair cost for each damage level, $P[R|D_k]$, with the conditional probability of the damage condition for each level of building vulnerability and seismic intensity, $P[D_k|I_v, I]$, given by Eq. (10):

$$P[R|I]=\sum_{D_k=1}^{5}\sum_{I_v=0}^{100}P\left[R|D_k\right]\times P\left[D_k|I_v,I\right] \tag{10}$$

To estimate the replacement costs associated with the different building conditions, an average cost value of 700 €/m^2 was considered for the building stock within the historical centre of the city of Horta, value that was in line with the one estimated by Dolce *et al*. (2006) from the reconstruction process undertaken in the aftermath of the Irpinia earthquake. Moreover, to account for built and cultural heritage issues, whereas the implementation of traditional building techniques and materials can be slightly more expensive than current solutions, this average cost value per unit area was considered 1000 €/m^2 for the BR building condition. It is worth noting that this value was already suggested in the past by Vicente *et al*. (2011) for the old city centre of Coimbra, Portugal.

Based on these probabilistic values it is then possible to estimate the global replacement costs for the entire study area (192 buildings) and to obtain the economic balance computed for each one of the three retrofitting packages, in relation to the BR buildings condition. This output is presented in Table 8 in the form of global savings associated to such economic balance. Moreover, the mean periods of inactivity referred by Nunes (2008) for the Archipelago of Azores (i.e. the mean amount of time elapsed between two earthquakes of intensities V < $I_{\text{EMS-98}}$ < VIII and $I_{\text{EMS-98}}$ ≥ VIII), are also included in Table 8 so that the economic viability of the retrofitting packages analysed in this work can be easily analysed.

From the analysis of Table 8 it is possible to observe that the three retrofitting packages proved to be cost effective for macroseismic intensities equal or higher than $I_{\text{EMS-98}}$ = IX. Notwithstanding this fact, for intensities of $I_{\text{EMS-98}}$ = VII and VII respectively, which are already within the mean period of inactivity of 12 years, global savings of about 1.08 and 5.85 million euros (M€) can be obtained with the application of RP1 to the 192 buildings of the old building stock of Horta. As it would be expected, the global savings obtained from the application of the herein analysed retrofitting packages are more expressive for the higher macroseismic intensities, as the reduction on the relative level of damage suffered by the buildings is more important for these intensities, and from a strictly economic point of view RP1 proved to be the most cost effective retrofitting package with global saving of around 20 million euros. However, it is important to note that these outputs must be seen and analysed along with the already discussed damage scenarios and loss estimation results, since although for some intensities retrofitting packages RP2 and RP3 could lead to lower economic savings but to a significant decrease in terms of human losses. As an example, considering the retrofitting package RP2, which has an estimated cost of 100 €/m^2, i.e. about 14% of the mean replacement cost, reductions of about 0.9%, 6.5%, 3.0% and 4.5% were obtained respectively in the ratios of deaths and severely injured, homeless, collapsed and unusable buildings, for a macroseismic intensity of $I_{\text{EMS-98}}$ = X. Repeating this exercise for the most expensive and complete retrofitting package, RP3, its costs represent about 33% of the mean replacement cost, but its implementation leads to a reduction of 51.7% over the mean vulnerability index value, which, in terms of loss estimation for a macroseismic intensity of $I_{\text{EMS-98}}$ = X, represents a decrease of 1.6%, 14.9%, 5.0% and 11.5% in terms of the respective ratios of deaths and severely injured, homeless and collapsed and unusable buildings.

As final comments, it is worth noting that in the aftermath of the macroseismic intensity VIII earthquake that struck the Azores earthquake in 1998, an overall amount of 330 million euros were spent for the reconstruction and retrofitting of the 3129 buildings spread over the Faial Island, a value that represents approximately 1/6 of the gross domestic product of Autonomous Region of Azores. If some of these retrofitting schemes had been studied and implemented before the earthquake, the cost would have been negligible when compared with this global amount of money spent in such a reconstruction process, as well as drastically reducing human and economic losses.

Table 8 Global savings obtained for each retrofitting package RPi (in millions of €)

Retrofitting package	Macroseismic Intensity, $I_{\text{EMS-98}}$							
	V	VI	VII	VIII	IX	X	XI	XII
	12 years of mean period of inactivity				20 years of mean period of inactivity			
RP1	-2.06 M€	-1.11 M€	1.08 M€	5.85 M€	12.24 M€	17.15 M€	19.23 M€	20.10 M€
RP2	-7.09 M€	-6.10 M€	-3.79 M€	1.20 M€	7.89 M€	12.53 M€	14.39 M€	15.13 M€
RP3	-16.86 M€	-15.58 M€	-12.63 M€	-6.20 M€	1.80 M€	5.86 M€	6.12 M€	5.91 M€

7 Final comments

The broad conclusions and recommendations from the exposed work converge towards the enhancement in terms of public awareness and perception, education, training and research concerning the seismic risk mitigation. Ideally, the strategy to mitigate seismic risk should address land use zoning (reducing exposure), planning and of adequate strengthening campaigns and the implementation of seismic building codes suitable both for new and existing structures (reducing the seismic vulnerability of the built environment). Moreover, with an appropriate and assertive policies, financial and institutional supports at both national and local levels it is possible to carry this strategy into a workable action plan.

As expected, in terms of damage and loss estimation, the results achieved for the case study of Horta's historical centre were found, not as impressive as in other potential case studies (e.g. historical centre of Faro city), due to the large influence of the vulnerability index over the loss estimation formulations and to the low range of the obtained vulnerability index values of the evaluated building stock, estimated through the application of the seismic vulnerability index methodology. Despite the simplifications inherent to the methodology itself, these results were well adjusted to the slight damage levels observed in the city of Horta, in the aftermath of the 1998 Azores earthquake.

With respect to the considered retrofitting solutions, their implementation led in general, to a reasonable improvement of the building stock global seismic behaviour, namely in terms of the vulnerability index values, reflecting with great accuracy its known influence over the shear strength capacity, ductility and on the improvement of the so-called box-behaviour. However, from loss estimation results, the enhancement observed by implementing these retrofitting packages could have been more expressive if the building stock seismic vulnerability was higher, therefore implicating higher vulnerability index values. Nonetheless, the enhancement observed with the retrofitting solution S5, relative to the implementation of a reinforced concrete strapping beam at the top of stone masonry walls executed along the whole perimeter of the building, have raised a few question marks regarding its effective contribution on the building's global seismic behaviour. Many authors argue that this widely applied technique may lead to the development of collapse mechanisms in load-bearing walls when strengthened to seismic loads, due to the important local increment of mass and rigidity at the top of masonry walls, introducing significant changes on the expected vibration modes, particularly in high rise buildings. Thus, the authors suggest that reinforced concrete strapping beams should be further addressed and examined through mechanical, numerical and experimental analysis, to better understand its real behaviour.

From the loss estimation results related to collapsed and unusable building rates obtained to the maximum observed macroseismic intensities in Faial of $I_{\text{EMS-98}}$ = IX and X, it is relevant to point out, on the one hand, an extremely low rate of collapsed buildings, and on the other hand, the significant rate of unusable buildings expected in the event of an earthquake within this range of intensities. With respect to human loss estimation, several factors have contributed to the low numbers attained when compared to the total number of inhabitants estimated for the case study area, among them the pronounced seasonality, low population density and again the low range of vulnerability index values obtained to this particular building stock. Nonetheless, the number of homeless population has resulted quite expressive, naturally following to some extent the trend observed of the rate of unusable buildings. Finally regarding economic losses, it is worth highlighting here that the three analysed retrofitting packages proved to be cost-effective for the highest macroseismic intensities, i.e., from $I_{\text{EMS-98}}$ = IX to XII, presenting maximum global savings of about 20.10 million euros. Moreover, for moderate to high macroseismic intensities ($I_{\text{EMS-98}}$ = VII and VIII), very interesting savings of about 5.85 and 1.20 million euros were obtained with the application of the retrofitting packages RP1 and RP2, respectively.

As a final comment, it is worth noting that although the results discussed in this work refer to the old city centre of Horta, they are valid and extendable to other typologically similar urban areas (a full discussion on the definition of building typologies to support risk mitigation at the urban scale is presented by Santos *et al*. (2013)) and the vulnerability-based approach presented can be easily applicable to other case studies.

Acknowledgement

This paper refers to work supported by the Portuguese Foundation of Science and Technology (FCT), under the research project "URBSIS: Assessing Vulnerability and Managing Earthquake Risk at Urban Scale" (PTDC/ECM-URB/2564/2012). The authors acknowledge to SPRHI and REg, and thank to Professor Aníbal Costa and Eng. Filipe Neves for having made available a dataset of information related to the reconstruction process of the Faial Island. The constructive comments and suggestions given by the anonymous reviewers are also acknowledged by the authors.

References

Anand AS (2000), "Non-engineered Construction in Developing Countries – an Approach Toward Earthquake Risk Preduction," *12th World Conf. Earthq. Eng*., Auckland, New Zealand, pp 1–22

Andrade HMC (2011), Caracterização de Edifícios Antigos, Edifícios "Gaioleiros" Universidade Nova de Lisboa.

Arshad S and Athar S (2013), *Rural Housing Reconstruction Program Post-2005 Earthquake - Learning from the Pakistan Experience - A Manual for Post-Disaster Housing Program Managers*, 116.

Astroza M, Ruiz S and Astroza R (2012), "Damage Assessment and Seismic Intensity Analysis of the 2010 (M_w 8.8) Maule Earthquake," *Earthq Spectra*, **28**: S145–S164.

Barata M (2005), "The Lisbon Earthquake of 1st November 1755—a Historical Perspectives Approach," *Int. Conf. 250th Anniv.*, 1755 Lisbon Earthq.

Benedetti D and Petrini V (1984), "Sulla Vulnerabilita Sismica di Edifici in Muratura: un Metodo di Valutazione: A Method for Evaluating the Seismic Vulnerability of Masonry Buildings," L'industria delle Costr 66–74.

Bernardini A, Giovinazzi S, Lagomarsino S, *et al*. (2007), "Vulnerabilità e Previsione di Danno a Scala Territoriale Secondo una Metodologia Macrosismica Coerente con la Scala EMS-98," *Proc. 12th Conf. Ital. Natl. Assoc. Earthq. Eng*. – ANIDIS.

Betti M, Galano L and Vignoli A (2014), "Comparative Analysis on the Seismic Behaviour of Unreinforced Masonry Buildings with Flexible Diaphragms," Eng. Struct., 61: 195–208. doi: 10.1016/j.engstruct.2013.12.038.

Bothara J and Brzev S (2011), *A TUTORIAL: Improving the Seismic Performance of Stone Masonry Buildings*, 1st ed. EERI, Oakland, California, USA

Bramerini F, Di Pasquale G, Orisini A, *et al*. (1995), "Rischio Sismico del Territorio Italiano: Proposta per una Metodologia e Risultati Preliminary," Technical Report SSN/RT/95/01, Rome, Italy

Cansado E, Oliveira CS, Fragoso M and Miranda V (1998), Regras Gerais de Reabilitação e Reconstrução de Edifícios Correntes Afectados Pela Crise Sísmica do Faial, Pico e São Jorge, iniciada pelo sismo de 9 de Julho de 1998.

Carreño M-L, Cardona OD and Barbat AH (2007), "Urban Seismic Risk Evaluation: A Holistic Approach," Nat Hazards, 40:137–172. doi: 10.1007/s11069-006-0008-8

Coaffee J (2008), "Risk, Resilience, and Environmentally Sustainable Cities," *Energy Policy*, **36**: 4633–4638. doi: 10.1016/j.enpol.2008.09.048

Costa A (2002), "Determination of Mechanical Properties of Traditional Masonry Walls in Dwellings of Faial Island, Azore," *Earthq Eng Struct Dyn*, 31:1361–1382. doi: 10.1002/eqe.167

Costa A, Oliveira CS and Neves F (2008), *Reinforcing Techniques More Commonly Used in Faial Reconstruction. Sismo 1998 – Açores, Uma década depois*, 1st ed., pp 531–555.

Costa AA, Arêde A, Costa A, *et al*. (2012), "Experimental Testing, Numerical Modelling and Seismic Strengthening of Traditional Stone Masonry: Comprehensive Study of a Real Azorian Pier," *Bull Earthq Eng*, **10**: 135–159. doi: 10.1007/s10518-010-9209-3

Cunha S (2013), "Técnicas de Reforço em Edifícios de Alvenaria," *MSc thesis*, University of Aveiro, Portugal. (in Portuguese)

D'Ayala D, Spence R, Oliveira C and Pomonis A (1997), "Earthquake Loss Estimation for Europe's Historic Town Centres," *Earthq Spectra*, **13**: 773–793. doi: 10.1193/1.1585980

D'Ayala D and Speranza E (2002), Housing Report: Single-family Stone Masonry House, **15**.

DM (2008), Decreto Ministeriale DM 14/01/2008, Norme tecniche per le costruzioni, **428**.

Dolce M, Kappos A, Masi A, *et al*. (2006), "Vulnerability Assessment and Earthquake Damage Scenarios of the Building Stock of Potenza (Southern Italy) Using Italian and Greek Methodologies," *Eng Struct*, **28**: 357–371. doi: 10.1016/j.engstruct.2005.08.009

Ferreira TM, Costa AA, Arêde A, Varum H and Costa A (2015), "In Situ Out-of-plane Cyclic Test of Original and Strengthened Traditional Stone Masonry Walls Resorting to Airbags," *J Earthq Eng*., Taylor & Francis. doi: 10.1080/13632469.2015.1107662

Ferreira TM, Vicente R, Mendes da Silva J a. R, *et al*. (2013), "Seismic Vulnerability Assessment of Historical Urban Centres: Case Study of the Old City Centre in Seixal, Portugal," *Bull Earthq Eng*, **11**: 1753–1773. doi: 10.1007/s10518-013-9447-2

Ferreira TM, Vicente R and Varum H (2014), "Seismic Vulnerability Assessment of Masonry Facade Walls: Development, Application and Validation of a New Scoring Method," *Struct. Eng. Mech.*, **50**(4): 541–561.

GNDT (1994), Scheda di Esposizione e Vulnerabilità e di Rilevamento Danni di Primo livello e Secondo Livello (Muratura e Cemento Armato), Grupo Nazionale per la Difesa dai Terrmoti - Servizio Sismico Nazionale, Rome, Italy.

Goula X, Roca A and Oliveira CS (2006), *Assessing and Managing Earthquake Risk - Geo-Scientific and Engineering Knowledge for Earthquake Risk Mitigation:*

developments, tools, techniques, Springer 564.

Grünthal G (1998), "European Macroseismic Scale 1998 (EMS-98), European Seismological Commission, Subcommission on Engineering Seismology," Working Group Macroseismic Scales, **15**: 101.

IDNDR (1994), "Yokohama Strategy and Plan of Action for a Safer World - Guidelines for Natural Disaster Prevention, Preparedness and Mitigation," World Conf. Nat. Disaster Reduct.

Maio R, Ferreira TTM, Vicente R and Estêvão J (2015), "Seismic Vulnerability Assessment of Historical Centres: Case Study of the Old City Centre of Faro, Portugal," *J Risk Res*. doi: 10.1080/13669877.2014.988285

Mendes N and Lourenco PB (2010), "Seismic Assessment of Masonry "Gaioleiro" Buildings in Lisbon, Portugal," *J Earthq Eng*, **14**(1): 80–101. doi: 10.1080/13632460902977474

Mitchelson M (2011), *Haiti and Christchurch Earthquakes Viewed through a Resilience lens - A Comparative Case Study*, 92.

Moreira VS (1989), *Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound. Seism, Port. Cont. Margin, NATO ASI S.* Springer Netherlands, pp 533–545.

Neves F, Costa A, Vicente R, *et al*. (2012a), "Seismic Vulnerability Assessment and Characterisation of the Buildings on Faial Island, Azores," *Bull Earthq Eng*, **10**: 27–44. doi: 10.1007/s10518-011-9276-0

Neves N, Arêde A and Costa A (2012b), "Seismic Analysis of a Building Block," *Bull Earthq Eng*, 1–33.

Nunes J (2008), General Description of the Azores Region Seismicity, In: Oliveira C., Costa A, Nunes JC (eds) Sismo 1998 – Açores, Uma década depois, 1st Editio. Horta, Faial Island, Azores, Portugal, pp 59–72.

Oliveira CS, Costa A and Nunes JC (2008), 1998 Azores Earthquake, One Decade after, Governo dos Açores, SPRHI S.A. ISBN 978-989-20-1223-0. (in Portuguese)

Oliveira CS, Lucas A and Guedes JHC (1990), MONOGRAFIA - 10 Anos após o Sismo dos Açores de 1 de Janeiro de 1980 - Volume I e II. Secretaria Regional da Habitação e Obras Públicas, Delegação da Ilha Terceira, Açores, Laboratório Nacional de Engenharia Civil, Angra do Heroísmo, Açores, Portugal.

Pagnini LC, Vicente R, Lagomarsino S and Varum H (2011), "A Mechanical Model for the Seismic Vulnerability Assessment of Old Masonry Buildings," *Earthq Struct*, **2**: 25–42.

Penna A (2015), "Seismic Assessment of Existing and Strengthened Stone-masonry Buildings: Citical Issues and Possible Strategies (2015)," *Bull Earthq Eng*, **13**(4): 1051-1071. doi: 10.1007/s10518-014-9659-0

Ranghieri F and Ishiwatari M (2014), "Learning from Megadisasters - Lessons from the Great East Japan Earthquake," **391**. doi: 10.1596/978-1-4648-0153-2

Santos C, Ferreira TM, Vicente R and Mendes da Silva JAR (2013), *Building Typologies Identification to Support Risk Mitigation at the Urban Scale - Case Study of the Old City Centre of Seixal, Portugal*, J Cult Herit, **14**(6): 449–463. doi: 10.1016/j.culher.2012.11.001

Silva V, Crowley H, Varum H and Pinho R (2014), "Seismic Risk Assessment for Mainland Portugal," *Bull Earthq Eng*., doi: 10.1007/s10518-014-9630-0

Simões A, Bento R, Cattari S and Lagomarsino S (2014), "Seismic Performance-based Assessment of "Gaioleiro" Buildings," *Eng Struct*, **80**: 486–500. doi:10.1016/j.engstruct.2014.09.025

Tomaževič M (1999), *Earthquake-resistant Design of Masonry Buildings*, Imperial College Press, London

Vicente R (2008), Estratégias e Metodologias Para Intervenções de Reabilitação Urbana - Avaliação da Vulnerabilidade e do Risco Sísmico do Edificado da Baixa de Coimbra, 471.

Vicente R, Ferreira T and Maio R (2014a), "Seismic Risk at the Urban Scale: Assessment, Mapping and Planning," *Procedia Econ Financ*, **18**: 71–80. doi: 10.1016/S2212-5671(14)00915-0

Vicente R, Ferreira TM, Maio R and Koch H (2014b), "Awareness, Perception and Communication of Earthquake Risk in Portugal: Public Survey," *Procedia Econ Financ*, **18**: 271–278. doi: 10.1016/S2212-5671(14)00940-X

Vicente R, Ferreira TMT, Maio R and Koch H (2014c), "Awareness, Perception and Communication of Earthquake Risk in Portugal: Public Survey," *Procedia Econ Financ*, **18**: 271–278. doi: 10.1016/S2212-5671(14)00940-X

Vicente R, Parodi S, Lagomarsino S, *et al*. (2011), "Seismic Vulnerability and Risk Assessment: Case Study of the Historic City Centre of Coimbra, Portugal," *Bull Earthq Eng*, **9**: 1067–1096. doi: 10.1007/s10518-010-9233-3

Vicente R, Silva JARM da, Varum H, *et al*. (2010), "Avaliação da Vulnerabilidade Sísmica do Núcleo Urbano Antigo do Seixal," *Proc 8th Port Congr Seismol Seism Eng*. doi: http://sismica2010.web.ua.pt/

Zonno G, Oliveira CS, Ferreira M a., *et al*. (2010), "Assessing Seismic Damage Through Stochastic Simulation of Ground Shaking: The Case of the 1998 Faial Earthquake (Azores Islands)," Springer - Surv Geophys, 31:361–381. doi: 10.1007/s10712-009-9091-1