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VULNERABILITY ASSESSMENT OF THE OLD CITY CENTRE OF HORTA, PORTUGAL: CALIBRATION AND APPLICATION OF A SCORING METHOD

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Abstract

Due to the scale and number of buildings involved, the methodologies currently available to assess the seismic vulnerability of urban areas usually require the treatment of a massive volume of data associated with the inspection and survey work, and for this reason the use of more simplified approaches is becoming more popular in the detriment of the later, particularly in this regard. Bearing in mind the high seismic vulnerability usually associated to the built environment within historical centres, this paper is focused on the calibration of a seismic vulnerability assessment method for old masonry buildings by treating a set of post-earthquake damage data collected just after the earthquake that struck the Azorean island of Faial on the 9th of July 1998. Based on this data, the weights associated to each of the parameters that compose the original formulation of the method were calibrated and the subsequent results discussed. Finally, the calibrated version of the seismic vulnerability assessment method was applied to the historical centre of Horta, and damage and loss scenarios were derived using a Geographical Information System (GIS) tool.

Keywords: Seismic vulnerability; Damage observation; Scoring method; Damage and loss scenarios

1. Introduction

As comprehensively discussed in [1], the definition of seismic vulnerability assessment approaches (qualitative and quantitative) naturally constrains its formulation and the level at which the evaluation is conducted. Within the wide diversity of methodologies and formulations documented in the literature, empirical methods have shown to be particularly suitable to buildings in historical centres, as damage data has been systematically collected over a significant number of past earthquakes worldwide. However, when such kind of information does not exist and the typological characteristics of the buildings to assess are significantly different from those used for the calibration of the applied methodology, the results obtained can be quite inaccurate and therefore there is a continuous need to adapt and recalibrate these approaches taking into account the context of each built environment. Thus, taking advantage of a wide set of damage data collected in the sequence of the magnitude VII earthquake that struck the Azores archipelago on July 9, 1998, this paper discusses the calibration and application of a seismic vulnerability assessment approach to the old city centre of Horta, in Faial Island. The calibrated methodology was then applied to a set of 192 traditional masonry buildings and the results analysed using a geographical information system (GIS) tool, wherein different modules were implemented aiming to obtain multiple outputs (damage and loss estimation maps) for different earthquake scenarios, namely, the number of collapsed buildings, death rate, number of unusable buildings and repair costs. It is worth noting that although this methodology has already been widely applied in the past to assess different case studies in Portugal, this is the first time that it is calibrated on the basis of Portuguese building damage data.

2. Vulnerability index methodology

Conceptually, the methodology used in this work is based on the calculation of a vulnerability index for each building as the weighted sum of 14 parameters, which individually evaluates one aspect related to the building's seismic response (see Table 1).

Table 1 – Vulnerability index associated parameters, classes and weights, adapted from [2]

Parameters		Class, C_{vi} A	B	C	D	Weight p_i	Relative weight
Group 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	
Group 2. Irregularities and interaction							
P7	Aggregate position and interaction	0	5	20	50	1.50	27/100
P8	Plan configuration	0	5	20	50	0.75	
P9	Regularity in height	0	5	20	50	0.75	
P10	Wall façade openings and alignments	0	5	20	50	0.50	
Group 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	
Group 4. Conservation state and other elements							
P13	Fragilities and conservation state	0	5	20	50	1.00	12/100
P14	Non-structural elements	0	5	20	50	0.50	

As can be seen in Table 1, these parameters are distributed into 4 vulnerability classes, C_{vi}, of growing vulnerability (A, B, C and D), each of which associated to a weight, p_i, that can range from 0.5 for the less important parameters to a maximum of 1.5 for the most important. The seismic vulnerability index for each building, I_v^*, is given by Eq. (1):

$$I_v^* = \sum_{i=1}^{14} c_{vi} \times w_i \tag{1}$$

Although the value of I_v^* initially ranges between 0 and 650, however for ease of use, it is usually normalised to fall within the range between 0 and 100, where the lower the value of I_v^*, the lower the seismic vulnerability of the building.

For the operational implementation of the methodology, an analytical expression that correlates hazard with the mean damage grade ($0<\mu_D<5$) of the damage distribution (*discrete beta distribution*) in terms of the seismic vulnerability value was proposed by [3], in Eqs. (2) and (3):

$$\mu_D = 2.5 + 3\tanh\left(\frac{I + 6.25V - 12.7}{3}\right) \times f(V, I) \tag{2}$$

$$f(V, I) = \begin{cases} e^{\frac{V}{2}(I-7)}, if\ I \leq 7 \\ 1 \qquad\quad, if\ I > 7 \end{cases} \tag{3}$$

where I is the seismic hazard described in terms of macroseismic intensity, V is the vulnerability index used in the Macroseismic Method that determines the position of the curve - see Eq. (4) -, and $f(V, I)$ is a function depending on the vulnerability index and intensity, introduced to understand the trend of the numerical vulnerability curves taken from the EMS-98 even for the lower extremes of the intensity grades (I = V and VI). This expression was proposed within the framework of an innovative macroseismic approach, allowing the vulnerability analysis of building typologies to be defined according to the EMS-98 European Macroseismic Scale [4] and qualitatively related to its vulnerability classes. The vulnerability index I_v can be related to the vulnerability index V, by means of Eq. (4), enabling the calculation of the mean damage grade, μ_D, and the subsequent estimation of physical, economic and human losses.

$$V = 0.592 + 0.0057 \times I_v \tag{4}$$

3. Calibration of the original formulation based on post-earthquake damage data

This section discusses the calibration of the weights associated with the 14 parameters presented in Table 1, through post-earthquake damage data obtained following the 1998 Azores earthquake that hit the central group of the archipelago of Azores (Portugal). From the technical and academic point of view, the 1998 Azores earthquake allowed the collection of an unprecedented amount of data concerning the characterisation of the building stock and the respective observed damage. This data was already partially treated by [5], that compiled this information in a comprehensive catalogue comprising a detailed characterisation of the old traditional rubble stone building stock and a detailed damage grade classification based on different damage mechanisms observed.

Zonno et al. [6] presented a proposal for the macroseismic intensity distribution map for the Faial island (depicted in Fig. 2), which was constructed on the basis of post-event field survey and damage observation campaigns. Although the credibility of this source, it is important to note that this kind of approaches are inevitably subjected to important uncertainties and therefore it is reasonable to assume that some particular areas could have been subjected to different intensities of those plotted on the map of Fig. 1.

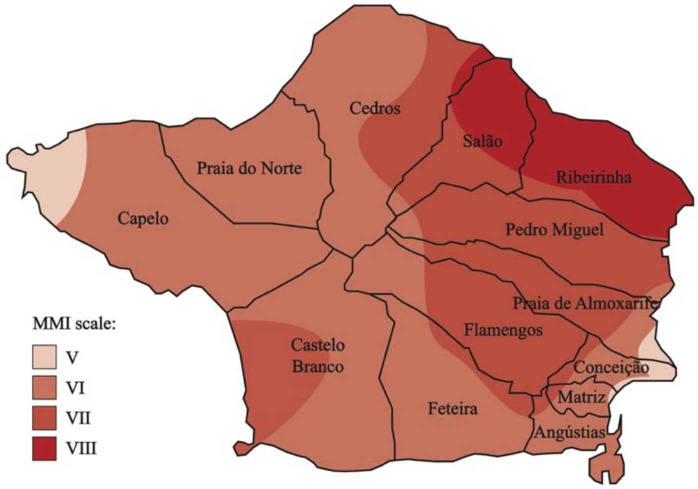


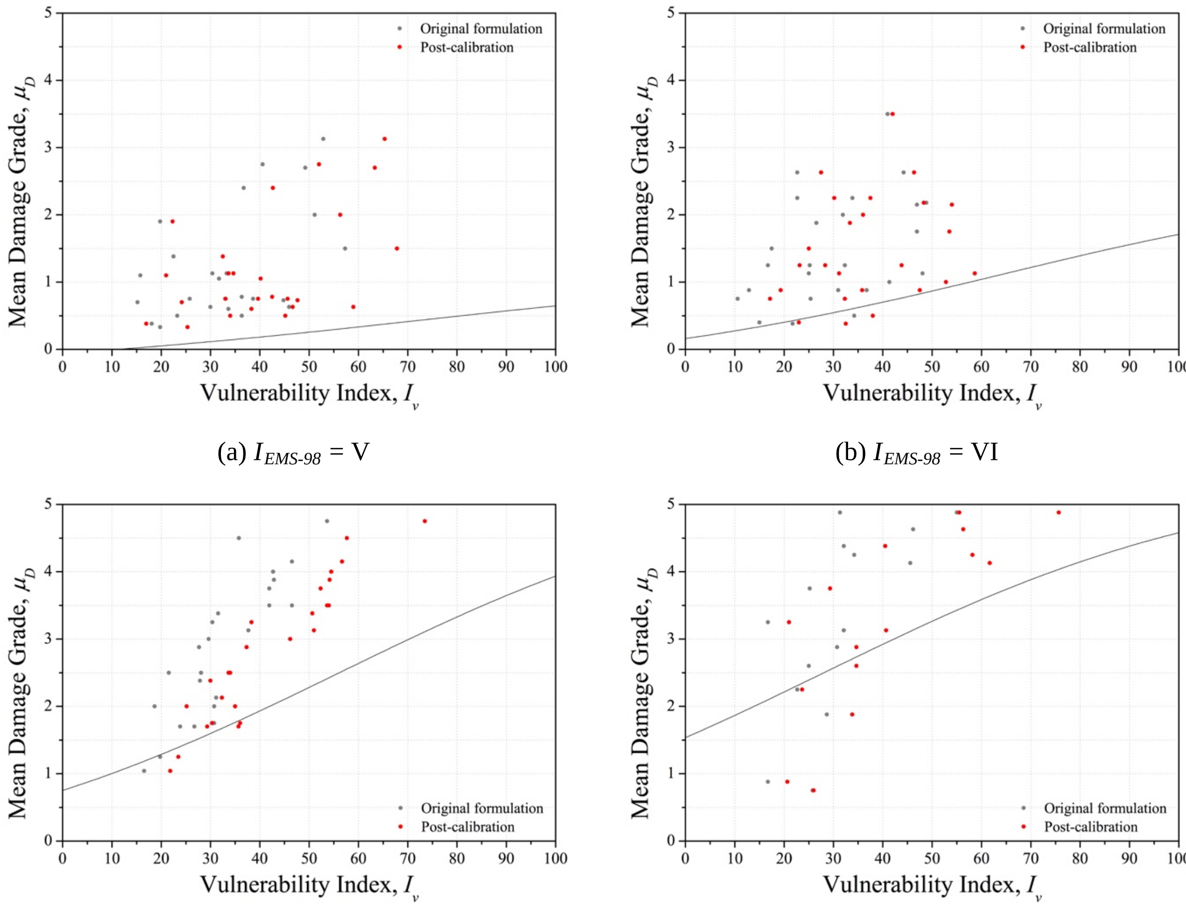
Fig. 1 – Modified Mercalli Intensity (MMI) scale intensity map of Faial island (from [6])

Thus, the calibration of the original vulnerability index method was carried out through its application to a set of 90 masonry buildings considered by the authors as representative of traditional Azorean construction and to which comprehensive information was available. This information was further enhanced with a vast collection of pictures provided to the authors by owners and municipal authorities. It is worth noting that, further than their representativeness in terms of material and constructive technology, buildings were selected so that the sample was composed by both rural and urban buildings, naturally presenting distinct characteristics and different damage grades, μ_D (classified in accordance with EMS-98 [7]).

Table 2 – Vulnerability index associated parameters, classes and new weights

Parameters		Class C_{vi} A	B	C	D	Weight p_i	Relative weight
Group 1. Structural building system							
P1	Type of resisting system	0	5	20	50	2.50	50/100
P2	Quality of resisting system	0	5	20	50	2.50	
P3	Conventional strength	0	5	20	50	1.00	
P4	Maximum distance between walls	0	5	20	50	0.50	
P5	Number of floors	0	5	20	50	0.50	
P6	Location and soil conditions	0	5	20	50	0.50	
Group 2. Irregularities and interactions							
P7	Aggregate position and interaction	0	5	20	50	1.50	20/100
P8	Plan configuration	0	5	20	50	0.50	
P9	Height regularity	0	5	20	50	0.50	
P10	Wall façade openings and alignments	0	5	20	50	0.50	
Group 3. Floor slabs and roofs							
P11	Horizontal diaphragms	0	5	20	50	0.75	18/100
P12	Roofing system	0	5	20	50	2.0	
Group 4. Conservation state and other elements							
P13	Fragilities and conservation state	0	5	20	50	1.00	12/100
P14	Non-structural elements	0	5	20	50	0.75	

Subsequently, these 90 buildings were grouped according to the intensity map depicted in the previous Fig. 1 and a mean damage grade, μ_D, was estimated for each building based on the 1998 post-earthquake damage data available. Following this procedure, it was then possible to plot a point cloud for each one of the four macroseismic intensities observed (refer to Fig. 2) and to analyse its mathematical correlation with the corresponding vulnerability functions obtained from Eq. (2). The analysis of the correlation between the initial point cloud and the previously referred vulnerability curves, and its later improvement, was made possible resourcing to Matlab® Curve Fitting Toolbox software. Additionally, a weighted least-squares fitting method was used, varying the parameters' weights, *pi*, associated to the vulnerability index I_v. This way it was then possible to obtain new p_i values that for each intensity I_{EMS-98} minimise the overall squared sum of residuals of all the evaluated macroseismic intensities (see Table 2). In the following Fig. 2 the global comparison between the original and the post-calibration results for the macroseismic intensities I_{EMS-98} =V, VI, VII and VIII is presented.



(a) I_{EMS-98} = V

(b) I_{EMS-98} = VI

(c) I_{EMS-98} = VII

(d) I_{EMS-98} = VIII

Fig. 2 – Global comparison between the original and the post-calibration results

As it can be seen, the calibration led to a more balanced distribution of the I_v results. After the calibration, the mean value of the seismic vulnerability index, I_v, changed from 32.05 to 40.07, with a standard deviation value, σ_{Iv}, equal to 13.63.

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

As part of the research project "URBSIS: Assessing Vulnerability and Managing Earthquake Risk at Urban Scale" commissioned by the City Council of Horta, a complete identification and inspection survey of old masonry buildings of the historical centre of Horta was carried out. The data gathered from the inspection of 192 buildings was processed and crosschecked with the corresponding case files found at the local Department of Urban Regeneration. A database management system integrated into a Geographical Information System (GIS) application was applied to manage, compare and spatially analyse all the information.

The masonry building stock of the old city centre of Horta was assessed by assigning a vulnerability index value, I_v, to each building, according to the methodology described in §2, and calibrated in the previous §3. As the methodology applied in this work requires accurate knowledge of the building characteristics, which can be only obtained by carrying out comprehensive and detailed inspections, the vulnerability assessment was undertaken in two phases:

- In the first phase, an evaluation of the vulnerability index, I_v, was estimated for those buildings for which detailed information was available (50 buildings out of 192), by filling in a set of five detailed checklists specifically created for the effect. These inspection and diagnosis checklists, used to survey each single element (roof, façade walls, timber floors, internal partition walls, etc.), were structured according to the building criteria, which in turn were previously defined in a hierarchical manner;

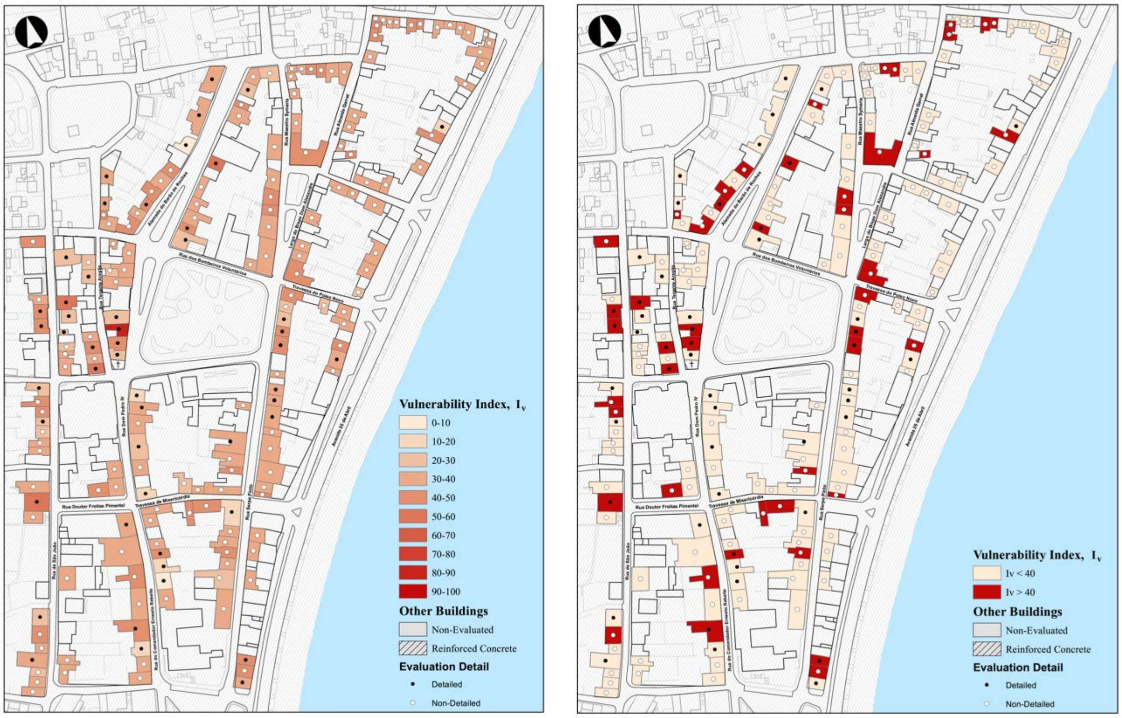
- In the second phase, a more expeditious approach for the assessment of the remaining 142 buildings was adopted (non-detailed exterior inspection) that used the mean values obtained from the detailed analysis of the first phase (detailed inspected buildings), assuming the masonry building characteristics homogeneous in this region.

4.1 Vulnerability assessment results

From the application of the vulnerability index methodology to the 50 buildings assessed in detail (corresponding to the first phase of the assessment) a mean value of the seismic vulnerability index, I_{vmean}, of 33.83 was obtained. With the introduction of the complementary approach, used in the assessment of the remaining 142 buildings for which the information was incomplete (second phase of assessment), the mean seismic vulnerability index value, I_{vmean}, increased to 35.92, which represents a difference of about 6%. Approximately 8% of the assessed buildings presented a vulnerability index value over 45, equivalent to vulnerability class A in the EMS-98 scale [7] and 4% had a I_v below 20, equivalent to vulnerability class B. The maximum and minimum I_v values obtained from the assessment were 13.65 and 80.38, respectively.

The standard deviation value, σ_{Iv}, associated with the detailed assessment was 13.43. With the introduction of data obtained from non-detailed assessment, this standard deviation value decreased to 8.04, representing a reduction of 40%. It is important to stress that the following results must be interpreted statistically, both by identifying a representative mean value and defining the upper and lower bounds of the vulnerability index results.

Fig. 3 (a) presents the overall distribution of the building stock's seismic vulnerability of the old city centre of Horta and Fig. 3 (b) highlights the buildings evaluated with $I_v \geq 40$.

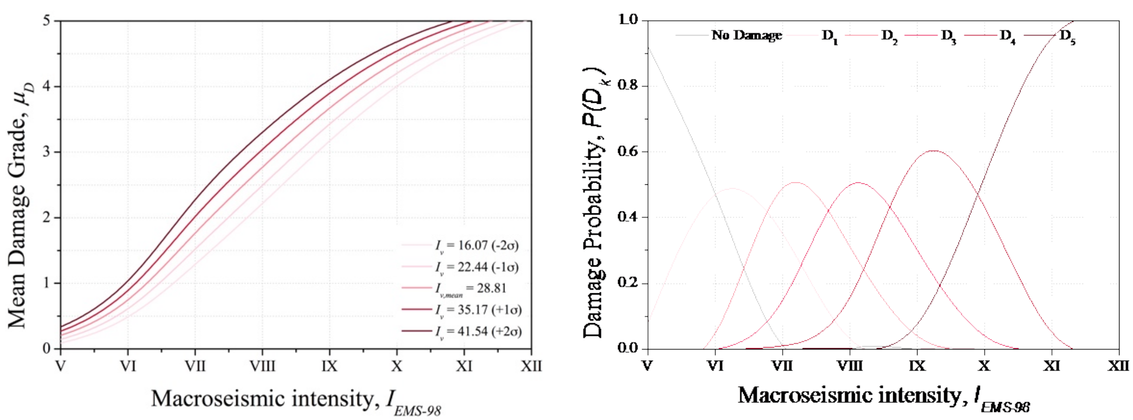


(a) (b)

Fig. 3 – Vulnerability index mapping of the old city centre of Horta (a) and identification of buildings with vulnerability index $I_v \geq 40$ (b)

4.2 Damage distribution and scenarios

As already discussed in §2, mean damage grades, μ_D, can be estimated for different macroseismic intensities resorting to Eq. (2), which correlates hazard with the mean damage grade of the damage distribution in terms of vulnerability index values [8]. Based on this analytical formulation, it is possible to derive vulnerability curves using the mean value and the upper and lower bound ranges of the vulnerability index distribution for different scenarios, as depicted in Fig. 4 (a). Fig. 4 (b) instead, presents the damage probabilities associated with each one of these scenarios of macroseismic intensity for the mean value of the vulnerability index, $I_{v,mean}$.



(a) (b)

Fig. 4 – Vulnerability curves (a) and mean damage grade distributions for $I_{v,mean}$ = 35.92 (b)

Moreover, Fig. 5 (a), (b), (c) and (d) present damage scenarios for earthquake intensities between I_{EMS-98} =VII and I_{EMS-98} =X, respectively.

(a) I_{EMS-98} = VII

(b) I_{EMS-98} = VIII

(c) I_{EMS-98} = IX

(d) I_{EMS-98} = X

Fig. 5 – Damage scenario for different macroseismic intensities, I_{EMS-98}

5. Loss assessment

Finally, the present section summarizes the loss estimation results for the old city centre of Horta, obtained from the damage scenarios previously presented in §4. Among several methodologies existing in the literature for loss estimation as a function of the probability of occurrence of a certain damage grade, the loss estimation results are herein presented in two ways:

- By the construction of damage scenarios based on global probabilistic distributions, using representative values of the vulnerability index for the building typology evaluated, and;
- By using GIS to estimate individual loss (building by building) and visualize loss scenarios, combining results obtained from the probabilistic calculations with individual building aspects and characteristics.

5.1 Collapsed and unusable buildings

The methodology adopted in this work for estimating probability of collapse and unusable buildings has been proposed by *Servizio Sismico Nazionale* (SSN) based on the work of [9] and involves the analysis of data associated with the probability of buildings to be deemed unusable after minor and moderate earthquakes. The probabilities associated with the exceedance of a certain damage grade are used in the loss estimation and affected by multiplier factors, which range from 0 to 1, and despite they may differ from proposal to proposal, they all involve statistical correlations. Bramerini et al. [9] have established these weighted factors and respective expressions on the basis of extensive damage data obtained from past events occurred in Italy. In the present paper the estimation of collapsed and unusable buildings were calculated by means of the expressions of the following Eqs. (5) and (6):

$$P_{collapse} = P(D_5) \tag{5}$$

$$P_{unusable\ buildings} = P(D_3) \times w_{ei,3} + P(D_4) \times w_{ei,4} \tag{6}$$

where $P(D_i)$ is the probability of the occurrence of a certain damage grade (from D_1 to D_5) and $W_{ei,\ j}$ are multiplier factors that indicate the percentage of buildings associated with the damage grades, D_i, that are expected to collapse or to lose their original serviceability conditions. In this study, the values of $W_{ei,3}$ and $W_{ei,4}$ were adopted from [2] and [10], and assumed equal to 0.4 and 0.6 respectively. Fig. 6 depicts the probability of collapsed and unusable buildings for the mean value of the vulnerability index, I_{vmean} = 35.92 and for other characteristic values of the vulnerability index ($I_{vmea\,n} - 2\sigma_{Iv}$; $I_{vmean} - \sigma_{Iv}$; $I_{vmean} + \sigma_{Iv}$; $I_{vmean} + 2\sigma_{Iv}$).

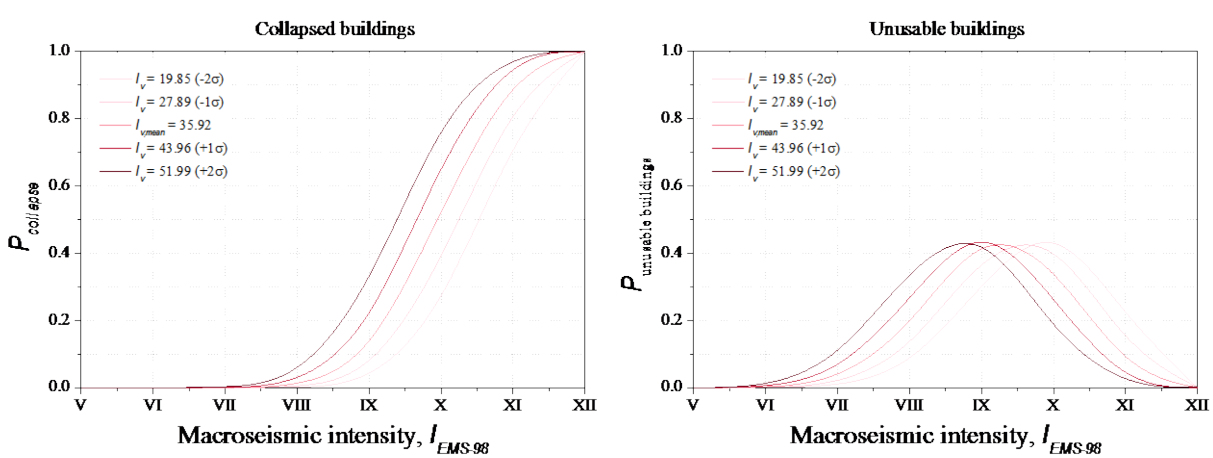


Fig. 6 – Probability of collapsed and unusable buildings for the representative values of the vulnerability index

5.2 Human casualties and homelessness

The proposal presented by *Servizio Sismico Nazionale* [9] was also used in this work to estimate casualty rates (deaths and severely injured) and homelessness. As in [2], the death and severely injures rates were defined as being 30% of the residents living in collapsed and unusable buildings. Regarding the survivors, it was assumed that they will require short-term sheltering. Casualties and homelessness rates were determined resorting to Eqs. (7) and (8), respectively:

$$P_{dead\ and\ severely\ injured} = 0.3 \times P(D_5) \tag{7}$$

$$P_{homeless} = P(D_3) \times w_{ei,3} + P(D_4) \times w_{ei,4} + 0.7 \times P(D_5) \tag{8}$$

Following the same output presentation used in the previous section, Fig. 7 shows the estimation of the number of deaths, severely injured and homelessness associated with the representative values of the vulnerability index, I_v, and Table 6 presents the overall results associated to that estimation, considering a total number of 1596 inhabitants.

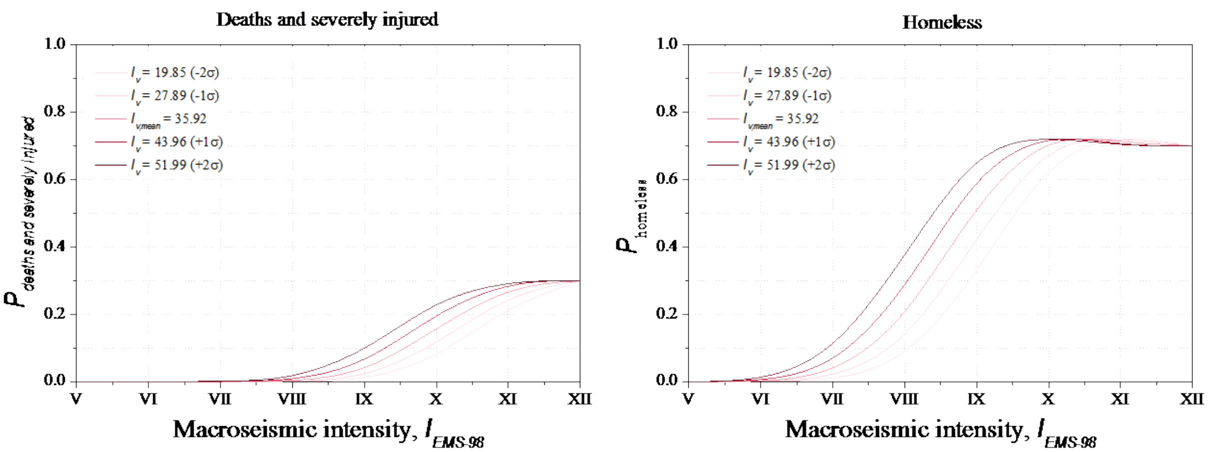


Fig. 7 – Probability of casualties and homelessness for the representative values of the vulnerability index

5.2 Economic loss

The estimated damage can be translated into economical value in euros or as an economic damage index, representing the ratio between the repair and the replacement costs after an earthquake. The correlation used in this work follows the same proposal as in [11], who have estimated the cost of typical repair actions from the analysis of post-earthquake damage data based on more than 50,000 buildings affected by Umbria-Marche (1997) and Pollino (1998) earthquakes. According to those authors, the repair cost probabilities for a certain seismic event characterised by an intensity I, $P[R|I]$, can be obtained from the product between the conditional probability of the repair cost for each damage level, $P[R|Dk]$, and the conditional probability of the damage condition for each level of building vulnerability and seismic intensity, $P[D_k|I_v,I]$, as described in Eq. (9):

$$P[R|I] = \sum_{D_k=1}^{5} \sum_{I_v=0}^{100} P[R|D_k] \times P\,[D_k|I_v, I] \tag{9}$$

To estimate the replacement costs associated with the different building conditions, an average cost value of 1000 €/m^2 was considered for the building stock within the historical centre of the city of Horta, value that was suggested and adopted in the past by [2] for the old city centre of Coimbra, in Portugal. It is worth noting that this value is also similar with the one suggested by [11]. Table 3 presents the estimated repair costs for the entire study area, both in global terms and in relation to the Gross Domestic Product (GDP) of the Autonomous Region of Azores (about 3,740 M€).

Table 3 – Estimated repair costs: Value in millions of euros and % of GDP

Total number of buildings: 192	**Macroseismic intensity, I_{EMS-98}**							
	V	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
Replacement costs (in millions of €)	0.37	2.77	15.77	37.36	60.50	73.03	77.51	77.96
Percentage of GDP	0.01%	0.07%	0.42%	1.00%	1.62%	1.95%	2.07%	2.08%

6. Conclusions

The application of the original seismic vulnerability index formulation for the assessment of 90 masonry buildings assumed representative of traditional Azorean (and Portuguese) masonry buildings was comprehensively examined, by identifying and discussing its main advantages and limitations. As intended, the calibration of the weights associated with the parameters that compose the original formulation have significantly improved the approximation between the vulnerability curve and the evaluated point cloud. Moreover, this calibration process has widened the spectrum of vulnerability index range values.

The post-calibration results are closely correlated to the observed building construction features and general fragilities of the built environment, proving the consistency of the seismic vulnerability assessment methodology herein considered. The level of damage estimated for the buildings of the old city of Horta is an indicator of their low resistance to seismic actions, and the moderate to high values of physical damage and loss obtained for intensities VII and VIII are a consequence of these buildings' high vulnerability. The integration of the obtained results in a GIS tool is undoubtedly an added value, particularly at the urban scale, as it enables the storage of several building features and survey information data, the assessment of seismic vulnerability, and the generation of damage and loss scenarios. These features, which provide the possibility of spatial result presentation, make GIS an effective tool in the support of mitigation strategies and management of seismic risk.

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