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SEISMIC VULNERABILITY ASSESSMENT OF EXISTING MASONRY BUILDINGS: CASE STUDY OF THE OLD CITY CENTRE OF FARO, PORTUGAL

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ABSTRACT

The seismic vulnerability and risk assessment of old city centre areas is truly essential in urban rehabilitation programs and should not be focused exclusively over recognized historical and patrimonial valuable buildings but also in relation to current old masonry buildings that are highly valued in urban context. In addition, due to their geographical, demographic or historical features some old city centres are particularly interesting and critical, in respect to seismic risk mitigation. An excellent example of this reality is the old city of Faro, Capital of the Algarve, Portugal, which is one of the most popular summer touristic destination in Europe in a prone seismic region. This fact explains the high seasonal flux of population, which together with the moderate to high seismic hazard of the Algarve region and a vulnerable building stock increases both the seismic and tsunami risk in this area.

From the exposed, this paper approaches the seismic vulnerability assessment of old building stock through the application of a simplified vulnerability method to the old city centre of Faro. Such method is based on a vulnerability index, which can be used to evaluate physical damage and to create human and economic loss scenarios in a broad sense (Vicente et al., 2011). 191 buildings were evaluated in accordance with the referred methodology and the results obtained were subsequently integrated into a Geographical Information System (GIS) tool, which allows the spatial analysis of results (Ferreira et al., 2013).This tool constitutes a very valuable instrument for city councils and regional authorities, whom can decide in a faster and more accurate way the best risk mitigation strategies to follow at the urban scale.

INTRODUCTION

The metropolitan region of Lisbon, the region of Algarve and the Azores Island, are the three most important seismic regions in Portugal, which have been damaged by earthquakes throughout the centuries. The Algarve region, whose administrative and political centre is Faro, is internationally

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recognised for its touristic visibility and leads a substantial impact on the Portuguese economy, despite its seasonality. The seismicity associated to this region derives from the offshore earthquake activity of the contact region of Euro-Asian and African plates and also from the activity of diverse local faults crossing the territory (Oliveira et al., 2004).

When analysing large-scale seismic vulnerability of individual buildings through simplified methodologies it is required a significant knowledge level of each single building, which even so is still incomparably lower than more detailed methodologies such as numerical analysis. It would be unreasonable and unaffordable to perform numerical analysis of each single building within historical centres. In this sense, to assemble the knowledge regarding the historical evolution and growth of the city under study and perceiving the fundamental structural characteristics and similarities among those buildings reduces the survey and inspection period, which is the most time-consuming task, entailing increased logistical expenses.

Faro, formerly named as Ossónoba and having appeared about the 8th Century before Christ, is the Capital of the southernmost city of mainland Portugal. In the present case study it was given particular attention to the ARU (Urban Rehabilitation Area) Ribeirinha (see Figure 1), in which the higher amount of both old masonry and residential buildings was found, and thus with increased interest for the purpose of this research. Originally associated to agriculture and fishing commercial activities, this area still preserves some of those traits by the existence of countless warehouses at the ground floor level of residential buildings. As documented in several historical documents related to its historical evolution, Faro has been victim of countless invasions and transformations throughout the centuries. One of the most significant catastrophes happened during the 18th Century, with the well-known 1755 earthquake followed two years after by a hurricane and also by the devastating wars occurred in the early 19th Century. The knock-on effect that these events have had, led to collapse the majority of the existing building stock. Once the reconstruction process was understandably long and complex and naturally realised new construction technologies, which were implemented over the ruined buildings, during this period Faro witnessed a densification of its building stock, supporting the complex architectural nature recurrently found in the majority of the surveyed building's backyards.

(a) (b)

Figure 1. Project area (a) and zone delimitation (b) of the Ribeirinha area within the city of Faro.

VULNERABILITY ASSESSMENT OF THE OLD CITY CENTRE OF FARO

As part of a study supported by the URBSIS project – Assessing Vulnerability and Managing Earthquake Risk at Urban Scale - and commissioned by the Faro City Council, a complete identification and inspection survey of the old masonry buildings inserted in the Ribeirinha area of Faro was made. The data gathered from the inspection of 354 buildings, spread over 80 000 m^2, was processed and then crosschecked with the corresponding case files founded at the local Department of Urban Regeneration, allowing a better knowledge of the existing structural typologies and its evolution throughout the years. As mentioned previously, the database management system integrated into a GIS application was applied to manage, compare and spatially analyse all the relevant information.

Due to the difficulties encountered in accessing the interior of all the buildings and time constraints, two different levels of detail were considered. Thus, the 354 buildings were divided into three classes based on the detail of the available information. The first class, composed of the 53 buildings for which it was possible to perform a detailed inspection, was studied by filling in detailed several checklists adapted from a similar research project, supported by the National Strategic Reference Framework (7th Framework European Program) and commissioned by the Seixal City Council (Ferreira et al., 2013). These inspection and diagnosis checklists were used to survey each construction element (roof, façade walls, timber floors, internal partition walls, etc.). The second class was composed of 138 buildings for which only exterior inspection was available. Finally, a third class composed of 163 buildings, grouped the excluded buildings, since both their undesirable construction characteristics (reinforced concrete or R.C. buildings), actual conservation states (rehabilitated or in ruin, *R*) or current occupation state (unoccupied, *U*) were not considered to be bound by this particular methodology. Figure 2 illustrates the percentages related to the each different group of buildings, out of 354 buildings founded in the Ribeirinha area of Faro. From this figure it is important to highlight two interesting observations resulting from this distribution. The first one concerns the percentage of assessable buildings of 54%, meaning that only roughly half of the total number of buildings was assessable to undergo a full inspection. The second observation regards the percentage of the full-inspected (detailed) buildings, which is apparently low (15%). In fact, this misleading percentage hides a significant statistical value according to the following arguments: the full-inspected buildings represent slightly more than a quarter of the assessable buildings; the majority of the partially-inspected (non-detailed) buildings were temporarily unoccupied due to the high seasonal flux of population that prevails in Faro.

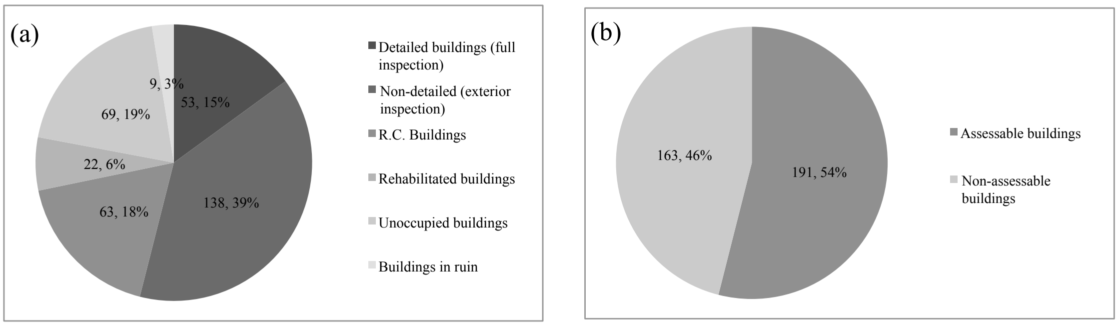

Figure 2. Percentage distribution of each different group of buildings pertaining to the Ribeirinha case study area (a). Distribution of the buildings with respect to its assessable condition (b)

VULNERABILITY INDEX METHODOLOGY

Despite being an already widespread methodology (Vicente et al., 2011; Ferreira et al., 2013), it's always important to understand from where it came and what is its purpose. The vulnerability index formulation herein applied was originally based on the GNDT II level approach (GNDT, 1994) for the vulnerability assessment of masonry buildings. This methodology is based on post-seismic damage observation and survey data covering a vast number of elements, focusing on the most important aspects and features that define building damage. Originally created in Italy, where it has been largely applied during the last 25 years, this methodology was adapted and improved for its use with Portuguese masonry buildings by Vicente (Vicente, 2008; Vicente et al., 2011)

Thence, each single building of the masonry building stock of the Ribeirinha area was assessed by the assignment of a vulnerability index value, I_v. This vulnerability index value was obtained by the calculation of a vulnerability index score for each building as the weighted sum of 14 parameters. These parameters were distributed into 4 vulnerability classes (C_{vi}) of growing vulnerability: *A*, *B*, *C* and *D*. Each parameter covers one aspect related to the building's seismic response. Subsequently, a weight, p_i, was assigned to each of the parameters, ranging from 0.50 for the less important parameters (in terms of structural vulnerability) to 1.5 for the most important (see Table 1). Although the value of I^*_v initially ranged between 0 and 650, this value was then normalised to fall within the range between 0 and 100 for ease of use. As will be discussed further on, the calculated vulnerability index was then used to estimate a building's damage condition based on the macroseismic intensity of the seismic action. Further explanation regarding each individual parameter definition can be consulted in the above-referred bibliography.

Table 1. Vulnerability index (I_v)

PARAMETER	Class C_{vi}				Weight	Relative weight over I_v	VULNERABILITY INDEX
	A	B	C	D	p_i		
1. Structural building system							
P1 Type of resisting system	0	5	20	50	0.75	46/100	$I^*_v = \sum_{i=1}^{14} C_{vi} \times p_i$
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		
3. Floor slabs and roofs							
P10 Wall facade openings and alignments	0	5	20	50	0.50	15/100	Normalised index $0 \leq I_v \leq 100$
P11 Horizontal diaphragms	0	5	20	50	1.00		
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		

The inspection and building assessment stage was divided into two distinct phases. In the first phase, an evaluation of the vulnerability index, I_v, was made for those buildings for which detailed information was available (53 buildings out of 354). In the second phase, a more expeditious approach for the assessment of the remaining 138 buildings was adopted, since the ratio of buildings available to assess was unworthy when compared to the associated required facilities. Moreover, one can assume that the inspected buildings ratio of 54%, when comparing to other study cases such as Seixal (Ferreira et al., 2013), is a sufficient sample to achieve valid scientific values. For the second phase, it was used the mean values obtained from the detailed analysis of the first group of buildings (full inspected buildings), considering that the masonry building's characteristics were homogeneous. Starting from this principle, the mean vulnerability index value obtained in the first detailed evaluation was used as a typological vulnerability index (average value) that could be affected by modifiers of the mean vulnerability index for each building. The classification of these modifiers influenced the final vulnerability index as a sum of the scores for all modifiers. These modifiers (shown in Table 2) are some of the parameters previously presented in Table 1.

Table 2 shows the seven modified parameters and their scores in relation to the average vulnerability value for each parameter.

Table 2. Vulnerability modifier factors and the corresponding scores

Vulnerability modifiers	Class C_{vi}				Modifier score:
	A	B	C	D	$\frac{p_i}{\sum_{i=1}^{7} p_i} \times (c_{vi} - \bar{c}_{vi})$

P5	Number of floors	-1.03	0.00	3.10	9.31	
P6	Location and soil conditions	0.00	0.52	2.07	5.17	p_i - parameter, i, weight assigned
P7	Aggregate position and interaction	-1.03	0.00	3.10	9.31	$\sum_{i=1}^{7} p_i$ - sum of parameter weights c_{vi} - modifier factor for vulnerability class
P8	Plan configuration	-2.07	-1.55	0.00	3.10	
P9	Height regularity	0.00	0.52	2.07	5.17	$\bar{c}_{vi}$ - average vulnerability class of parameter i,
P12	Roofing system	-2.76	-2.07	0.00	4.14	defined by the detailed analysis
P13	Fragilities and conservation state	-2.76	-2.07	0.00	4.14	

In this second phase, the vulnerability index, I_v, is then defined according to the sum of the modifier parameter scores for each non-detailed assessed building and the final vulnerability index resulted as:

$$\overline{\overline{I_v}} = \overline{I_v} + \sum \Delta I_v \qquad (1)$$

where $\overline{\overline{I_v}}$ is the final vulnerability index, $\overline{I_v}$ is the average vulnerability index from the detailed assessment, and $\sum \Delta I_v$ is the sum of the modifier scores. 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 (in this case masonry buildings).

According to the application of the vulnerability index methodology to 53 buildings in a detailed manner, which corresponded to the first phase of the assessment, a mean value of the seismic vulnerability index, $\overline{I_v}$, of 36.15 was obtained. With the introduction of the complementary approach, used in the assessment of the remaining 138 buildings for which the information was incomplete (second phase of assessment), the mean seismic vulnerability index value decreased to 34.12, which represents a 6% difference in relation of its original value $\overline{I_v}$.

Approximately 20% of the assessed buildings had a vulnerability index value over 40 (see Figure 3) and 14% over 45 (equivalent to vulnerability class A in the EMS-98 scale (Grünthal, 1998). Only 4% of the buildings had an I_v below 20 (equivalent to vulnerability class B). The maximum and minimum I_v values obtained from the detailed assessment were 63 and 15, respectively. Figure 3 shows the histogram and the best-fit normal distribution curves that resulted from the detailed (53 buildings) and non-detailed (138 buildings) assessments.

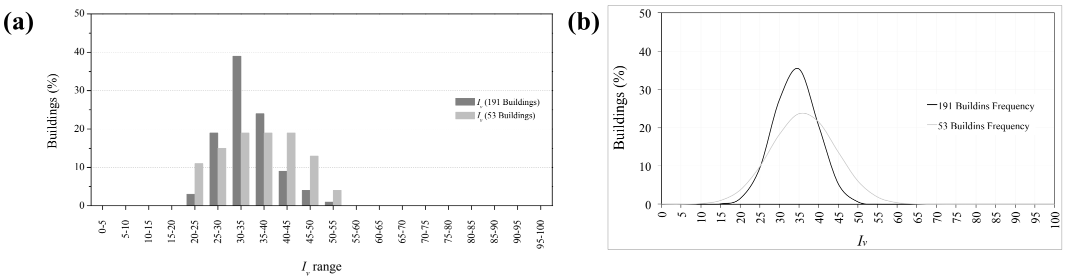

Figure 3: Vulnerability index distributions: (a) histograms and (b) best-fit normal distributions

The standard deviation value, σ_{Iv}, associated with the detailed assessment was 9.51. With the introduction of data obtained from non-detailed assessment, this standard deviation value decreased to 7.03, which represents a 26% reduction. It is important to stress that the outputs from this methodology must be interpreted statistically, by identifying a representative mean value and defining the upper and lower bounds of the vulnerability index results. These results were well adjusted to the building characteristics and fragilities, a consequence of the method's robust nature.

Figure 4 shows the spatial distribution of building stock's seismic vulnerability in zones Z_1, Z_2 and Z_3 of the Ribeirinha area. These results allowed for the identification of areas where more vulnerable buildings were located and also to identify the most vulnerable buildings or typologies. From analysing this figure one observes that Z_3 was the most vulnerable of the Ribeirinha area. Also from the right side of Z_1 resulted significant vulnerability indexes. Once more, it is important to refer that unoccupied and "in ruin" buildings (78 buildings out of 354) will seriously exacerbate this scenario.

(a) (b)

Figure 4. Vulnerability index mapping of buildings within the Ribeirinha area (a) and the identification of buildings with $I_v \geq 40$ (b)

DAMAGE DISTRIBUTIONS AND SCENARIOS

Mean damage grades, μ_D, were estimated for different macroseismic intensities based on the vulnerability index. For this purpose, an analytical expression that correlates hazard with the mean damage grade ($0 < \mu_D < 5$) of the damage distribution, in terms of vulnerability value, as shown in Eq. (2), has been proposed by Bernardini et al. (2007):

$$\mu_D = 2.5 \times \left[1 + tanh\left(\frac{I + 6.25 \times V - 13.1}{Q}\right)\right] ; 0 \leq \mu_D \leq 5 \quad (2)$$

where I is the seismic hazard described in terms of macroseismic intensity, V is the vulnerability index (see Eq. (3)), and Q is a ductility factor that describes the ductility of a certain constructive typology (ranging from 1 to 4). The vulnerability index, V, determines the position of the curve, while the ductility factor, Q, determines the slope of the vulnerability function (i.e., the rate of damage increase with rising intensity). This study adopted a ductility factor, Q, of 3.0, providing the best fit for the comparison between the *GNDT* curves and *EMS-98* functions. The regression analysis and parametric studies performed by Sandi and Floricel (1995) also resulted in a mean value of 3.0 for masonry buildings of fairly ductile behaviour. The vulnerability index, I_v, can be related to the vulnerability index, V (used in the Macroseismic Method), given by Eq. (3), enabling the calculation of the mean damage grades with Eq. (2) and the subsequent estimation of physical principal, economic and human loss (Vicente et al., 2011).

$$V = 0.592 + 0.0057 \times I_v \quad (3)$$

Figure 5 shows the vulnerability curves for the mean value of the vulnerability index, $I_{v,mean}$, and the upper and lower bound ranges ($I_{v,mean} - 2\sigma_{Iv}$; $I_{v,mean} - 1\sigma_{Iv}$; $I_{v,mean} + 1\sigma_{Iv}$; $I_{v,mean} + 2\sigma_{Iv}$) for events of different macroseismic intensity. The same figure also presents two examples of mean damage grade distributions obtained through the use of a *beta* probability distribution for events of different seismic intensity and the mean value of the building vulnerability index. The variance of the *beta* distribution was defined using a values of 8 for parameter t, 0 for parameter a, and 5 for parameter b.

The use of a GIS tool makes it possible to spatially represent the global damage distribution, μ_D, of the building stock in an analysis, enabling the identification of more vulnerable areas and buildings, which can be very useful for the planning of urban management and protection strategies.

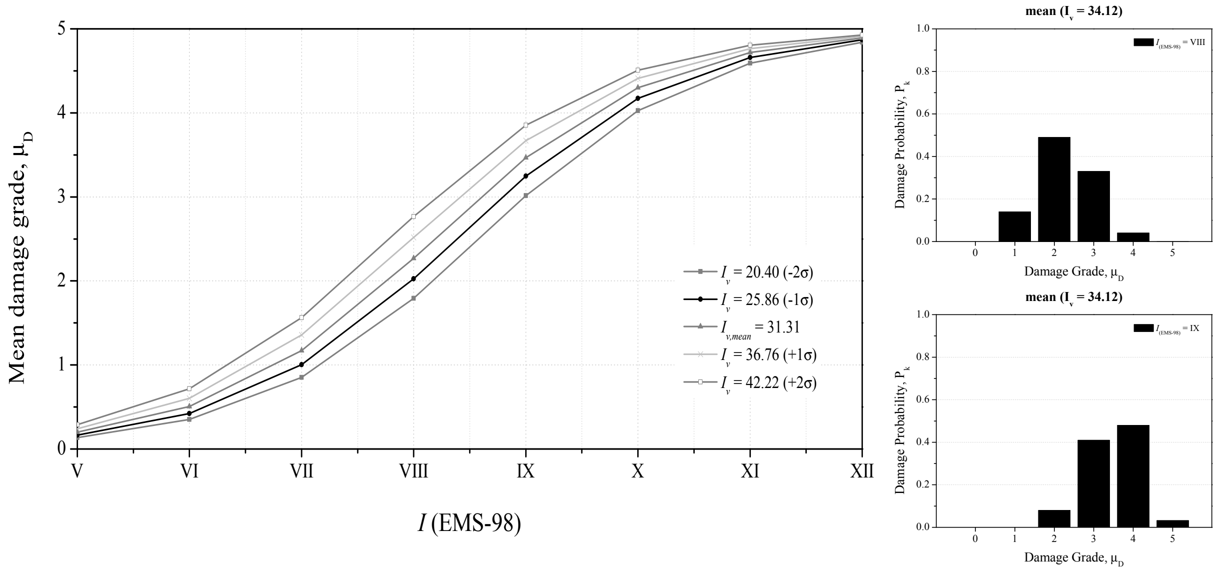

Figure 5: Vulnerability curves and mean damage grade distributions for $I_{v,mean}$=34.12.

Figure 6 present the damage scenarios for earthquake intensities from *I*(EMS-98)=VII to *I*(EMS-98)=X. The estimated damage ranged from 1.71 to 3.12 for the earthquake scenario corresponding to *I*(EMS-98)=VIII and from 2.93 to 4.09 for *I*(EMS-98)=IX. In particular, buildings with a vulnerability index higher than the mean value (I_v>$I_{v,mean}$), for which severe damages (3≤ μ_D<4) and potential local collapse (μ_D>4) are expected, required reassessment with a more detailed methodology.

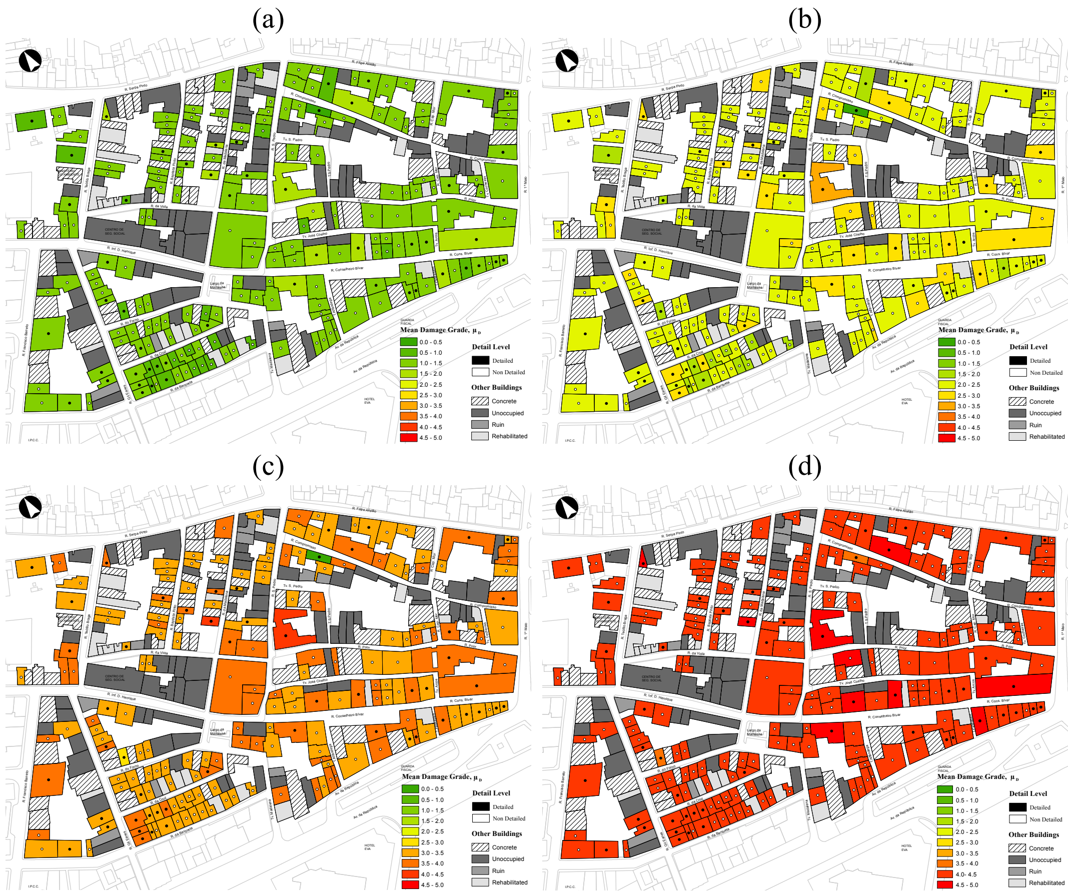

Figure 6: Damage scenario for *I*(EMS-98)=VII (a), *I*(EMS-98)=VIII (b), *I*(EMS-98)=IX (c) and *I*(EMS-98)=X (d)

FRAGILITY CURVES

Fragility curves are another way to represent the estimated damage and define the probability of exceeding a certain damage grade or state, D_k ($k \in [0;5]$). This probability is obtained directly from the physical building damage distributions derived from the beta probability function for a determined building typology. Fragility curves define the relationship between earthquake intensity and damage (in five damage states) through a continuous probability function, expressing the conditional cumulative probability of reaching or exceeding a certain damage state. Eq. (4) shows the discrete probabilities, $P(D_k=d)$, derived from the difference of cumulative probabilities $P_D[D_i \geq d]$.

$$P(D_k = d) = P_D[D_k \geq d] - P_D[D_{k+1} \geq d] \quad (4)$$

Fragility curves are influenced by the parameters of the beta distribution function and allow for the estimation of damage as a continuous probability function. Figure **7** shows the fragility curves obtained for a mean vulnerability index of $I_{v,mean}$=34.12 and for a value corresponding to the mean plus the standard deviation value, σ_{Iv} ($I_{v,mean}$+σ_{Iv}=39.70).

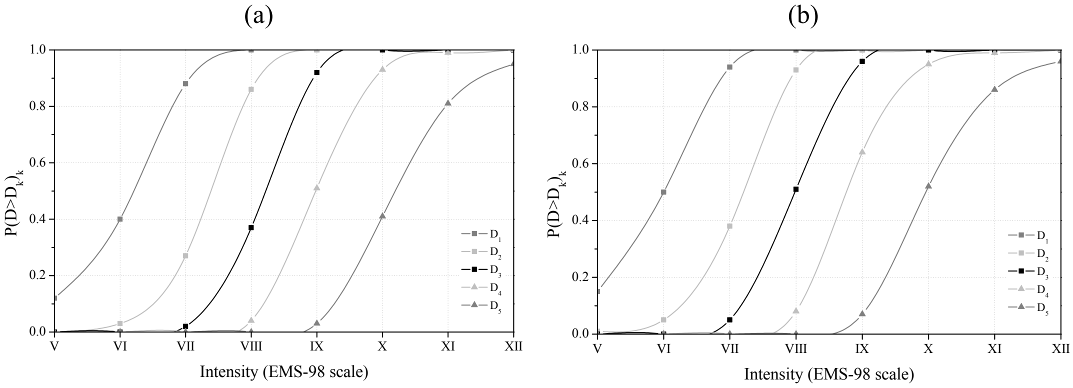

Figure 7: Fragility curves for $I_{v,mean}$=34.12 (a) and (b) I_v=39.70 (b)

FINAL COMMENTS

The results achieved in this case study can be easily correlated to the observed building construction features and general fragilities of the building stock of the Ribeirinha area, if analysed together with the ratio of unoccupied and "in ruin" buildings, respectively 19% and 3% of the 354 buildings within this area. This impressive ratio concerns a sum of 78 buildings with advanced structural and non-structural damages, evidencing the severity of the obtained results. Furthermore, these extremely vulnerable buildings are compromising both the structural behaviour of neighbouring buildings and the efficiency of the escape and evacuation routes due to their partial or global collapse. Thus, from an overall perspective, the evaluated building stock was found in a poor conservation state and in need of interventions focused on the reducing the seismic vulnerability of those buildings. Although being scarcely populated in these days, the Ribeirinha historical area is still inserted in a moderate to high seismic hazard region and then its high vulnerability must not be neglected. Thus, the sporadic number of tie-rods or another usual elements beneficial to the seismic behaviour of buildings was founded undoubtedly insufficient.

The vulnerability index methodology has been proved once more to be very suitable for large-scale analysis due to the amount of information needed, the affordable supply of time, manpower and economical resources. However, there are some aspects that should be improved, as the definition of each parameter weight and the uncertainties associated with the empirical vulnerability curves. The integration of a GIS tool was fundamental to speed the vulnerability assessment on this urban scale, once allowed the storage of building features and survey information, assessment of seismic vulnerability, damage and risk scenario construction. The strategy developed for the particular study case of the Ribeirinha area of the city of Faro, integrating scoring methods and GIS tools, can be easily adapted and applied for other Mediterranean surrounding cities to identify weaknesses and vulnerable areas to further establishment of appropriate retrofitting strategies in order to reduce both physical damage and economical losses from future seismic events.

From comparing the deterministic scenarios of damage and loss performed in this study with the observed fragilities and both structural and construction features of buildings, it is fundamental to raise concerns regarding the frequently inadequate implemented interventions on historical building, which increases substantially the seismic vulnerability of these buildings. In truth, this reality is a serious cultural problem, because people often associates safety only reinforced concrete, discrediting the conventional and original materials of these valuable buildings, such as masonry or wood elements. Another usual interventions are the partial or global suppression of structural walls for commerce purposes, the increase in the number of floors and the replacement of original wooden roof structures with heavier structures, often out of reinforced concrete.

The authors are very confident about the reliability of this methodology and strongly believe that these quite clear outputs could be of great importance for decision makers and responsible authorities to reduce the impact of such natural disaster.

ACKNOWLEDGEMENTS

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