16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1872

Registration Code: S-XXXXXXXX

DEVELOPMENT OF A METODOLOGY FOR THE SEISMIC VULNERABILITY ASSESSMENT OF EXISTING RC BUILDINGS

T.M. Ferreira[(2)] , H. Rodrigues[(3)] , R. Vicente[(4)] , A. Costa[(5)]

[(1)] *Civil Engineer*
[(2)] *Postdoctoral researcher, RISCO – Department of Civil Engineering, University of Aveiro, Aveiro, Portugal, tmferreira@ua.pt*
[(3)] *Senior Lecturer, RISCO – Department of Civil Engineering, School of Technology and Management, Polytechnic Institute of Leiria, Leiria, Portugal, hugo.f.rodrigues@ipleiria.pt*
[(4)] *Associate Professor, RISCO – Department of Civil Engineering, University of Aveiro, Aveiro, Portugal, romvic@ua.pt*
[(5)] *Full Professor, RISCO – Department of Civil Engineering, University of Aveiro, Aveiro, Portugal, agc@ua.pt*

Abstract

Recent earthquakes, all over the world have demonstrated that a large portion of existing reinforced concrete buildings exhibits high seismic vulnerability. The evaluation of the seismic vulnerability of reinforced concrete buildings is a challenge and allows the construction of damage and loss scenarios in case of a seismic event, supports the setting of the building rehabilitation strategies.

Bearing in mind the exposed, this paper aims to develop a simplified methodology for assessing the seismic vulnerability of reinforced concrete buildings, which is then applied to a group of 91 buildings affected by recent earthquakes with different macroseismic intensities. The methodology is based on the evaluation of 8 parameters associated to different factors that affect the seismic response of the building, namely its structural features, foundation conditions and position within the urban mesh. The formulation of each parameter and the relative weight attributed to each one of them were defined on the basis of post-earthquake damage observation and expert opinion.

Keywords: Seismic vulnerability index; RC buildings; Damage mechanisms; Damage scenarios.

1. Introduction

It is undeniable that in high seismic prone areas, human and economic loss is due to severe physical damage levels of constructions and partial or total collapse of non-seismically designed or retrofitted buildings. The lack of specific guidelines, in the form of provision codes, is not the only reason for such a context, but also the unprepared technical and professional community to carry out retrofitting actions with quality control and specialized workmanship. In conceptual terms, seismic risk is function of three probabilistic components: hazard, exposure and vulnerability. In the case of structures, the latter component assumes particular importance, since retrofitting and strengthening action reduce intrinsic vulnerability of buildings, consequently, seismic risk. Therefore, the need to develop procedures with adapted resources, to mitigate the effects of such natural hazards, that are scientifically sound and at the same time are intelligible to the non-technical community, owners and decision–makers, improving their perception and awareness. To assess the structural vulnerability, it is fundamental the use of approaches suitable for the assessment scale pursued (regional district, urban area, aggregate, singular building), and therefore the qualitative or quantitative nature of the approach to adopt must be limited by the level of detail and building information available.

The empirical approaches are exclusively based on post-observation of damage to different building typologies of past events, associating macroseismic intensities to damage levels. Analytical approaches imply computational effort and the detailed modelling of the structure that in many cases should be the representative of a specific building typology using mean values for the mechanical properties and geometrical layout. Moreover, there exists different approaches, heuristically based, in which seismic vulnerability of buildings is attributed based on the expert opinion [1]. Nevertheless in the last decades the scientific community has engaged in reconnaissance missions, gathering technical information from past events has been of great importance in the validation of vulnerability assessment and risk methodologies, numerical studies in reducing physical vulnerability of the building stock, as well as for civil protection bodies in the mitigation and emergency planning [2]. Among the several simplified seismic vulnerability assessment approaches that could be cited here, the P25 scoring method, proposed by [3], the “Rapid Visual Screening of Buildings for Potential Seismic Hazards” presented by ATC-21 [4] and the methodologies proposed by GNDT II [5] and by [6]–[8], are worthy of note.

Based on the exposed, this paper presents and discusses two phases of a proposed methodology for evaluating the seismic vulnerability of existing reinforced concrete buildings. The first part discusses the evaluation parameters, the definition of vulnerability classes and the attribution of the individual weights. The second part consists in the attribution of a mean damage grade to a group pf 91 buildings, evaluated and classified in accordance to the EMS-98 Macroseismic scale [9], form which a vulnerability function was derive for this specific building typology (Reinforced Concrete Buildings). The backbone of the assessment procedure presented in the following sections is based on a similar approaches developed for masonry building typology and successfully applied and improved in the scope of many past research projects (see [10]–[12]).

2. Seismic vulnerability assessment of reinforced concrete frame buildings

As thoroughly discussed in [2], the methodology to assess the seismic vulnerability of a building should take into account its typology, the scale of the assessment and resources available (economical and human). The methodology presented herein, based on post-earthquake damage observation and expert opinion, is still in a preliminary stage of development, being clear the need to evolve to a more robust method. Nevertheless, at this stage, it can be already seen as a rapid screening approach that could aid in the identification of more fragile and damage prone buildings in the case of a strong earthquake.

As already referred, the method was inspired on similar approaches for masonry buildings [13]. Conceptually it is composed of 8 evaluation parameters, divided into 3 groups associated to factors related to foundation conditions, building position within the urban mesh, structural features. The first group includes parameter P1, that assess the soil and foundation conditions and typology. Group 2 includes parameter P2, which assess the interaction with neighbouring buildings. The third group includes parameters P3 to P8 and assesses the building age, eventual irregularity in plan and height, the existence of potential conditions for short-column and soft-storey mechanisms and the presence of other vulnerable elements that influence the seismic vulnerability. Since one of the main objectives of the approach, is to be simplified and based on visual observation, seismic detailing is implicitly assessed by parameters in group 3, namely parameter P3 – Building Age – that should reflect the respect for seismic and structural building code requirements at date in respect to seismic capacity design criteria and ductility rules. Hence, in particular this parameter is to be defined regionally, redefining its vulnerability classes and criteria, due to differences from low to high seismically prone areas and countries. The detailed explanation of the assessment rules for each parameter, with the definition of the vulnerability classes, can be found in [14].

2.1 Seismic vulnerability index for reinforced concrete frame buildings

This methodology calculates a vulnerability index for each building. The eight parameters to assess are classified in accordance to four growing vulnerability classes, C_{vi}, A, B C and D. As referred before each parameter evaluates a specific feature that influences/rules the seismic response of the building (choosing the vulnerability class that best applies). To each parameter is associated a weight, p_i, ranging from 0.5 for the less important ºparameters to 2 for the parameters with most impact over the seismic vulnerability of the building (see Table 1).

Table 1: Evaluated parameters of the vulnerability index, I_v, respective vulnerability classes and weights

Parameter	**Class C_{vi}**				**Weight**
	A	**B**	**C**	**D**	**p_i**
Group 1. Foundations					
P1 Building implantation	0	5	20	50	1.5
Group 2. Relative position					
P2 Building position	0	5	20	50	0.5
Group 3. Structural features					
P3 Building age	0	5	20	50	1.5
P4 Irregularity in plan	0	5	20	50	2.0
P5 Irregularity in height	0	5	20	50	2.0
P6 Soft-storey mechanism	0	-	-	50	2.0
P7 Presence of short columns	0	5	20	50	2.0
P8 Presence of other vulnerable elements	0	5	20	50	0.5

The vulnerability index, I_v^*, calculated using equation 1, ranges from 0 to 500. However, for the sake of easier interpretation and use, this index is normalized through the average sum for an interval for 0 to 100, designated from that point on as, I_v.

$$I_v^* = \sum_{i=1}^{8} C_{vi} \times p_i \tag{1}$$

As observed in table 1, parameters P4 and P5, related to building irregularity in height and plan, and parameters P6 and P7, related to the presence of short column and soft-storey mechanisms, are the most influent over the vulnerability index calculation, with a weight of 2.0.

2.2 Application of the methodology to 91 buildings

The methodology was applied to 91 existing RC buildings spread throughout the world, namely in Japan, China, Italy, Peru, Spain, Turkey, United States, Haiti, New Zealand, Indonesia and Mexico (see Fig. 1), which were affected by strong earthquakes in the last four decades. For the assessment of these buildings, photographic and technical reports gathered and developed by academic and research institutions in the scope of reconnaissance and post-earthquake missions, were used. In some of the cases, the information was complemented with other sources of information, such as plans, elevations and structural design drawings, material testing, as well as geotechnical information. As will be discussed further, in that cases the confidence factor associated to the evaluation is naturally higher than in the remaining.

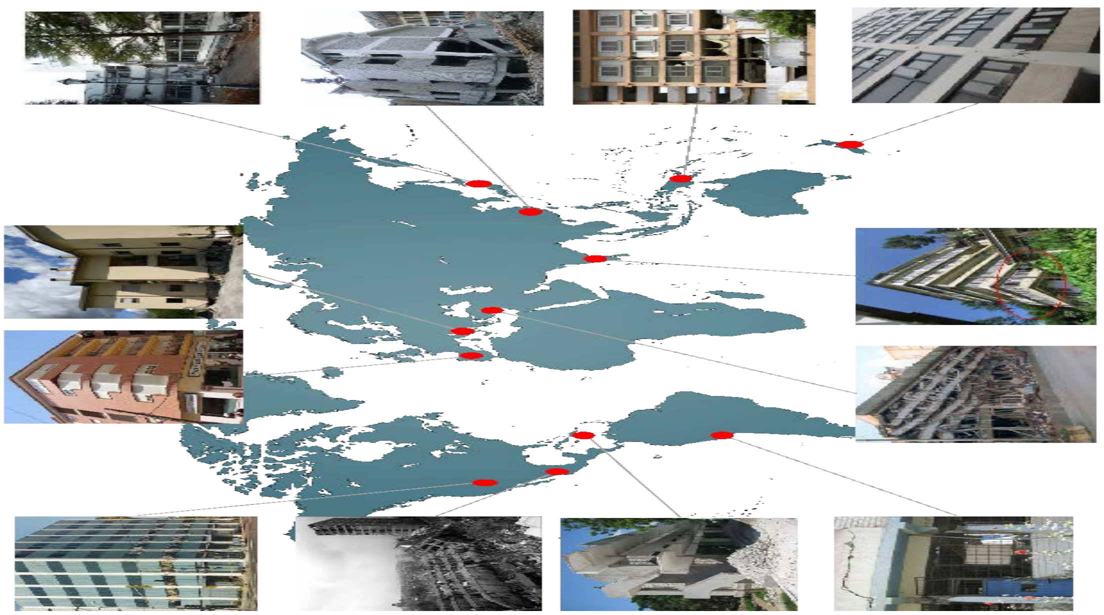


Fig. 1 - Geographical distribution of Groups of buildings assessed

The overall results obtained from the application of the vulnerability index, as well as the confidence factor associated to each parameter, are presented and discussed next.

From the application of the methodology 91 buildings, resulted the mean vulnerability index, I_v, of 38.71, with the standard deviation, σ_{Iv}, of 12.30. Fig. 2 presents the histogram of the vulnerability index values obtained.

Fig. 2 - Distribution of the analysed buildings over ranges of vulnerability index values

The range between 30 and 40 present the highest fraction of vulnerability index values, containing 30% of the buildings. 45% of the building stock has an I_v over 40 and about 18% a value over 50. The maximum and minimum values calculated were 75 and 7.5 respectively. Fig. 3 presents the vulnerability classes distribution of the evaluation parameters over the percentage of buildings assessed.

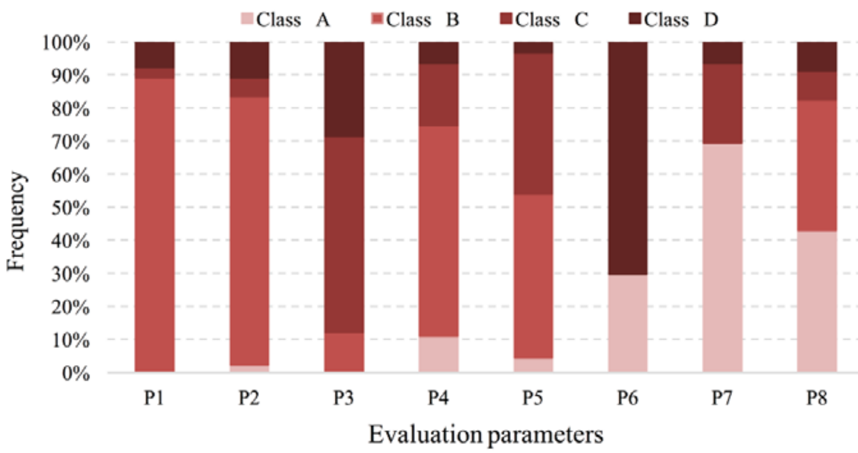
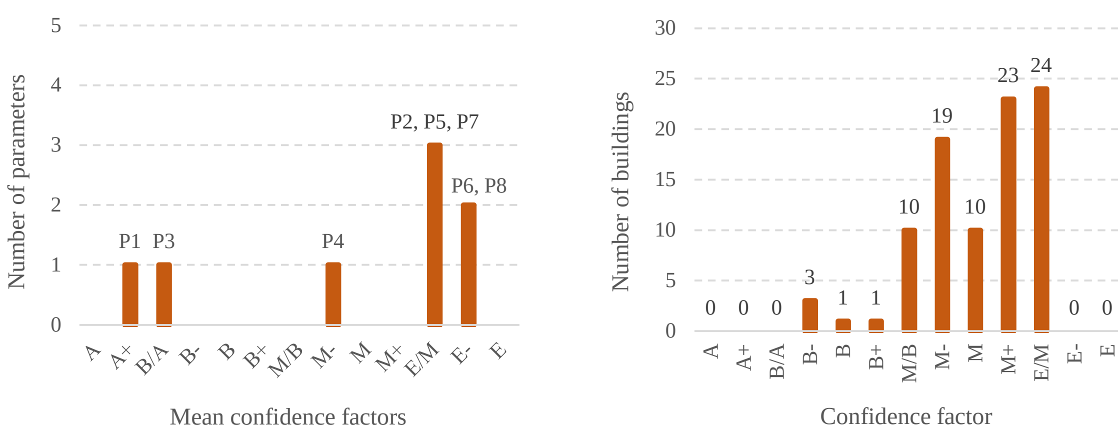


Fig. 3 - Influence of each one of the evaluation parameters on the final value of I_v.

From the analysis of Fig. 3 it is possible to observe that Parameter P6, which assess the soft-storey mechanism, is the one that presents the higher number of buildings belonging to vulnerability class D (about 70% of the buildings assessed), followed by Parameter P3, which accounts for the age of the building, with about 28%. Parameter P7, dedicated to the short columns, and Parameter P8, which assesses the presence of non-structural elements, are the third and the fourth parameter with a more percentage of buildings evaluated with vulnerability class D, with about 69% and 43%, respectively.

The classification of each parameter on the analysis of the buildings have also involved the association of a confidence factor (CF), which reflects the confidence of the classification taking into account the detail and the trustworthiness of the information used. The uncertainty in the attribution of the parameter's class can have different origins, such as, the impossibility of observing directly a certain structural or constructive element, or the total lack of information. The confidence factors attributed were: E (Elevated); M (Medium); L (Low) and A (Absent). Fig. 4 (a) and Fig. 4 (b) present respectively the distribution of the mean confidence factors obtained from the evaluation of the parameters that compose the I_v and the global assessment of the 91 pilot-buildings.



(a) (b)

Fig. 4 - Distribution of the confidence factor associated with the evaluation parameters (a) and the global assessment (b).

As can be seen in Fig. 4 (a), the mean CF E/M is the one that has been used more times, having been assigned to Parameters P2, P5 and P7 (position into the aggregate, irregularities in height and short columns). The second confident factor with greater expression is the E-, with Parameters P6 and P8 (soft-storey mechanisms and other structural elements). Finally, due to the lack of information on the type of soil, Parameter P1, which evaluates the building location, is the one that presents the lowest mean confidence factor (A+). Fig. 4 (b) presents the mean confidence factor associated with the buildings classification, i.e., corresponding to the average of the confidence factor attributed to each parameter assessed. The average confidence factor E/M is the one that has the most expression with 24 buildings (about 22% of the total sample), followed by the CF M+ with 23 buildings (about 21%). From this analysis it is further possible to observe that there are 5 buildings with an average confidence factor lower than M/B. The average CF B- has 3 buildings (about 3%), whereas the average CFs B and B+ present 1 building each (about 1%).

3. Damage estimation and construction of vulnerability curves

After the analysis of the vulnerability index for the RC buildings, it is important to estimate the mean damage grade, μ_D, associated to each one of them. The attribution of the mean damage grade was carried out individually by a group of experts, being the average value obtained from their evaluations assumed as final. Following this procedure, it was possible to get a more reliable value to obtaining the damage expression. As so far there are no curves proposed and validated for RC buildings able to correlate the severity of the action with a mean damage grade defined according to the European Macroseismic Scale EMS-98 [9], the information collected for the 91 pilot-building was used for this purpose. Thus, a new correlation curve between the vulnerability index, the macroseismic intensity registered *in situ* and the observed damage was then obtained.

Fig. 5 presents the variations on the mean damage grade, μ_D, obtained for each building, organized by macroseismic intensity. It is worth noting that, due to the reduced number of buildings assed for intensities $I_{\text{EMS-98}}$=V and $I_{EMS\text{-}98}$=VI, such intensities were excluded from the sample subsequently used for constructing the vulnerability curves. In consequence to that, the estimation of cumulative losses due to frequent, low-intensity earthquakes in a given timeframe, is limited and therefore further efforts should be made to enlarge the damage database, mainly for intensities $I_{\text{EMS-98}}$=V and $I_{EMS\text{-}98}$=VI.

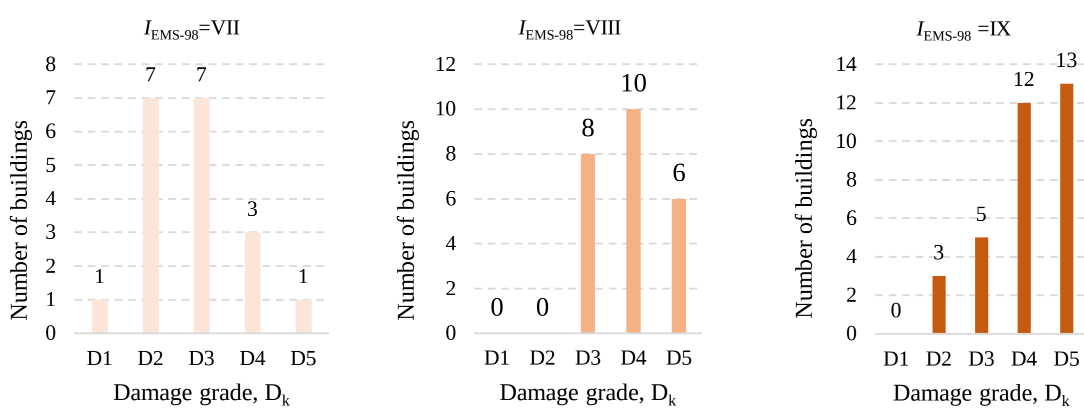


Fig. 5 - Histograms of damage for macroseismic intensities VII, VIII and IX.

From the analysis of Fig. 5 it can be noted that, for a seismic scenario with intensity equal or higher than VIII, most of the buildings considered in this analysis present mean damage grades of D_k=4 and D_k=5, which means severe damage or collapse.

The methodology used in the elaboration of the seismic vulnerability study is an adapted version of the European Macroseismic Scale, EMS-98, originally proposed by [15]. In that work, the authors have elaborated a vulnerability index for each building typology based on 5 values representative of the vulnerability: V_I^*, V_I^-, V_I^+, V_{Imin} and V_{Imax}, where V_I^* corresponds to the most probable value for a specific building typology and the values of V_{Imin} and V_{Imax} correspond to the lower and the upper value of the range of values that each typology can assume (see Table 2). A vulnerability index, V, ranging between 0 and 1 is associated to each typology, describing it from A to F, where A is the seismically most resistant typology and F corresponds to the less resistant one.

Table 2: Vulnerability indexes for each reinforced concrete building typology (adapted from [16])

Building typology		**Vulnerability class**				
		$\mathbf{V_{Imin}}$	$\mathbf{V_I^-}$	$\mathbf{V_I^*}$	$\mathbf{V_I^+}$	$\mathbf{V_{Imax}}$
Reinforced Concrete (RC)	Frame in RC without Earthquake Resistant Design (E.R.D) - RC1	0.3	0.49	0.644	0.8	1.02
	Frame in RC moderate E.R.D. - RC2	0.14	0.33	0.484	0.64	0.806
	Frame in R.C high E.R.D. - RC3	-0.02	0.17	0.324	0.48	0.7
	Shear walls without E.R.D. - RC4	0.3	0.367	0.544	0.67	0.86
	Shear walls moderate E.R.D. - RC5	0.14	0.21	0.384	0.51	0.7
	Shear walls high E.R.D. - RC6	-0.02	0.047	0.224	0.35	0.54

As it is presented in Eq. (2), a new vulnerability function that relates mean damage grades, μ_D, and macroseiemic intensities, $I_{\text{EMS-98}}$ [9], adjusted to RC building typology was obtained from the vulnerability index value V. Such formulation is based on the same mathematical expression of previous vulnerability curves proposed for other building typologies (namely for unreinforced masonry building) and can assume values between 0 and 5.

$$\mu_D = a \times \left[1 + \tanh\left(\frac{x + b \times V - 11.6}{Q}\right)\right] \tag{2}$$

This mean damage grade, μ_D, depends on the variables a and b, which were obtained through successive calibrations in order to find the optimum value for variables: x, that represents the seismic intensity; V, the vulnerability index; and Q, a ductility coefficient factor that dependents on the structural typology. Based on the vulnerability index V, it is then possible to calculate the probabilities of exceed each mean damage grade proposed in the EMS-98 (D1 to D5) in function of the macroseismic intensity.

The value of V is obtained through Eq. (3), where d and e are values that dependent on the building typology and I_v is the vulnerability index obtained from the analysis of each building.

$$V = d + I_v \times e \tag{3}$$

Resorting to equation (3), and using the values of V_{Imin} and V_{imax} (presented in Table 2), the unknowns e and d could be computed (e=0.0104 and d=-002). It should be noted that this hypothesis is based on the assumption that, in this way, all the types of reinforced concrete buildings present Table 2 are considered.

$$V = -0.02 + I_v \times 0.0104 \tag{4}$$

The curve fitting tool available in Matlab® was applied to equation (3) in order to obtain the damage expression based on the mean damage grade obtained for each of the 91 building evaluated. Using as a fixed value the mean vulnerability index value ($I_{v,mean}$ = 38.79), and assuming that the curve has a development of hyperbolic shape, a new expression usable to estimate the mean damage grade (μ_D) was obtained, equation (5). The values resulting from variables a and b were respectively 2.839 and 10.79. The coefficient of ductility, Q, assumed in this work as 5.0, has been selected in accordance with what is defined in international guide lines and in the Portuguese National code for the design of RC structures "Code for Design of Reinforced and Prestressed Concrete Structures (REBAP)" [17].

$$\mu_D = 2.839 \times \left[1 + \tanh\left(\frac{I + 10.79 \times V - 11.6}{5}\right)\right] \tag{5}$$

Fig. 6 shows the comparison between the results obtained and the analytical expressions given by Equation (5), considering the $I_{v,mean}$=38.73 and the individual damage grade observed for each one of these buildings. Additionally, 3 yellow dots, representing the mean values obtained from the I_v for each intensity, were also included.

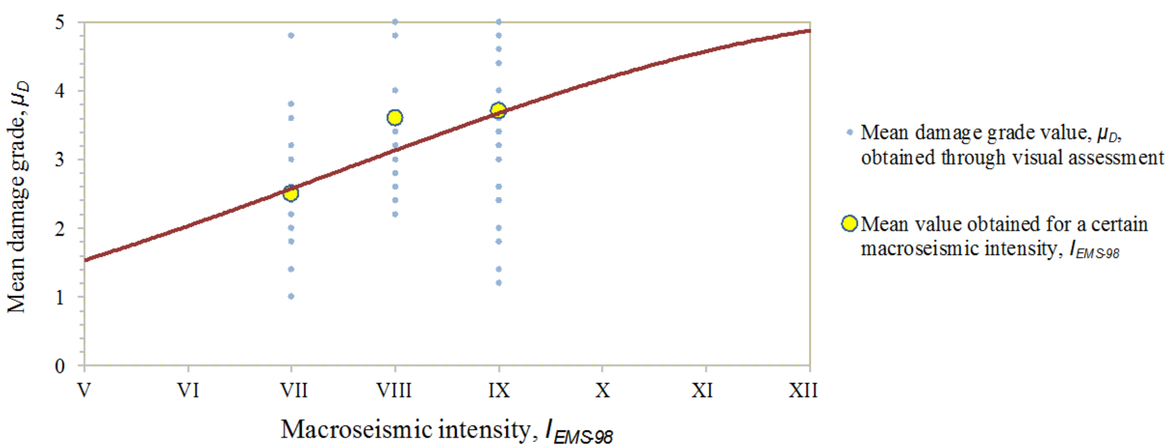


Fig. 6 - Best curve fit to the average values of the assessed buildings with damage.

Finally, Fig. 7 presents the vulnerability curves obtained with the average value of the vulnerability index, with the addition and subtraction, single and double, of the standard deviation value obtained from the sample of 91 buildings. The analysis of the curves shows that the variation range of the degree of damage for each seismic intensity is important.

Based on the vulnerability curves presented in the Fig. 7, it is possible to observe that a building with a vulnerability index value higher then 51, that is an usual value for irregular buildings, or with structural issues related with probable soft-storeys or short columns, can present a mean damage grade between 2 and 3 for a seismic intensity of V, which means that it can present unneglectable structural damages. For seismic intensities between VIII and IX, the expectable mean damage grade can be 4 or higher, meaning that important and significant structural damages, or even collapse, can occur. For a regular building without important structural issues, the vulnerability index can be around 25, which represent a mean damage grade of 1 for a seismic intensity of V, and a mean damage grade of lower then 3 for a macroseismic intensities between VIII and IX, presenting some structural damages without collapse.

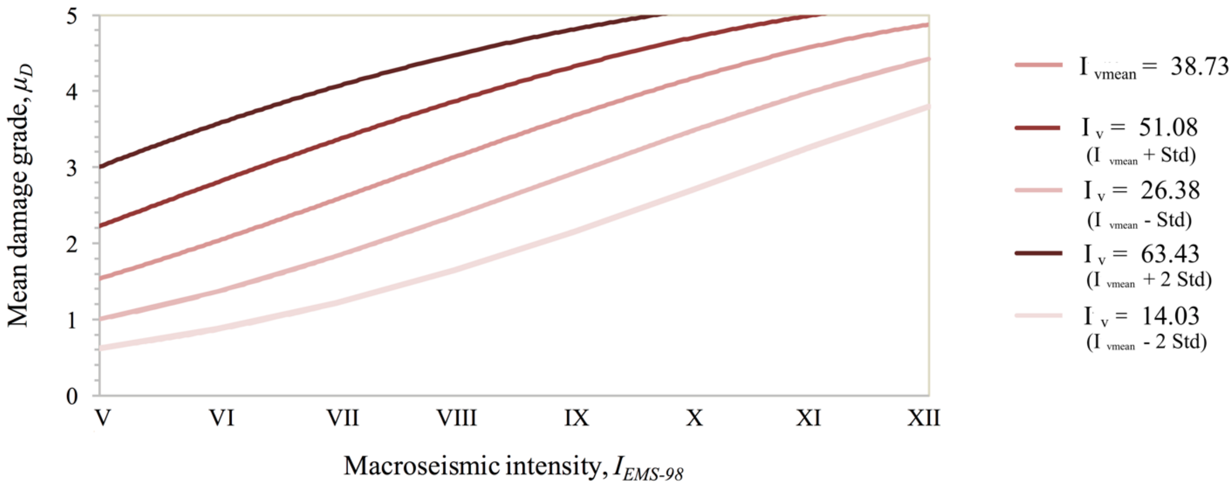


Fig. 7 - Vulnerability curves for RC buildings.

4. Final comments

From the obtained results, it is possible to draw some important conclusions. At first, from the analysis of the seismic vulnerability index, it was possible to identify the parameters with high influence in the behaviour of RC buildings under seismic loads, allowing to calibrate the weights associated with the evaluation parameters that compose the I_v. Regarding the mean degree of confidence of each parameter, the analysis allowed to know which parameters should have a more detailed study in future, in order to improve and control the quality of the vulnerability index results. The development and calibration of an equation that characterise the medium damage level, allowing for the estimation of the level of damage in a RC building, when subjected to a certain seismic intensity. In general, when a building has a high vulnerability index, this means that is more probable to have higher damage levels even if subjected to a reduced seismic intensity.

From the exposed, it is possible to say that this simplified method can be an interesting resource for performing large-scale seismic vulnerability assessments of RC buildings, particularly in view of the development and implementation of risk management plans and mitigation actions.

5. References

[1] R. Vicente, T. M. Ferreira, R. Maio, A. A. Costa, J. Estêvão, H. Varum, e C. S. Oliveira, «Metodologia de avaliação da vulnerabilidade sísmica: calibração e validação macrossísmica», em *5as Jornadas Portuguesas de Engenharia de Estruturas (JPEE). Paper Nr. 262.*, 2014.

[2] T. Ferreira, «Avaliação da vulnerabilidade sísmica de núcleos urbanos antigos. Aplicação ao núcleo urbano antigo do Seixal.», Faculdade de Engenharia da Universidade do Porto, 2010.

[3] I. Bal, F. Gulay, e S. Tezcan, «A new approach for the preliminary seismic assessment of RC buildings: P25 Scoring Method», em *The 14thWorld Conference on Earthquake Engineering*, 2008.

[4] ATC-21, «Rapid visual screening of buildings for potential seismic hazards: a handbook», Redwood

City, California, USA, 1988.

[5] GNDT-SSN, «Scheda di esposizione e vulnerabilità e di rilevamento danni di primo e secondo livello (murata e cemento armato)», *Grup. Naz. per la Dif. dai Terremoti, Roma*, 1994.

[6] M. Hirosawa, S. Sugano, e T. Kaminosono, «Seismic evaluation method and restoration techniques for existing and damaged buildings developed in Japan», em *Retrofitting and restration of buildings in Japan*, Internatio., Ministry of Construction, 1993, pp. 1–69.

[7] A. Yakut, A. Erberik, S. Akkar, e H. Sucuoglu, «Rapid Seismic Assessment Procedures for Turkish Building», em *Seismic Evaluation and Rehabilitation of Structures*, Springer, 2012, pp. 15–35.

[8] D. C. Rai, «A generalized method for seismic evaluation of existing buildings», *Curr. Sci.*, vol. 94, n. 3, pp. 363–370, 2008.

[9] G. Grünthal, «Cahiers du Centre Européen de Géodynamique et Séismologie: Volume 15 - European Macroseismic Scale 1998 (EMS-98)», *Eur. Cent. Geodyn. Seismol. Luxemb.*, 1998.

[10] R. Vicente, S. Parodi, S. Lagomarsino, H. Varum, e J. A. R. Mendes da Silva, «Seismic vulnerability and risk assessment: case study of the historic city centre of Coimbra, Portugal», *Bull. Earthq. Eng.*, vol. 9, n. 4, pp. 1067–1096, 2011.

[11] T. M. Ferreira, R. Vicente, J. A. R. Mendes da Silva, H. Varum, e A. Costa, «Seismic vulnerability assessment of historical urban centres: case study of the old city centre in Seixal, Portugal», *Bull. Earthq. Eng.*, vol. 11, n. 5, pp. 1753–1773, 2013.

[12] T. M. Ferreira, R. Vicente, e H. Varum, «Seismic vulnerability assessment of masonry facade walls: development, application and validation of a new scoring method», *Struct. Eng. Mech.*, vol. 50, n. 4, pp. 541–561, 2014.

[13] R. Vicente, «Estratégias e metodologias para intervenções de reabilitação urbana. Avaliação da vulnerabilidade e do rísco sísmico do edificado da Baixa de Coimbra», Universidade de Aveiro, 2008.

[14] J. Silva, «Metodologia de Avaliação da Vulnerabilidade Sísmica de Edifícios em Betão Armado», Universidade de Aveiro, 2015.

[15] S. Giovinazzi e S. Lagomarsino, «A macroseismic method for the vulnerability assessment of buildings», em *Proceedings of the 13th World Conference on Earthquake Engineering. Vancouver, BC, Canada, Paper No.896 (on CD)*, 2004.

[16] S. Giovinazzi, «The vulnerability assessment and the damage scenario in seismic risk analysis», Technical University Carolo-Wilhelmina at Braunschweig, Braunschweig, Germany and University of Florence, Florence, Italy, 2005.

[17] REBAP, «Regulamento de estruturas de betão armado e pré-esforçado», em *Decreto- Lei no 349-C/83 de 30 de Julho*, 1983, p. 211.