A probabilistic approach based on a vulnerability index to assess seismic risk of buildings in urban areas. Application to Barcelona.

Armando Aguilar-Meléndez[a,b], Luis G. Pujades[c], Alex H. Barbat[c], Mario G. Ordaz[d], Josep de la Puente[a], Nieves Lantada[c], Héctor E. Rodríguez-Lozoya [e]

Abstract

Nowadays, different risks are frequently assessed to take actions to increase the resilience in cities. The present work is mainly related to the probabilistic assessment of seismic risk of buildings in urban areas. Particularly, we described the main characteristics of the VIM_P which is considered as the probabilistic version of the Vulnerability Index Method (VIM). The VIM_P requires essential information to compute seismic risk of buildings in urban areas: a) results of seismic hazard of the site where the studied buildings are located (frequency of exceedance vs macroseismic intensities), and; b) basic data of the structure of the studied buildings to classify each building into a structural typology. The seismic vulnerability computed in the VIM_P for each building is represented by probability density functions beta type, which describe the probability distribution of a vulnerability index. In the VIM_P the seismic risk of buildings is computed through the convolution of the seismic hazard and the seismic vulnerability, considering a semi-empirical damage function. The seismic risk computed is expressed in terms of annual frequencies of exceedance of damage grades. Additionally, to show the applicability of the VIM_P, we assessed the seismic risk of 69982 dwelling buildings of Bar-

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[a] Barcelona Supercomputing Center (BSC), Spain. Corresponding author. e-mail: aguilar.uv2@gmail.com

[b] University of Veracruz (UV), Mexico.

[c] Polytechnic University of Catalonia (UPC), Spain.

[d] National Autonomous University of Mexico (UNAM).

[e] University Autonomous of Sinaloa, Mexico.

celona. According to the results, the damage state 5 (collapse) has an annual frequency of occurrence greater than $1x10^{-5}$, in a percentage of the buildings of the Eixample district, that ranges between 52.58 and 70.7 (with a mean value of 56.55).

1 Introduction

The Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, 2015) is an example of a specific initiative to increase the resilience in cities, this framework gives continuity to the Hyogo Framework that was valid until 2015 (ISDR-UN, 2005). In both documents, it is highlighted the importance of to know the different risks that exist to increase the resilience in cities. In this context and for the case of seismic risk, it is possible to identify that in the last decades have been proposed different methodologies to assess this type of risk in urban zones. For instance, Table 1 includes some relevant methodologies to compute seismic risk. In these methodologies, it is possible to highlight the Hazus methodology, which was proposed in the USA with the objective of assessing seismic risk in urban areas of that country (FEMA, 99). Some years later it was developed a European project with some similitudes to Hazus (Vacareanu et al, 2004; Mouroux & Le Brun, 2006). This European project was identified with the short name of Risk-UE (Mouroux & Le Brun, 2006). Because of this last project, two standardized methodologies were proposed to assess seismic risk of buildings in urban areas: a) the LM1 method or vulnerability index method (VIM) and; b) the LM2 method or capacity spectra method (Milutinovic & Trendafiloski, 2003). Since then, both methodologies have been widely validated (Irizarry et al, 2010; Lantada et al, 2010; Lantada et al, 2009a; Barbat et al, 2006; Faccioli, 2006; Lagomarsino & Giovinazzi 2006; Faccioli et al, 2003).

In the present paper, we described a probabilistic method based on a vulnerability index (VIM_P**)**, which it is a derivation of the VIM (Aguilar et al, 2010). The main objectives considered to propose the VIM_P were the following: a) to offer both simplified and probabilistic methodology to compute seismic risk results, that cannot be obtained applying the VIM and that they can contribute to offer a valuable information about the seismic risk of buildings in urban areas; b) to incorporate a major quantity of probabilistic elements to compute seismic risk in a procedure based on a vulnerability index.

Table 1. Main characteristics of relevant methodologies to assess seismic risk in urban areas (adapted from Aguilar et al in press)

Methodology	a) Seismic Hazard	b) Seismic Vulnerability	c) Seismic Risk	Computer codes available to apply the methodology
ATC-13 (1985)	Selection of a ground motion in terms of a MMI grade.	It is implicitly considered in the damage probability matrix of each facility type.	Damage state probabilities base on damage probability matrices, for each facility type.	None
HAZUS (FEMA, 2015a)	a) Deterministic ground motion analysis; b) USGS probabilistic ground motion maps; c) Other probabilistic or deterministic maps of ground motion	Capacity curves for specific structural typologies.	Damage states probabilities based on fragility curves for specific structural typologies.	Hazus to be executed in ArcGIS
GNDT II (Benedetti, et al 1988)	Value of PGA	Vulnerability index, with scores and weights, according to characteristics of buildings.	Damage degree (0-1)	
Risk-UE Vulnerability index method (VIM) or LM1 method (Milutinovic, & Trendafiloski, 2003).	A seismic scenario in terms of a macroseismic intensity obtained by means of: a) probabilistic method; b) deterministic method.	A total vulnerability index for each building classified into a structural typology.	Damage grade probabilities (5 no-null damage states), for each building, based on a damage function depending of a vulnerability index and a macroseismic intensity.	CRISIS99 (only for probabilistic seismic hazard assessment)
Risk-UE LM2 method (Milutinovic, & Trendafiloski, 2003).	Demand spectrum	Capacity curves for structural typologies.	Damage states probabilities (4 no-null damage states), for each building into a group of buildings; based on fragility curves, for each structural typology.	CRISIS99 (only for probabilistic seismic hazard assessment)
CAPRA (Cardona, et al, 2012)	Seismic hazard scenarios obtained by means of a probabilistic assessment	Vulnerability functions for structural typologies.	Probabilities of occurrence of damage states based on fragility curves, for each structural typology.	-CRISIS2007 (probabilistic seismic hazard assessment) -ERN- Vulnerabilidad (Vulnerability assessment) -CAPRA-GIS V2.0 (Seismic risk)

According to the context previously mentioned the objectives of the present document are: i) to highlight the main differences between the VIM_P and the VIM; ii) to offer detailed information about the main characteristics of the VIM_P, whose basic concepts were defined by Aguilar et al (2010, 2008); iii) to show basic examples of the main results of seismic vulnerability and seismic risk that can be computed according to the VIM_P; and iv) to show the main results of seismic vulnerability and seismic risk of 69982 dwelling buildings of Barcelona, that we computed using the VIM_P. To satisfy the previous objectives, we divided this document into the following parts: **section 1)** it correspond to the introduction; **section 2**) here we mentioned the main characteristics of the VIM, and we described an example where we assessed the seismic risk of two buildings using this last method; **section 3)** in this other part we mentioned the principal characteristics of the VIM_P, and we described the procedure to use the VIM_P to compute the seismic risk of the same two buildings considered in the example of section 2; **section 4)** here we highlight the main procedure that we apply to use the VIM_P to assess the seismic risk of 69982 dwelling buildings of Barcelona and we show the main results that we computed for these buildings; **section 5**) in this last part we included conclusions. Note that, the description of the VIM (section 2) is incorporated essentially due to the following two reasons: a) some procedures of the VIM are also valid for the VIM_P and; b) the description of the VIM is helpful to identify clearly the differences between this method and the VIM_P.

2 Vulnerability index method (VIM) to assess seismic risk scenarios of buildings in urban zones

The VIM proposed in the Risk-UE project to compute seismic risk (Milutinovic & Trendafiloski, 2003; Mouroux and Le Brun, 2006; Lantada et al, 2009a) can be summarized in following three steps: a) assessment of seismic hazard in the site where buildings are located; b) assessment of seismic vulnerability of the buildings; and; c) assessment of seismic risk of the buildings.

According to the VIM, the main purpose of the assessment of the seismic hazard is to determine a seismic hazard scenario in terms of a macroseismic intensity. On the other hand, in the VIM, the main objective in the assessment of seismic vulnerability is to determine a vulnerability index value (between 0 and 1), that represents the seismic vulnerability of each studied building. To determine the seismic risk, it is computed a mean damage grade of each studied building according to a semi-empirical damage function. This function depends on both the vulnerability index and the macroseismic intensity (Lantada et al, 2009a, 2010; Milutinovic & Trendafiloski, 2003). The mean damage grade computed previously it is used to generate a complete distribution of the damage in the building (five no-null damage states are considered). Finally, it is computed a weighted mean damage index. These seismic risk results can be used, for instance, to generate maps of scenarios of damage.

The VIM was mainly defined by Giovinazzi and collaborators (Giovinazzi, 2005; Giovinazzi et al, 2006; Barbat et al, 2006; Milutinovic & Trendafiloski, 2003). However, the VIM has as references other vulnerability index methods (Bernardini, 2000; Benedetti et al, 1988), and different methodologies as the ATC-13 (1985), among others. The EMS-98 scale was also a fundamental support for the generation of the VIM (Gruntal, 98). This last method has been applied to assess the seismic risk of important cities as Nice, Bitola, Catania, Barcelona, Thessaloniki, etc. (Brgm, 2004; Milutinovic et al, 2004; Spence & Brun, 2006; Kappos et al, 2008; Castillo et al, 2011; Pitiliakis et al, 2006, Lantada et al, 2010; Athmani et al, 2015; Guardiola-Víllora & Basset-Salom, 2015; Ruiz et al, 2015; Lestuzzi et al, 2016; Cherif et al, 2016; Faccioli et al, 2004; ICC/CIMNE, 2004; Kostov et al, 2004, Lungu et al, 2004).

To highlight the main differences between both methods VIM and VIM_P, we assessed seismic risk of two buildings of Barcelona. It is important to underline that both methods are valid to assess the seismic risk of numerous buildings. However, only for comparative purposes, we included in the present document a basic example related to the assessment of the seismic risk of just two buildings. These buildings are named BCN1 and BCN2, and their data are in Table 2. In the next part of this section, we included an extended description of both the VIM and its application to assess the seismic risk of these two buildings.

Table 2. Data of two buildings at Barcelona, Spain

Data	**Building BCN1**	**Building BCN2**
1. Structural Typology	*Unreinforced masonry bearing walls with composite steel and masonry slabs*	*Irregular concrete frames with unreinforced masonry infill walls*
2. Reliability factor in the assignment of the structural typology	7	7
3. Conservation state	Good	Good
4. Number of levels	2	3
5. Construction date	1970	1975
6. Type of terrain	Rock	Rock

2.1 Seismic hazard in the VIM

According to VIM, the seismic hazard scenario can be determined by two types of procedures: deterministic and probabilistic (Milutinovic & Trendafiloski, 2003; Faccioli, 2006; Faccioli et al, 2003). We included essential comments about each one of these two types of procedures in the following sections of this document because the type of procedure to assess seismic hazard is one of the differences, between both methods VIM and VIM_P.

2.1.1 Deterministic assessment of a seismic hazard scenario

To determine a seismic hazard scenario the VIM considers the following two deterministic options (Faccioli et al, 2003): a) “a reference earthquake” defined by a magnitude or an epicentral intensity, related to a specific seismic source; or b) a local macroseismic intensity, or other intensity parameter associated to a damaging real earthquake that occurred in the region of interest (Faccioli et al, 2003). More extended recommendations to get the seismic hazard considering a deterministic procedure were documented by Faccioli and collaborators (2003).

2.1.2 Probabilistic assessment of a seismic hazard scenario

In the VIM it is possible to determine a seismic hazard scenario performing a probabilistic seismic hazard assessment (PSHA), which is based mainly on the approach of Cornell and Esteva (Cornell, 1968; Esteva, 1970). For this purpose, CRISIS99 (Ordaz et al, 1999; Aguilar, 2001; Ordaz et al, 2013; Aguilar et al, 2017) was selected as the standard code of the Risk-UE project to perform a PSHA (Faccioli et al, 2003). Particularly, the results of seismic hazard that can be computed by CRISIS99 are, for instance, annual frequencies of exceedances of PGA. Therefore, if CRISIS99 is chosen to determine the seismic hazard scenario required in the VIM, then the following steps are necessary: a) to perform a PSHA in terms of frequencies of exceedance of PGA (Peak Ground Acceleration); b) to use the results of the PSHA to select a seismic hazard scenario in terms of PGA, for a specific return period in years, and; c) to convert the PGA value determined in the previous step to a macroseismic intensity, applying a relationship between PGA and macroseismic intensities.

It is important to mention that nowadays the recent versions of CRISIS as CRISIS2015 or R-CRISIS (Ordaz et al, 2015; Aguilar et al, 2017; ERN, 2017) allows applying two procedures to determine curves of frequencies of exceedance of macroseismic intensities. The first procedure is the same that was mentioned previously for CRISIS99 and the second procedure consists in to perform a PSHA in terms of macroseismic intensities (Ordaz et al, 2015; Aguilar et al, 2017), to obtain directly a curve of macroseismic intensities versus exceedance rates. Currently, both procedures are valid, and the selection of the procedure depends on different factors as the data available, the attenuation relationships available, etc.

To assess the seismic risk of buildings BCN1 and BCN2 according to the VIM, it is necessary to determine a seismic hazard scenario for a rock site in Barcelona, where the buildings are located (Table 2).

Table 3 shows the seismic hazard scenarios that were computed according to the two procedures mentioned previously to perform a PSHA with CRISIS. In

Table 3 it is possible to observe that the results obtained by both procedures are different.

Table 3. Probabilistic scenarios of seismic hazard computed for a bedrock site in Barcelona (Aguilar et al, 2013).

No. of procedure	Main steps of the procedure	Seismic hazard scenarios [Macroseismic intensities]	
		Tr = 475 years	Tr = 2475 years
1	i) Perform a PSHA in terms of PGA and, ii) to convert the seismic hazard curve of PGA versus exceedance rate to a curve of macroseismic intensities versus exceedance rate.	6.4	6.7
2	i) Perform a PSHA directly in terms of macroseismic intensities.	6.0	6.8

2.2 Seismic vulnerability in the VIM

2.2.1 Total vulnerability index by building

Seismic vulnerability of buildings is a measure of the capacity of each building to withstand without damage, during the presence of seismic ground motions with different features. In the VIM, the seismic vulnerability of each building is represented by means of a total vulnerability index, which is computed by Eq. 1 (Milutinovic & Trendafiloski, 2003; Barbat et al, 2006).

$$\overline{V_I} = V_I^* + \Delta V_R + \Delta V_m \qquad 1$$

where $\overline{V_I}$ means total vulnerability index, V_I^* is the vulnerability index by structural typology, ΔV_R, means regional vulnerability index and, ΔV_m is the sum of the scores related to all the factors that modify the vulnerability of each building. ΔV_R and ΔV_m are optional values, however, V_I^* is basic, because this term represents the mean value of the seismic vulnerability of a building according to its structural typology. Therefore, to assess the seismic vulnerability of a building according to this procedure, at least the value of V_I^* must be assigned. For this reason, in the VIM is fundamental to know the structural typology of each building that will be assessed. The ΔV_R term can be used if it is considered that the buildings that have been classified in some structural typology (Table 4, Milutinovic & Trendafiloski (2003)) are not properly characterized by the representative values of vulnerability, that according to Milutiovic & Trendafiloski (2003) correspond to the structural typology chosen (Table 4). In other words, ΔV_R allows adjusting the value of the vulnerability index by structural typology, V_I^* (Milutinovic & Trendafiloski, 2003) to avoid the creation of a new structural typology. On the other hand, the term ΔV_m represent the sum of the different modifiers, which can be used to include additional characteristics of the buildings that increase or reduce its seismic vulnerability.

These modifiers can be related to features of the building or they can represent a condition between the building and its surrounding environment. For instance, the conservation state is a feature of the building, but the position of the building respect to its adjacent buildings is a condition between the building and its environment.

More probable vulnerability index of a building according to its typology (V_I^*)

Milutinovic and Trendafiloski (2003) defined the main structural typologies and their respective values of V_I^*. Table 4 shows some examples of values of V_I^*. According to typologies of Table 4, the buildings BCN1 and BCN2 (Table 2) can be classified as typologies M33 and RC32, respectively. Then, according to Table 4 the values of V_I^* for buildings BCN1 and BCN2, are 0.704 and 0.522, respectively. If researchers consider that it is not necessary to use ΔV_R values and they determine that there are not data to consider values to compute ΔV_m then $\overline{V_I} = V_I^*$. However, it is desirable to dispose of more data about the buildings that just the structural typology, to consider vulnerability modifiers that contribute to doing a better description of the seismic vulnerability of each studied building.

Table 4**.** Structural typologies and their corresponding representative values of vulnerability, in terms of the vulnerability index (Milutinovic and Trendafiloski, 2003).

Group	**Typology**	**Description**	**Representative values of vulnerability****				
			V_I^{min}	V_I^-	V_I^*	V_I^+	V_I^{max}
Masonry	M31	*Unreinforced masonry bearing walls with wooden slabs*	0.46	0.650	0.740	0.830	1.02
	M32	*Unreinforced masonry bearing walls with masonry vaults*	0.46	0.650	0.776	0.953	1.02
	M33	*Unreinforced masonry bearing walls with composite steel and masonry slabs*	0.46	0.527	0.704	0.830	1.02
	M34	*Unreinforced masonry bearing walls with reinforced concrete slabs*	0.30	0.490	0.616	0.793	0.86
Concrete	RC32	*Irregular concrete frames with unreinforced masonry infill walls*	0.06	0.127	0.522	0.880	1.02
Steel	S3	*Steel frames with unreinforced masonry infill walls*	0.14	0.330	0.484	0.640	0.86
	S5	*Steel and RC composite systems*	-0.02	0.257	0.402	0.720	1.02
Wood	W	W*ood*	0.14	0.207	0.447	0.640	0.86

** V_I^* is the more probable value of the vulnerability index for the corresponding typology. V_I^- and V_I^+ delimit the range of the probable values of the vulnerability index for the corresponding typology. V_I^{min} and V_I^{max} increase the range of the probable values of the vulnerability index to include the less probable values of the vulnerability index, for the same typology.

Regional vulnerability factor (ΔV_R)

As was mentioned previously the use of ΔV_R is optional, therefore, the decision of the application of ΔV_R values must be taken according to the data of each project and the decisions of the researchers. However, to determine values of ΔV_R, it is recommended consider the opinion of regional experts. For example, in the case of Barcelona, a proposal of regional factors of vulnerability for buildings in that city was documented by Lantada (2007). In this case, the regional vulnerability factors are in function of both the structural typology and the construction period (Table 5). Therefore, for buildings BCN1 and BCN2 (Table 2), the regional vulnerability modifiers are 0.046 and -0.022, respectively (Table 5).

Vulnerability modifiers (ΔV_m)

Vulnerability modifiers allow considering additional characteristics to the structural typology for each building. For instance, Table 6 and Table 7 show scores related to two specific modifiers of the vulnerability related to the conservation state of the building and the number of levels of the building, respectively. The data in these last two tables correspond to characteristics of buildings of the city of Barcelona (Lantada, 2007). The vulnerability modifiers that were considered for buildings BCN1 and BCN2 are summarized in Table 8. For this reason, according to the VIM the total vulnerability index of buildings BCN1 and BCN2 is equal to 0.67 and 0.42, respectively (Table 9). Conforming to these values, the building BCN1 has a higher level of seismic vulnerability than building BCN2.

Table 5. Regional modifiers of seismic vulnerability for the main structural typologies of Barcelona (Lantada, 2007).

Periods	**Building period**	**Spanish building codes**	**Mandatory in Barcelona**	**Constructive practice with lateral resistant elements**	**Level of seismic design**	**Regional modifier of the vulnerability (ΔV_R)**				
						M31	**M32**	**M33**	**M34**	**RC32**
I	<1940	-	-	Absence	No	+0.198	+0.162	+0.234	-	-
II	1941-1962	-	-	Deficient	No	+0.135	+0.099	+0.171	-	-
III	1963-1968	Recommendation MV-101 (1963)	Not defined	Deficient	No	+0.073	+0.037	+0.109	+0.134	+0.228
IV	1969-1974	Seismic code PGS-1 (1968)	Yes	Acceptable	Low	+0.010	-0.026	+0.046	+0.009	+0.103
V	1975-1994	Seismic code PDS (1974)	Yes	Acceptable	Low	-0.052	-0.088	-0.016	-0.053	-0.022
VI	1995-2002	Seismic code NCSE-94 (1995)	No	Acceptable	Low	-0.052	-0.088	-0.016	-0.053	-0.022
VII	2002-2010	Seismic code NCSE-02 (2002)	Yes	Acceptable	Low	-0.052	-0.088	-0.016	-0.053	-0.022

Table 6. Vulnerability modifiers in function of the conservation state of buildings in Barcelona (Lantada, 2007).

Conservation state	Modifier by conservation state	Code
Significant reparations are required (deficient and ruins condition)	+0.04	D or O (deficient)
Intermediate (regular)	0	R (regular condition)
Modifications are not necessary (normal)	-0.04	N (normal or good condition)

Table 7. Vulnerability modifiers in function of number of levels of the buildings in Barcelona (Lantada, 2007)

Typology	No. of levels	Modifier by number of levels	
		Buildings of 1940 or built before 1940	Buildings that were built after 1940
Masonry	Low (1 to 2)	-0.02	-0.04
	Medium (3 to 5)	+0.02	0
	High (6 or more)	+0.06	+0.04
Reinforced concrete (low seismic code)	Low (1 to 3)	-0.04	
	Medium (4 to 7)	0	
	High (8 or more)	0.08	

Table 8. Vulnerability modifiers and their respective scores for buildings BCN1 and BCN2.

Modifier of vulnerability	Building BCN1	Scores	Building BCN2	Scores
Conservation state	Good	-0.04	Good	-0.04
Number of levels Built date	2 1970	-0.04	3 1975	-0.04
ΔV_m=		-0.08		-0.08

Table 9. Values of each term of Eq. 1 to compute the total vulnerability index of buildings BCN1 and BCN2.

Building	V_I*	ΔV_R	ΔV_m	$\overline{V_I}$
BCN1	0.704	0.046	-0.08	0.67
BCN2	0.522	-0.022	-0.08	0.42

2.3 Seismic risk in the VIM

In the VIM, a semi-empirical expression (Eq. 2) allows estimating mean damage grade, in function of both a total vulnerability index and a macroseismic intensity (Milutinovic & Trendafiloski, 2003; Giovinazzi, 2005; Lagomarsino & Giovinazzi, 2006; Barbat et al, 2006). This analytic expression (Eq. 2) was obtained mainly considering damage probability matrices (DPMs), which were defined according to the EMS-98 scale (Grünthal, 1998). At the same time, other elements of this scale as the vulnerability classes (Giovinazzi, 2005) were considered to define Eq. 2.

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25\overline{V_I} - 13.1}{2.3}\right)\right] \tag{2}$$

Eq. 2 allows estimating only a mean damage grade, for this reason, to completely define the damage probability matrices, it can be assumed that the damage probability, follows a beta probability density function (*pdf*) (Lantada et al, 2009a). This beta *pdf* can be represented by Eq. 3.

$$PDF : p_\beta(x) = \frac{\Gamma(t)}{\Gamma(r)\Gamma(t-r)} \frac{(x-a)^{r-1}(b-x)^{t-r-1}}{(b-a)^{t-1}} \qquad a \le x \le b; t, r > 0 \tag{3}$$

where *a*, *b*, and *r* are parameters of the distribution and Γ is the gamma function. In the case of the VIM, *a* is set to 0 (none damage state) and *b* is set to 6 (destruction damage state) (Lantada et al, 2009a). On the other hand, the parameter *t* affects the scatter of the distribution; therefore, it can take different values. However, since the damage distribution in the EMS98 scale (Grüntal, 1998) is considered as a binomial distribution (Giovinazzi et al, 2006) it was determined that 8 was an appropriate value for *t* because, with this value, the beta distribution is like the binomial one (Lantada et al, 2009a). The parameter *r* is defined as a function of μ_D according to Eq. 4.

$$r = t(0.007\mu_D^3 - 0.0525\mu_D^2 + 0.2875\mu_D) \tag{4}$$

Then, it is possible to compute the probability that the damage be less or equal to a damage grade $p_\beta(x)$ if the value of *r* is integrated in Eq. 3, and the limits are 0 and the *k*-damage grade (Lantada et al, 2009a). With that result, it is possible to use Eq. 5 compute the probability of occurrence of each damage grade *k*.

$$p_k = P_\beta(k+1) - P_\beta(k) \tag{5}$$

Finally, Eq. 6 can be used to compute a weighted mean damage index.

$$DS_m = \sum_{k=0}^{5} k.P\left[DS_k\right] \tag{6}$$

where *k* takes the integer values from 0 to 5 for the damage grades *k* and $P[DS_k]$ are the respective probabilities (Lantada et al, 2009a). Table 10 shows a simplified description of the five no-null damage grades that are considered in the VIM method. Additionally, Table 12 has a detailed description of each one of the five damage grades (including a simplified diagram) for two common structural typologies: masonry buildings and reinforced concrete buildings.

To obtain seismic risk results for buildings BCN1 and BCN2 (Table 2) it is possible to consider the seismic hazard scenario No.2 of

Table 3, for a return period of 475 years, and the total vulnerability index of buildings BCN1 and BCN2 (Table 9). Then for these values, the mean damage grade μ_D is equal to 0.37 for the building BCN1 and equal to 0.1 for the building BCN2. Additionally, the damage distributions for buildings BCN1 and BCN2, that can be obtained applying equations 3 to 5, are shown in Figure 1a and Figure 1b, respectively. Finally, the weighted mean damage indexes (DS_m) for both buildings are shown in Table 11.

Table 10. Damage grades in the VIM to describe the levels of seismic damage (Milutinovic and Trendafiloski, 2003).

	Damage grade	Structural damage	Non-structural damage
1	Negligible to slight damage	None	Slight
2	Moderate damage	Slight	Moderate
3	Substantial to heavy damage	Moderate	Heavy
4	Very heavy damage	Heavy	Very heavy
5	Destruction	Very heavy	

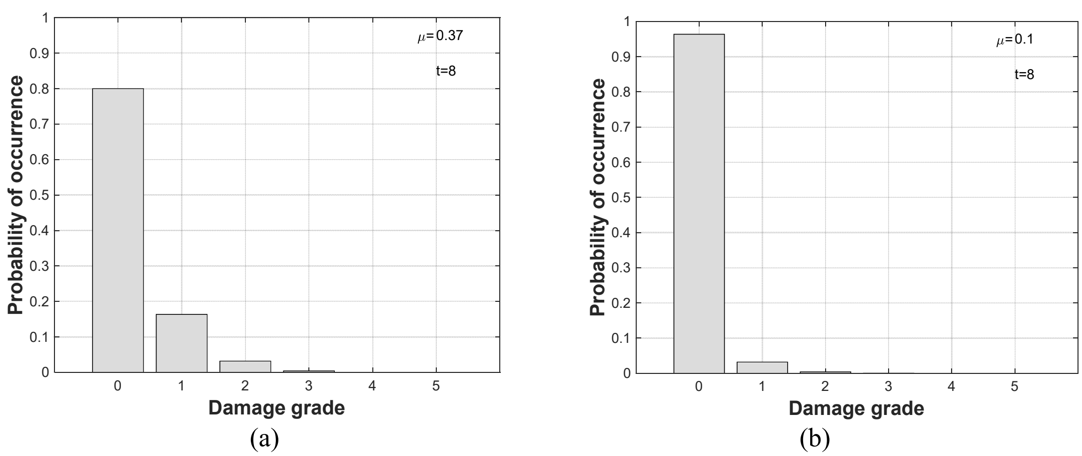


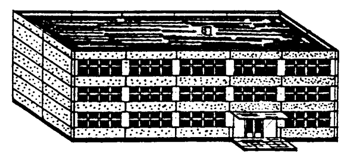
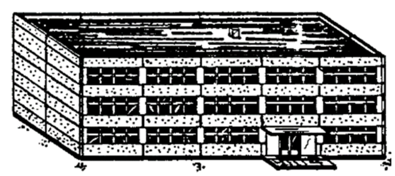
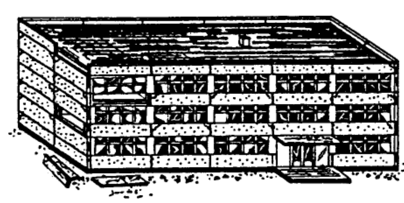
Figure 1. Damage distribution for both buildings BCN1 (a) and BCN2 (b) located in Barcelona, according to the VIM, for a macroseismic intensity equal to 6.0 (Tr = 475 years)

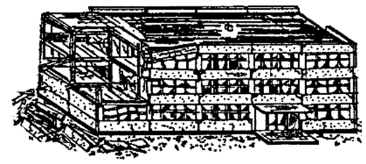
Table 11. Results of seismic risk according to the VIM for the seismic hazard scenario 2 of

Table 3 related to a return period of 475 years

Building	**Mean damage grade (μ_D)**	**Weighted Mean Damage Index (DS_m)**
BCN1	0.37	0.24
BCN2	0.10	0.04
BCN1 & BCN2 (arithmetic mean)	0.235	0.14

Table 12. Classification of damage for both masonry and reinforced concrete buildings (EMS-98). (Grünthal, 1998).

Grades	**Complementary description**	
	Masonry buildings	**Reinforced concrete buildings**
1- Negligible to slight damage (no structural damage, slight non-structural damage)	Hair-line cracks in very few walls. Fall of small pieces of plaster only 	Fine cracks in plaster over frame members or in walls at the base. 
2- Moderate damage (slight structural damage, moderate non-structural damage)	Cracks in many walls. Fall of fairly large pieces of plaster. 	Cracks in columns and beams of frames and in structural walls. 
3- Substancial to heavy damage (moderate structural damage, heavy non-structural damage).	Large and extensive cracks in most walls. Roof tiles detach. 	Cracks in columns and bean column joints of frames at the base and at joints of coupled walls 

4- Very heavy damage (heavy structural damage, very heavy non-structural damage)	Serious failure of walls; partial structural failure of roofs and floors 	Large cracks in structural elements with compression failure of concrete and fracture of rebars. Collapse of a few columns or of a single upper floor. 
5- Destruction (very heavy structural damage)	Total or near total collapse 	Collapse of ground floor or parts (e. g. wings) of buildings. 

On the other hand, if it is required an analysis as a group of buildings about the previous seismic risk results (Table 11), then it is possible to determine that the group consisting of the buildings BCN1 and BCN2, has in average a weighted mean damage index equal to 0.14. The application of the VIM essentially concludes with the computation of the damage distribution (Figure 1) and the weighted mean damage index (Table 11).

3 Probabilistic method based on a vulnerability index (VIM_P) to assess seismic risk of buildings in urban zones.

In this section, we described the VIM_P that is a derivation of the VIM but with the incorporation of a probabilistic approach that is summarized in Eq. 7. This equation was adapted from McGuire (2004) and it allows to compute annual frequencies of exceedance of five no-null damage grades (Table 12). For this purpose, the following three elements are considered: a) the seismic hazard in the site where each building is located; b) the seismic vulnerability of each building and; c) the earthquake damage that both the seismic hazard and the seismic vulnerability can generate in each studied building.

$$\nu[D > D_k] \approx \sum_I \sum_V P\left[D > D_k \mid V, I\right] P\left[V\right] \gamma'\left[I\right] \qquad 7$$

In Eq. 7 the approximation is because of is being included the frequency, $\gamma'[I]$, which is obtained from the seismic hazard assessment, rather than the probability $P[I]$ (McGuire, 2004).

$\gamma'[I]$ is the annual frequency of occurrence of the seismic intensity (McGuire, 2004). According to McGuire (2004) in Eq. 7 the value of $\gamma'[I]$ can be considered as a "very close estimator of the probability" for values of $\gamma[I] < 0.1$, where $\gamma[I]$ is the annual frequency of exceedance of the seismic intensity. A similar criterion is summarized by Ellingwood (2006) according to this phrase: "the annual probability and annual mean rate of occurrence are numerically interchangeable for randomly occurring events with probabilities less than 0.01/year". In the present work, we considered as reference value, the value proposed by McGuire (2004). $P[V]$ is the probability of occurrence of the index of seismic vulnerability. $P[D > D_k \mid V, I]$ is the probability that damage D will be exceeded given that a seismic intensity I, and an index of seismic vulnerability V have occurred. In Eq. 7 the total probability theorem is applied and it is considered that the intensity I and the vulnerability V are independent random variables (Aguilar et al, 2010).

For the operational implementation of the VIM_P two codes are recommended: CRISIS and USERISK. The different versions of code CRISIS have been widely validated to perform PSHA (Aguilar et al, 2017). The code USERISK was developed since 2011 exclusively to compute seismic risk according to the VIM_P, and it has been successfully applied for this purpose (Aguilar, 2011). Therefore, for identification reasons it was defined the CRISIS&USERISK procedure, to recognize the case when both codes CRISIS2015 and USERISK2015 (Aguilar et al, 2015) are simultaneously applied to assess seismic risk of buildings in urban areas, according to the VIM_P (Figure 2). The CRISIS&USERISK procedure was applied in the present work to compute the seismic risk of dwelling buildings of Barcelona.

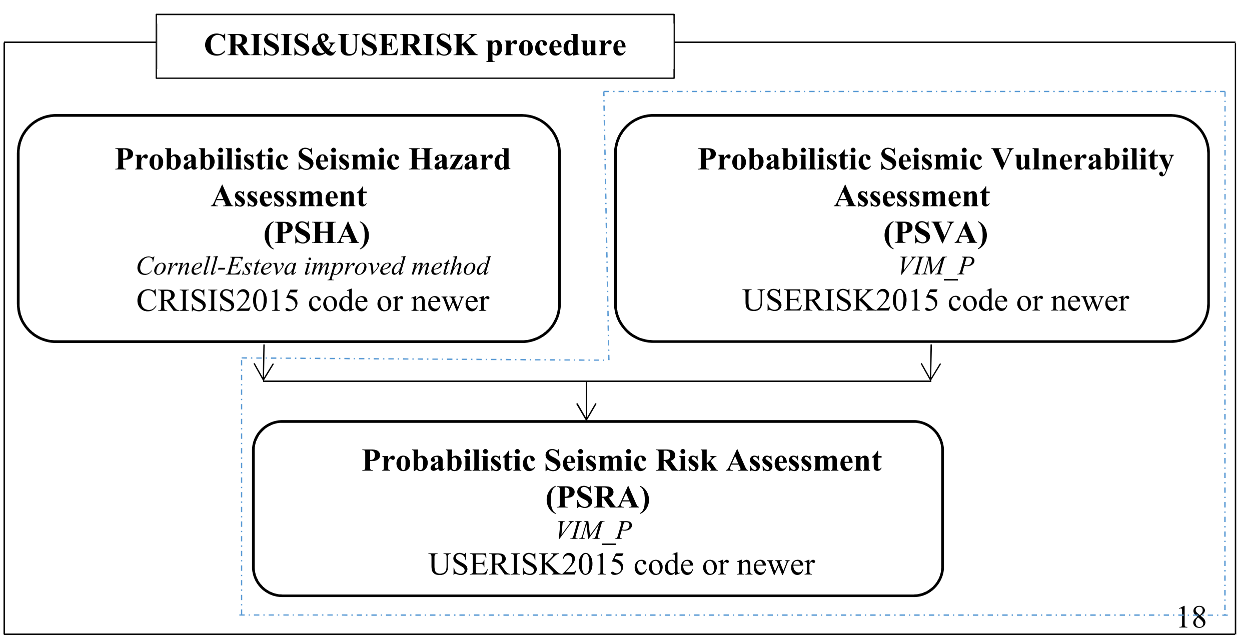


Figure 2. Diagram of the CRISIS&USERISK procedure to assess seismic risk of buildings in urban areas. Dotted line corresponds to the VIM_P (adapted from Aguilar et al, in press).

3.1 Seismic hazard in the VIM_P

To compute seismic risk of buildings according to the VIM_P it is required a curve of seismic hazard, that represent the frequency of exceedance of macroseismic intensities. This curve must be computed performing a PSHA which can be executed using a recent version of CRISIS as CRISIS2015 or R-CRISIS. In this point, it is possible to highlight that there are significant differences between the VIM and the VIM_P about the data of seismic hazard used to compute seismic risk and about the way to compute this seismic hazard. For instance: 1) a deterministic procedure to assess seismic hazard is valid in the VIM, but not in the VIM_P; 2) in both methods is valid to apply a PSHA, however, in the VIM a point of the seismic curve computed is enough to define a seismic hazard scenario. This point corresponds to the value of intensity that can occurs for the chosen return period, according to the results of PSHA. In other words, in the VIM the frequency of exceedance is only a reference value to select the seismic hazard scenario, but this frequency value is not included in the seismic risk computations. On the opposite, in the VIM_P at least a segment of the seismic hazard curve computed through a PSHA must be considered to define the seismic hazard. At the same time, the values of frequency of exceedance of the macroseismic intensities are considered in the computation of seismic risk.

To compute the seismic risk of buildings BCN1 and BCN2 (Table 2) it is necessary to assess the seismic hazard at a rock site of Barcelona because according to the data (Table 2), these buildings are located in that type of ground. If a PSHA is performed then it is possible to obtain a seismic hazard curve as the curve of Figure 3, which was computed applying CRISIS2012 (Aguilar et al, 2013). According to this curve, the macroseismic intensity of VI has a return period of 475 years. Similarly, the macroseismic intensity of V has approximately a return period of 100 years. It is also possible to observe in the same seismic hazard curve of Barcelona that the macroseismic intensity that has a return period of 2475 years is a value lower than VII.

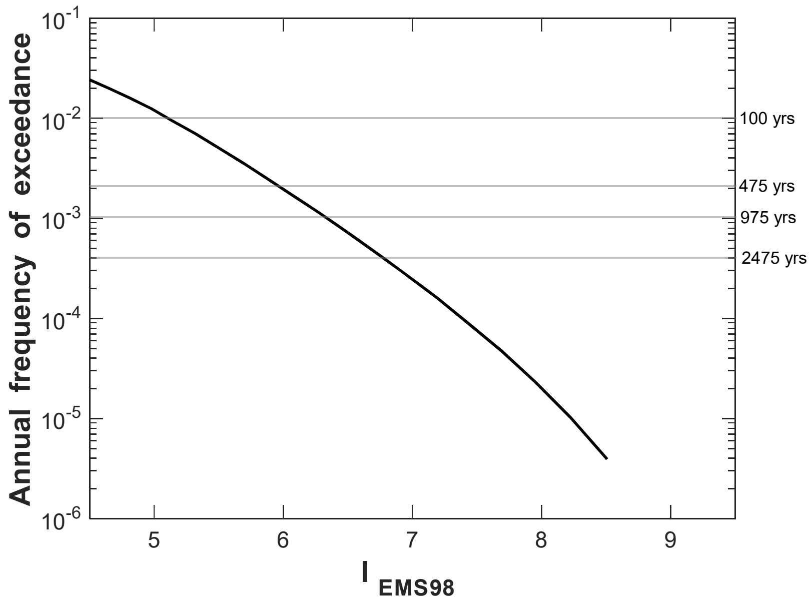


Figure 3. Seismic hazard curve for a rock site in Barcelona computed by means of CRISIS2012 in terms of macroseismic intensities (Aguilar et al, 2013).

3.2 Seismic vulnerability in the VIM_P

As was mentioned previously, the seismic vulnerability is a measure of the expected structural response of a building during the presence of strong seismic ground motions. For this reason, the data used in the VIM_P to assess the seismic vulnerability of buildings are for instance the following: a) structural typology; b) levels of the building; c) main characteristics of the structural materials of the building; d) age of the building; and; e) conservation state of the building. On the other hand, the reliability of these data it is also relevant. For this reason, the VIM_P considers the reliability of the datum of the structural typology of each studied building in the process to assess the seismic vulnerability.

It is possible to note that a fundamental difference between the methods VIM and VIM_P is the way in that the seismic vulnerability is represented or modelled. In the VIM, the seismic vulnerability of a building is represented by a number called total vulnerability index (Eq. 1). This total vulnerability index is mainly a value between 0 and 1. Cero means low seismic vulnerability and 1 means high seismic vulnerability. However, the total vulnerability index of the VIM method corresponds to the mean value of a probability density function beta type (Figure 4) in the VIM_P. This *pdf* beta type is named best vulnerability curve and it is the main representation of seismic vulnerability of a building. This best vulnerability curve allows to represent the seismic vulnerability of a building but at the same time it represents a substantial part of the important uncertainty, that is related to the assessment of the seismic vulnerability of a building. Additionally, to consider the reliability in the datum of the structural typology of each building, other two vulnerability curves are considered to represent another part of the uncertainty related to the seismic vulnerability. Summarizing, in the VIM_P three *pdf* beta type represent the seismic vulnerability of each building: a) lower curve, b) best curve and, c) upper curve.

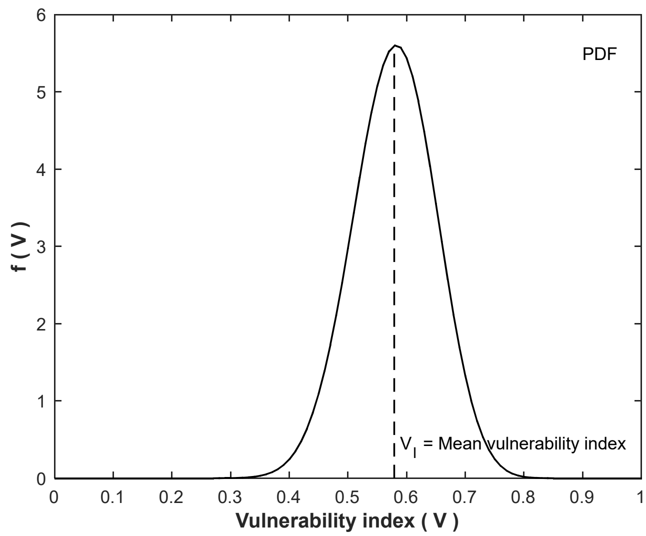


Figure 4. Example of a probability density function beta type, which is used in the VIM_P to define the best curve of seismic vulnerability of a building.

The main reasons that were considered by Aguilar and colleagues (2010) to choose the *pdf* beta type to model the seismic vulnerability of buildings are the following: a) the *pdf* beta type can take an important variety of shapes (including distributions with important dissymmetry), depending on the values of two parameters (α and β); b) the *pdf* beta type is helpful to represent variables which values are restrained to a range, as in this case where the vulnerability index is restrained to a range, for instance, the range defined by 0 and 1; c) the *pdf* beta type has been used with good results to represent variables related to the seismic risk of buildings (McGuire, 2004; ATC-13, 1985). In the following part of this document, we described the main steps of the VIM_P, to determine the best curve of seismic vulnerability of each building.

3.2.1 Best vulnerability curve

To define the *pdf* beta type that represents the best vulnerability curve of a building it is essential to determine the values of α_m and β_m of the beta function (Eq. 8).

$$f(V;\alpha_m,\beta_m)=\frac{\Gamma(\alpha_m+\beta_m)}{\Gamma(\alpha_m)\Gamma(\beta_m)}\frac{\left(V-V_a\right)^{\alpha_m-1}\left(V_b-V\right)^{\beta_m-1}}{\left(V_b-V_a\right)^{\alpha_m+\beta_m-1}} \qquad V_a\le V\le V_b\,;\alpha_m,\beta_m>0 \qquad 8$$

where V is the seismic vulnerability index, α_m and β_m are the shape parameters, V_a and V_b are the lower and upper limits, respectively, of the distribution, and Γ is the gamma function.

With the purpose of simplifying the computations, it is possible to express the general form of the probability function beta type (Eq. 8), in terms of the probability function beta standard (Eq. 9).

$$f\left(\frac{V-V_a}{V_b-V_a};\alpha_m,\beta_m\right)=\frac{\Gamma(\alpha_m+\beta_m)}{\Gamma(\alpha_m)\Gamma(\beta_m)}\left(\frac{V-V_a}{V_b-V_a}\right)^{\alpha_m-1}\left(1-\frac{V-V_a}{V_b-V_a}\right)^{\beta_m-1} \quad V_a\le V\le V_b\,;\alpha_m,\beta_m>0 \qquad 9$$

To obtain the values of the parameters α_m and β_m it is considered that the beta function satisfies the following conditions: 1) the mean value of the function is equal to the mean of the values of the vulnerability index, which is determined by Eq. 1 $\left(\overline{V_I}\right)$ when V_a=0 and V_b=1 (Figure 5), and equal to $\frac{\overline{V_I}-V_a}{V_b-V_a}$ when $V_a \neq 0$ and/or $V_b \neq 1$ (Eq. 10), and; 2) the values of V_c and V_d (Figure 5) determine the confidence interval of 90% (Eq. 11).

$$\left(\frac{\overline{V_I}-V_a}{V_b-V_a}\right)=\frac{\alpha_m}{\alpha_m+\beta_m} \qquad 10$$

$$0.9=\int_{y_1}^{y_2} f\left(y\right)dy = B_{y2}(\alpha_m,\beta_m)-B_{y1}(\alpha_m,\beta_m) \qquad 11$$

where y_1 and y_2 correspond to V_c and V_d, respectively; $B_{y2}(\alpha_m, \beta_m)$ and $B_{y1}(\alpha_m, \beta_m)$ are the incomplete beta functions (beta cumulative distribution function), for values of y_2 and y_1, respectively.

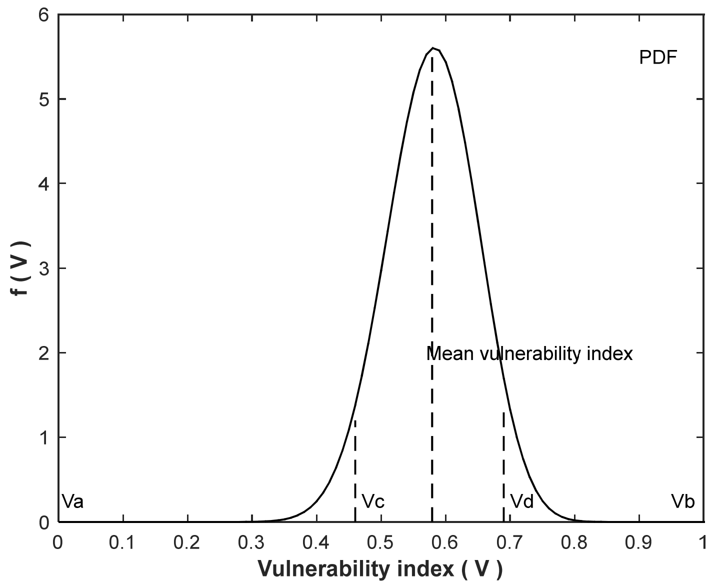


Figure 5. Example of a PDF beta that according to the VIM_P correspond to the best curve of seismic vulnerability of a building. In these *pdf´s* their mean value is equal to the mean vulnerability index, and the 90% confidence interval is delimitated by the values of V_c and V_d.

Therefore, the procedure to estimate the *pdf* beta that represents the best curve of seismic vulnerability of a building can be summarized in four steps: 1) assessment of $\overline{V_I}$; 2) determination of V_c and V_d; 3) determination of V_a and V_b; 4) estimation of values of α_m and β_m of the *pdf* beta type that completely defines the curve of the best estimation of seismic vulnerability. In the following sections, we described details about these main four steps required to obtain the best curve of seismic vulnerability of each studied building. At the same time, we calculate the best curve of seismic vulnerability for buildings BCN1 and BCN2 (Table 2).

Determination of the best curve of seismic vulnerability

Step 1. Computation of mean vulnerability index

According to the VIM_P, the first step to assess the best curve of seismic vulnerability of a building is to compute the mean vulnerability index, $\overline{V_I}$. For this purpose, Eq. 1 is applied. Then, for buildings BCN1 and BCN2 (Table 2), the values of $\overline{V_I}$ are 0.67 and 0.42, respectively (Table 9).

Step 2. Determination of values of V_c and V_d

To compute values of V_c and V_d (Figure 5), that define the confidence interval of the 90% of the best curve of seismic vulnerability of each building, it is possible to consider two criteria (I and II). In this section, we describe the criterion I. However, in Appendix 2, we included the criterion II that can be applied in special cases according to the researcher's judgment. In the criterion I to compute V_c and V_d it is considered that values V_I^{min} and V_I^{max} (Table 4) correspond to values V_c and V_d, respectively. That is, it is considered that the confidence interval of the 90% of the best curve of seismic vulnerability of each building is defined by values of V_I^{min} and V_I^{max}. In other words, it is considered that in 90% of the cases the index of seismic vulnerability of each building it will be a value between V_I^{min} and V_I^{max}. According to this criterion, values of V_c and V_d, that define the confidence interval of the 90%, will be the same for all the buildings that are classified into the same structural typology. This case is represented by Eq. 12 and Eq. 13. According to this criterion I, the values of V_c and V_d are in a range between -0.02 and 1.02. Therefore, if criterion I is applied then the pair of values (V_c, V_d) for buildings BCN1 and BCN2 according to Table 4 are (0.46, 1.02) and (0.06, 1.02), respectively.

$$V_c = V_I^{\min} \tag{12}$$

$$V_d = V_I^{\max} \tag{13}$$

Appendix 2 describes in detail the criterion II to determine values of V_c and V_d. In this criterion, the values of V_c and V_d can exceed the range defined by the values of -0.02 and 1.02. A common reference about the use of values of the vulnerability index greater than 1.02 occurs mainly in special monumental buildings (Goded et al, 2016; Goded et al, 2012).

Step 3. Determination of values of V_a and V_b

According to the VIM, it is reasonable that the seismic vulnerability of the major part of the buildings can be represented with values of the vulnerability index between -0.02 and 1.02 (Milutinovic and Trendafiloski, 2003). These values correspond to the minimum value of V_I^{min} and the maximum value of V_I^{max}, that were considered by Milutinovic and Trendafiloski (2003) to define the representative values of vulnerability for the typologies that were included in the VIM method. At the same time, those values correspond to the values of V_c and V_d in the VIM_P if criterion I is chosen.

In the VIM_P the values of V_a and V_b, determine the range of values that the vulnerability index V can reach (Eq. 9). Therefore, in order to facilitate the comparison and interpretation of results of seismic vulnerability, the values of V_a and V_b must be equal for all the studied buildings in the same urban area. For this purpose, if the criterion I to determine values of V_c and V_d is chosen, then the range delimited by V_a and V_b, must be a range wider than the range delimited by V_c and V_d. Additionally, it is possible to remember that according to Milutinovic and Trendafiloski (2003), V_I^- and V_I^+ define the range of probable values for the buildings of the same structural typology and V_I^{min} and V_I^{max} increase the range, to include the less probable values of the vulnerability index for the same structural typology. Then if in criterion I of the VIM_P, $V_c = V_I^{min}$ and $V_d = V_I^{max}$, it is possible to consider that the values of V_a and V_b can delimit a range slightly higher than the range defined by V_c and V_d. For this purpose, in the present work, we are proposing to use the values of -0.04 and 1.04 for V_a and V_b, respectively. That is, values close to the values of V_c (-0.02) and V_d (1.02), respectively. This proposed is also based on the following: a) the fact that the 90% of the values of the vulnerability index will be into the range defined by V_c and V_d (Figure 5) and; b) in the assumption that the 100% of the values of the vulnerability index will be into the range defined by V_a and V_b. On the other hand, the difference between V_a and V_c and V_b and V_d, respectively, is of 0.02, which has a magnitude order similar to the increment of the vulnerability related to common modifiers of the vulnerability (Milutinovic and Trendafiloski, 2003). These previous recommendations can be summarized in Eq.14 and Eq. 15. In any case, the range defined by V_a and V_b must be greater than the range delimited by V_c and V_d.

$$V_a = -0.04 \tag{14}$$

$$V_b = 1.04 \tag{15}$$

On the other hand, if criterion II is chosen then it is possible to apply Eq.16 and 17 to determine the values of V_a and V_b, respectively.

$$V_a = \text{Min}\left[\,(\text{Min}(V_c)-0.02),\ -0.04\right] \tag{16}$$

$$V_b = \text{Max}\left[\,(\text{Max}(V_d)+0.02),\ 1.04\right] \tag{17}$$

Step 4. Determination of values of α_m and β_m

To compute α_m and β_m it is considered the following three stages: i) β_m is proposed, then, $\overline{V_I}$, V_a and V_b are applied to compute the value of α_m according to Eq.18.

$$\alpha_m = \frac{-\beta_m \cdot \dfrac{\overline{V_I} - V_a}{V_b - V_a}}{\left(\dfrac{\overline{V_I} - V_a}{V_b - V_a} - 1\right)} \tag{18}$$

ii) It is computed the cumulated probability that exists in the cumulative distribution function beta type (Eq. 11), according to the values of β_m, α_m, V_c, and V_d, previously determined.

iii) It is verified if the cumulative probability assessed is equal to the 90%. If this condition is not satisfied, then the procedure return to the stage i and a new β_m is proposed. But, if the condition it is satisfied then the present values of β_m and α_m define the probability density function beta type, which corresponds to the best curve of seismic vulnerability of the studied building. The standard deviation of this probability function beta type can be computed with Eq. 19.

$$\sigma_{\bar{V}} = \sqrt{\frac{\alpha_m \beta_m}{\left(\alpha_m + \beta_m\right)^2 \left(\alpha_m + \beta_m + 1\right)} \cdot (V_b - V_a)^2} \qquad 19$$

We applied the procedure previously described to compute the best curve of seismic vulnerability of the buildings BCN1 and BCN2. The values of α_m and β_m, V_a and V_b, that define these curves of the buildings BCN1 and BCN2 (Figure 6) are shown in Table 13. These curves were computed both using USERISK2015 and according to the criteria I to determine V_c and V_d. In Table 13, we included the mean and the standard deviation that we computed according to Eq. 20 and Eq. 19, respectively.

Table 13. Results of seismic vulnerability of buildings BCN1 and BCN2. Values of α_m and β_m that define the best seismic vulnerability curve for each building, according to the criterion I to assess the values of V_c and V_d.

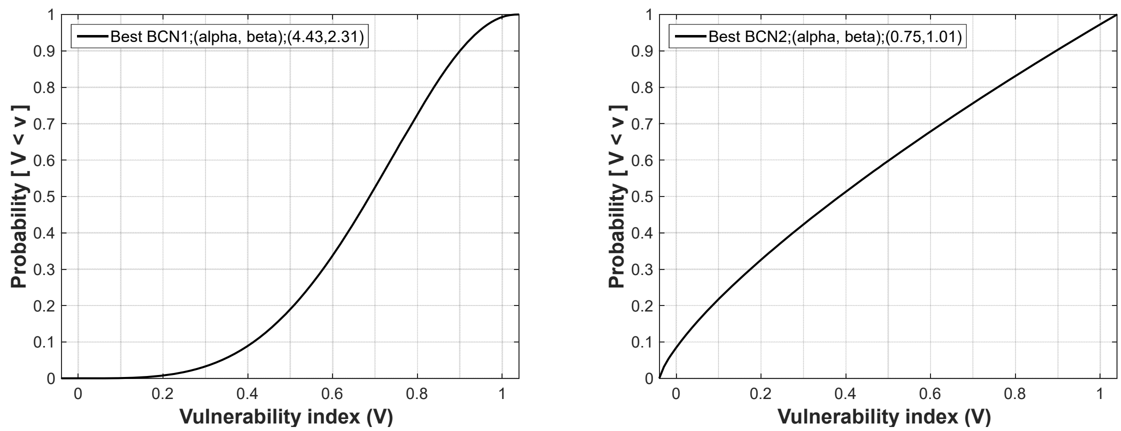
	V_a = -0.04; V_b = 1.04 (criterion I)			
Building	α_m	β_m	***Mean***	***Standard deviation***
BCN1	4.43	2.31	0.67	0.18
BCN2	0.75	1.01	0.42	0.32

$$Mean = \left(V_b - V_a\right)\left(\frac{\alpha_m}{\alpha_m + \beta_m}\right) + V_a \qquad 20$$

To compare the seismic vulnerability curves of buildings BCN1 and BCN2 (Figure 6) it is possible, for instance, to compute the probability that the vulnerability index V is greater than 0.8. These values are shown in Table 14 and according to these results, the building BCN1 has higher seismic vulnerability than building BCN2.

Table 14. Probabilities that the vulnerability index V is greater than 0.8, according to the best curves of seismic vulnerability of buildings BCN1 and BCN2.

	BCN1	**BCN2**
P(V>0.8)	0.273	0.169



(a) (b)

Figure 6. Results of seismic vulnerability of buildings BCN1 and BCN2. Cumulative density functions (*CDF*) beta type, which represent the best curve of the seismic vulnerability of the buildings BCN1 (a) and BCN2 (b), respectively. These seismic vulnerability curves were computed considering the criterion I to determine V_c and V_d, and the values of V_a and V_b equal to -0.04 and 1.04, respectively.

It is convenient to highlight that the best curves of seismic vulnerability defined in the VIM_P, allows representing in a reasonable way, an important proportion of the uncertainty that exists in the assessment of the seismic vulnerability. For instance, it is possible to observe that the seismic vulnerability curve of building BCN1(Figure 6a) is a curve that represents less uncertainty in the determination of the seismic vulnerability curve of the building BCN1 than the seismic vulnerability curve of building BCN2 (Figure 6b). This last affirmation is because in the building BCN1 the value of the vulnerability index varies in a range of about 0.2 to 1, but in the building BCN2 the vulnerability index range between about 0 and 1. On the other hand, with the purpose of considering the uncertainty in the determination of the structural typology, the VIM_P includes the assessment of the lower and upper curves of seismic vulnerability.

Determination of lower and upper curves of seismic vulnerability

The lower and the upper curves of seismic vulnerability are computed applying a similar procedure to the one used to obtain the best curve of seismic vulnerability of a building. The main difference is that the mean values of these additional vulnerability curves are assessed according to Eq. 21, for the lower curve, and Eq. 22 for the upper curve. The rest of the process is essentially the same that it is used to compute the best curve of seismic vulnerability.

$$\overline{V_{I\_L}} = \overline{V_I} - \frac{I_f - f}{I_f} \cdot \phi \cdot \sigma_{\overline{V}} \qquad 21$$

$$\overline{V_{I\_U}} = \overline{V_I} + \frac{I_f - f}{I_f} \cdot \phi \cdot \sigma_{\overline{V}} \qquad 22$$

where I_f and ϕ are parameters of the reliability model that are calibrated in each study; f is the reliability factor in the assignation of the structural typology of each studied building; $\sigma_{\overline{V}}$ is the standard deviation that is computed according to Eq. 19. The Eq. 21 and 22 were defined due to the fact that when the reliability in the assignation of the structural typology is a low value, it produces an increase in the value of the uncertainty in the determination of the mean index of the seismic vulnerability. In our work, it was considered appropriate define reliability factors f between 0 and 10, corresponding to zero the case of null reliability and to 10 the condition where the reliability is complete. At the same time, it was considered that an appropriate value for I_f was 10, and 1.96 for ϕ. This proposition was done considering that the maximum variation of the mean vulnerability index (in the 95% of the cases), it will be determined by the values that delimit the confidence interval of 95%.

On the other hand, the values of V_c and V_d to assess the lower and upper curves of seismic vulnerability can be also determined by means of Eq. 12 and Eq. 13, if the criterion I is selected. However, if criterion II is selected then it is possible to use the equations indicated in Appendix 2 for that purpose. To continue with the example of buildings BCN1 and BCN2 we applied the procedure described previously to compute the lower and upper vulnerability curves of the building BCN1 and BCN2. Table 15 shows the computed values of α and β that define both lower and upper seismic curves for each building (Figure 7). In this case, we considered the criterion I to determine the values of V_c and V_d , and the values of V_a and V_b of -0.04 and 1.04, respectively.

According to the three curves of Figure 7a that represent the seismic vulnerability of the building BCN1, the probability that in the building BCN1 the vulnerability index is greater than 0.6 vary between 45.7% and 82.7%, with a mean value of 66.2%. Similarly, according to the three curves of Figure 7b that represent the seismic vulnerability of the building BCN2, the probability that the index of vulnerability is greater than 0.6 varies between 17.45% and 54.79%, with a mean value of 32.11%. Conforming to these results it is possible to affirm that the building BCN1 is significantly more vulnerable to earthquakes than the building BNC2. On the other side, it is important to highlight that the separation that exists between the three curves of vulnerability for the same building (Figure 7), depends mainly on the reliability factor f, that describes the reliability in the assignation of the structural typology of the studied building.

This reliability factor is equal to 7 for buildings BCN1 and BCN2 (Table 2; Table 15). The separation between the three curves of vulnerability also depends on the standard deviation of the *pdf* beta type, which represents the best curve of seismic vulnerability.

Table 15. Results of seismic vulnerability of buildings BCN1 and BCN2. Values of α, β, f and ϕ of *PDFs* beta type, that define both the lower and upper seismic vulnerability curves of each one of these buildings, according to criterion I to define V_c and V_d.

Seismic vulnerability curve (Criterion I)	V_a= -0.04; V_b=1.04							
	Building BCN1				Building BCN2			
	α	β	f	ϕ	α	β	f	ϕ
Lower	2.53	2.01	7	1.96	0.27	0.81	7	1.96
Upper	4.1	1.31	7	1.96	1.22	0.81	7	1.96

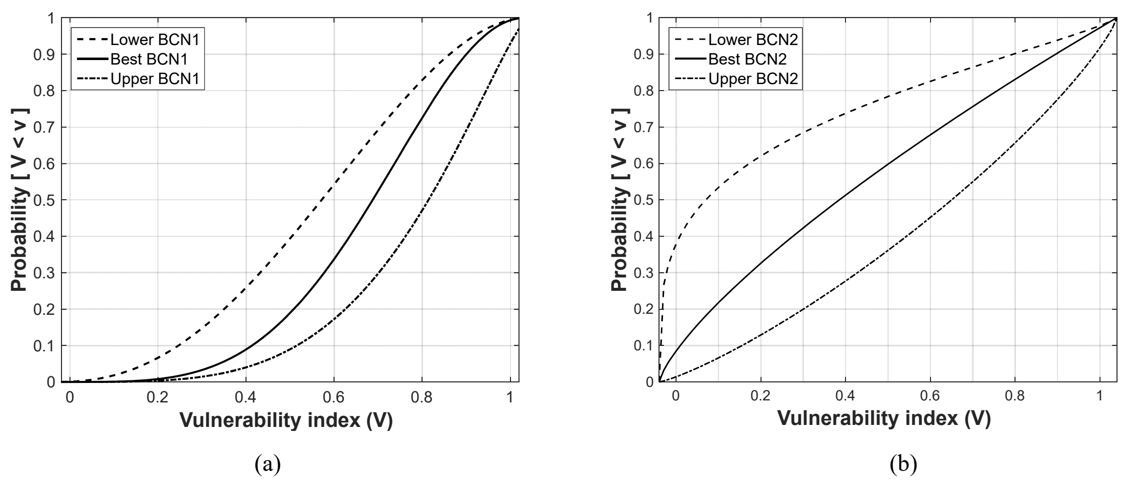


Figure 7. Seismic vulnerability curves (CDFs beta type) of buildings BCN1 (a) and BCN2 (b), computed according to criterion I to define V_c and V_d (Table 13; Table 15).

3.2.2 Seismic vulnerability curves for a group of buildings

For analysis purpose, it is possible to obtain representative curves of seismic vulnerability for a group of buildings. For instance, it is possible to obtain a single curve that represents the best curve of seismic vulnerability of the group consisting of buildings BCN1 and BCN2. This seismic vulnerability curve for a group of buildings is determined computing the geometric mean of the values of α and β, that define the seismic vulnerability curve of each building. For this purpose, it is possible to apply Eq. 23 and Eq. 24. We applied this procedure to determine the unique seismic vulnerability curve that represents the best seismic vulnerability of the group consisting of buildings BCN1 and BCN2. This curve corresponds to the curve with the continuous line in Figure 8 and it is defined by the values of α and β of Table 16. In the same figure, but in dotted lines, it is possible to observe the best vulnerability curves of buildings BCN1 and BCN2.

$$\alpha_{g-mean} = \sqrt[n]{\alpha_1 \cdot \alpha_2 \cdots \alpha_n} \quad 23$$

$$\beta_{g-mean} = \sqrt[n]{\beta_1 \cdot \beta_2 \cdots \beta_n} \quad 24$$

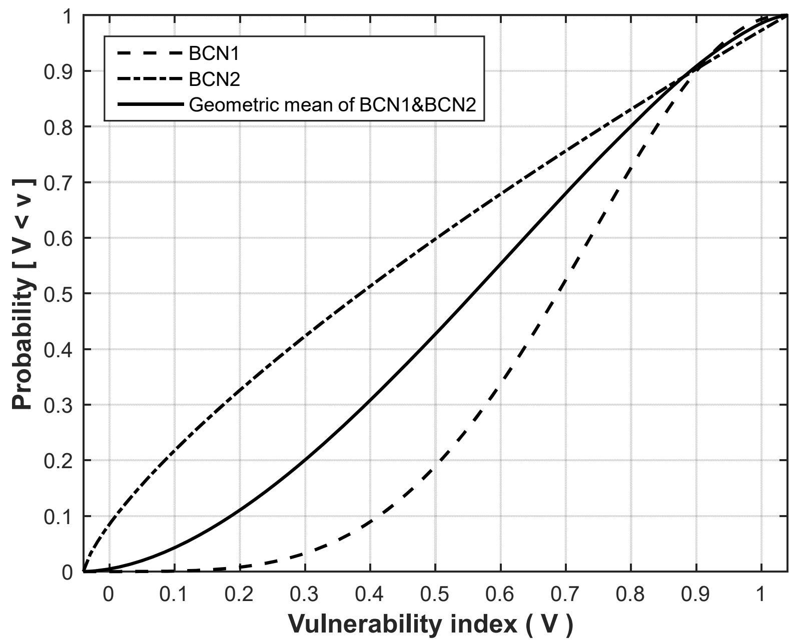


Figure 8. Best curves of seismic vulnerability of: a) building BCN1, b) building BCN2 and, c) group consisting of buildings BCN1 and BCN2.

Table 16. Results of seismic vulnerability. Values of α and β that define the best curves of seismic vulnerability of: a) building BCN1; b) building BCN2; C) group consisting of buildings BCN1 & BCN2

Seismic vulnerability curve (Criterion I to define V_c and V_d)	**V_a= -0.04; V_b=1.04**	
	α	**β**
BCN1	4.43	2.31
BCN2	0.75	1.01
BCN1&BCN2	1.823	1.527

3.3 Seismic risk in the VIM_P

3.3.1 Seismic risk by building in the VIM_P

In the VIM_P the seismic risk of buildings is assessed applying Eq. 7. For this purpose, the values of the third term of Eq. 7 are determined from the results of seismic hazard that were computed according to the section 3.1. Particularly, in this case, must be considered the values of the macroseismic intensities and their respective frequencies of exceedance, that were selected to assess the seismic risk, according to the results of the PSHA. Additionally, it is necessary to note that according to McGuire (2004) the assessment of $\gamma'[I]$ for the case $\gamma'\left[I = 7\right]$ must be computed by the difference of $\gamma\left[I \geq 6.5\right] - \gamma\left[I \geq 7.5\right]$. At the same time, a similar criterion must be considered to assess any value of $\gamma'\left[I\right]$. On the other hand, the values of the second term of Eq. 7 are computed from the *pdf* beta that defines the seismic vulnerability of each building. For instance, the probability of occurrence of the vulnerability index equal to 0.5 can be determined by the following difference $P\left[V = 0.5\right] = P\left[V \geq 0.49\right] - P\left[V \geq 0.51\right]$. The values of each one of the terms of this last equation are determined through the evaluation of the beta incomplete function, corresponding to each curve of seismic vulnerability previously determined according to section 3.2. At the same time, the values of the vulnerability index to be applied in Eq. 7 correspond to the values included in the range defined by V_a and V_b. To determine the values of the first term of Eq. 7 it is possible to apply Eq. 5, which allows computing probabilities of occurrence of different damage states in terms of a value of the vulnerability index and a value of the macroseismic intensity. Then it is possible to observe that in the VIM_P it is applied the same damage function that in the VIM. This damage function is a semi-empirical function, therefore, a pending improvement of the VIM_P is the development of a damage function, based on a complete probabilistic definition.

We applied the previous procedure to compute the seismic risk results of buildings BCN1 and BCN2 (Table 2). Particularly, we obtained the results of Table 17 and Figure 9 applying USERISK2015 and considering both the seismic hazard of a rock site of Barcelona (Figure 3) truncated to 475 years, and the seismic vulnerability curves of Figure 7a. According to these results, it is possible to observe, for instance, that in the building BCN1 the annual frequency of exceedance of the damage grade 4 is a value between 6.40 x10^{-6} and 3.19 x10^{-5}, with a mean value of 9.68 x10^{-6}. Therefore, only in the upper curve the annual frequency of exceedance of the damage grade 4 is greater than 1x10^{-5}.

Table 17. Results of seismic risk of building BCN1 expressed in terms of annual frequencies of exceedance of damage states.

Seismic vulnerability curves of building BCN1	**ν (D≥1)**	**ν (D≥2)**	**ν (D≥3) [1/year]**	**ν (D≥4)**	**ν (D=5)**
Lower	2.15E-3	4.77E-4	7.65E-5	6.40E-6	1.11E-7
Best	3.13E-3	7.15E-4	1.16E-4	9.68E-6	1.64E-7
Upper	5.59E-3	1.58E-3	3.12E-4	3.19E-5	7.03E-7

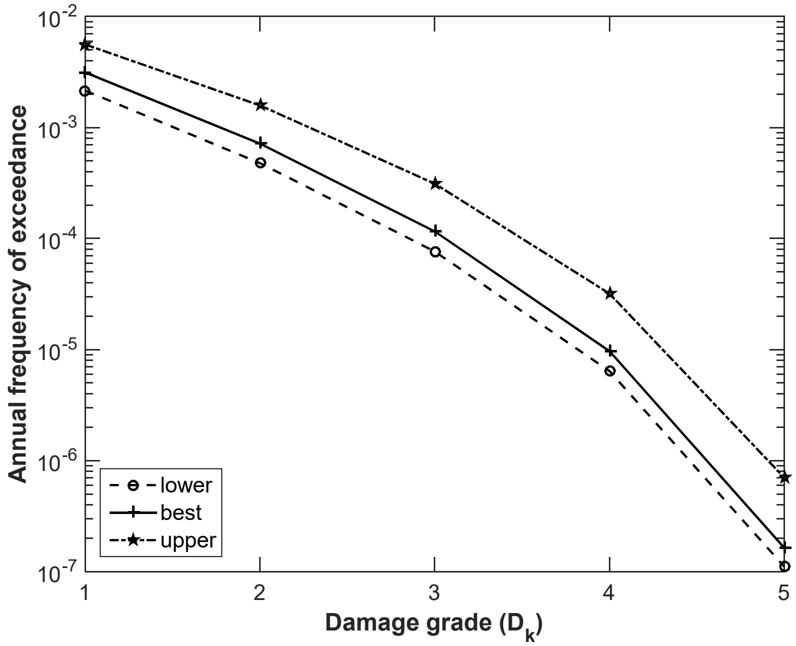


Figure 9. Seismic risk curves of building BCN1, which were computed considering the seismic vulnerability curves of Figure 7a, and the seismic hazard curve of (Figure 3) but truncated to 475 years.

Similarly, we computed the seismic risk of building BCN2 considering the seismic vulnerability curves of Figure 7b, and the seismic hazard of a rock site of Barcelona (Figure 3) truncated to 475 years. According to the results of seismic risk of the building BCN2 (Table 18 and Figure 10), the annual frequencies of exceedance of the damage grade 4, is a value between 7.44×10^{-6} and 2.72×10^{-5}, with a mean value of 1.08×10^{-5}. In this case, only in the lower curve the annual frequency of exceedance of the damage grade 4 is lower than 1×10^{-5}. Therefore, conforming to the previous results the building BCN2 has a level of seismic risk higher than the building BCN1 because the BCN2 has greater values of frequencies of exceedances of the damage grade 4, than the building BCN1.

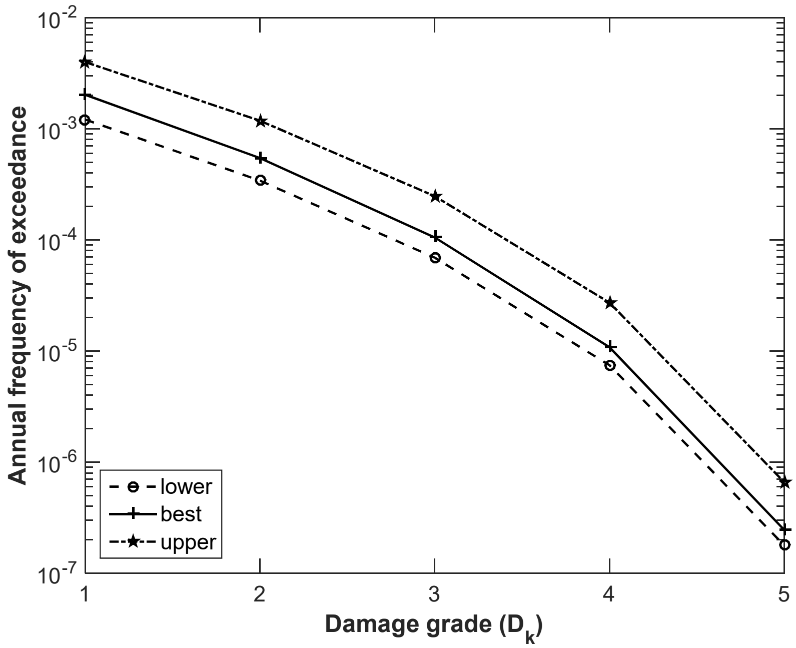


Figure 10. Seismic risk curves of building BCN2, which were computed considering the seismic vulnerability curves of Figure 7b, and the seismic hazard curve of (Figure 3) but truncated to 475 years.

Table 18. Results of seismic risk of building BCN2 expressed in terms of annual frequencies of exceedance of damage states.

Seismic vulnerability curves of building BCN2	**ν (D≥1)**	**ν (D≥2)**	**ν (D≥3) [1/year]**	**ν (D≥4)**	**ν (D=5)**
Lower	1.21E-3	3.41E-4	6.91E-5	7.44E-6	1.78E-7
Best	2.02E-3	5.44E-4	1.05E-4	1.08E-5	2.45E-7
Upper	3.98E-3	1.18E-3	2.47E-4	2.72E-5	6.60E-7

3.3.2 Seismic risk in the VIM_P for a group of buildings

To represent the seismic risk of a group of buildings, it is possible to compute an arithmetic mean considering the frequencies of exceedance for each damage state, of each building that is part of the group. For instance, Figure 11 shows the annual frequencies of exceedance of damage states of the best curve of seismic risk of the group consisting of buildings BCN1 and BCN2 (Table 19). This last curve was obtained applying the procedure described previously, with the data summarized in Table 19.

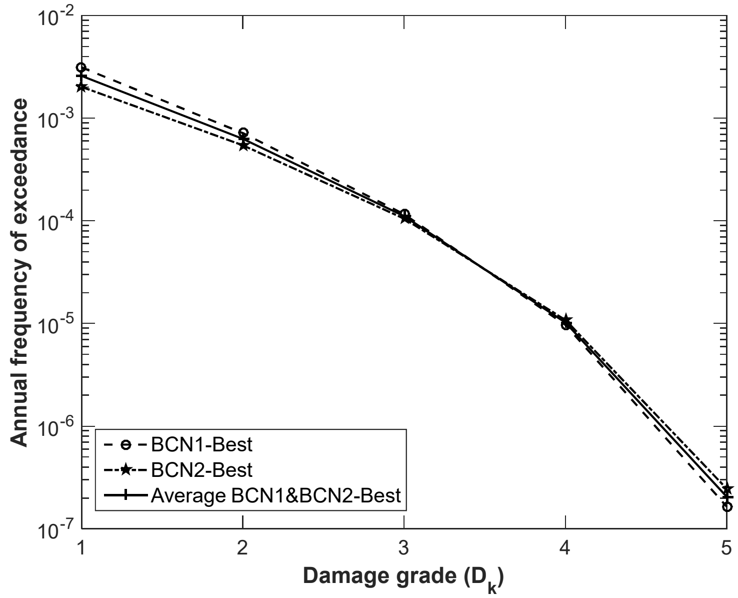


Figure 11. Best seismic risk curves of buildings BCN1 and BCN2 and of the group consisting of buildings BCN1 and BCN2 (Table 19).

Table 19. Results of seismic risk expressed in terms of annual frequencies of exceedance of damage states of the following buildings: a) BCN1; b) BCN2 and; c) group consisting of buildings BCN1 and BCN2.

Best curves of seismic risk	**ν [D≥D1]**	**ν [D≥D2]**	**ν [D≥D3] [1/year]**	**ν [D≥D4]**	**ν [D=D5]**
BCN1	3.13E-3	7.15E-4	1.16E-4	9.68E-6	1.64E-7
BCN2	2.02E-3	5.44E-4	1.05E-4	1.08E-5	2.45E-7
Arithmetic mean BCN1 & BCN2	2.58E-3	6.30E-4	1.11E-4	1.02E-5	2.05E-7

3.3.3 Seismic risk computed with more than one seismic hazard curve

The VIM_P is a versatile methodology that allows computing seismic risk considering three seismic hazard curves, for instance, the mean curve, the 16th percentile curve, and the 84th percentile curve. Then, for the case of Barcelona could be considered the seismic hazard curves of Figure 12, which were adapted from the work of Secanell et al (2004).

Nowadays, there are important discussions about the pertinence of representing the seismic hazard only with a single curve, or through several seismic curves (Marzocchi et al, 2015). For this reason, both options are available in the VIM_P. If it is considered three seismic hazard curves as in Figure 12, then nine curves of seismic risk are computed. For instance, Figure 13 shows the seismic risk curves of building BCN1 that we computed with the seismic hazard curves of Figure 12 and the seismic vulnerability curves of Figure 7a. Similarly, we used the seismic hazard curves of Figure 12 and the seismic vulnerability curves of Figure 7b to compute the seismic risk curves of Figure 14, that correspond to the building BCN2.

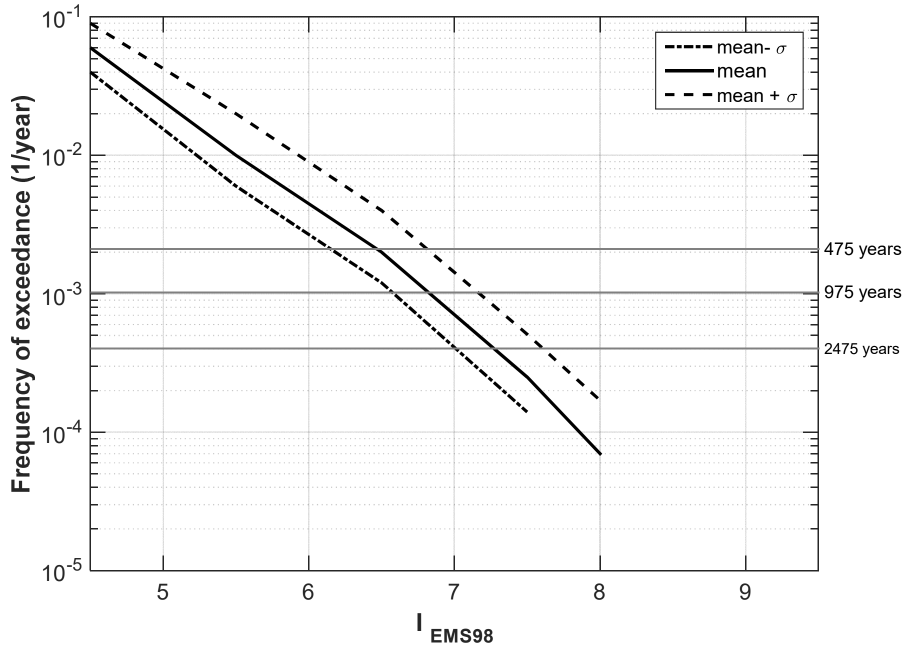


Figure 12.Seismic hazard curves of Barcelona city (adapted from Secanell et al, 2004) in terms of macroseismic intensities.

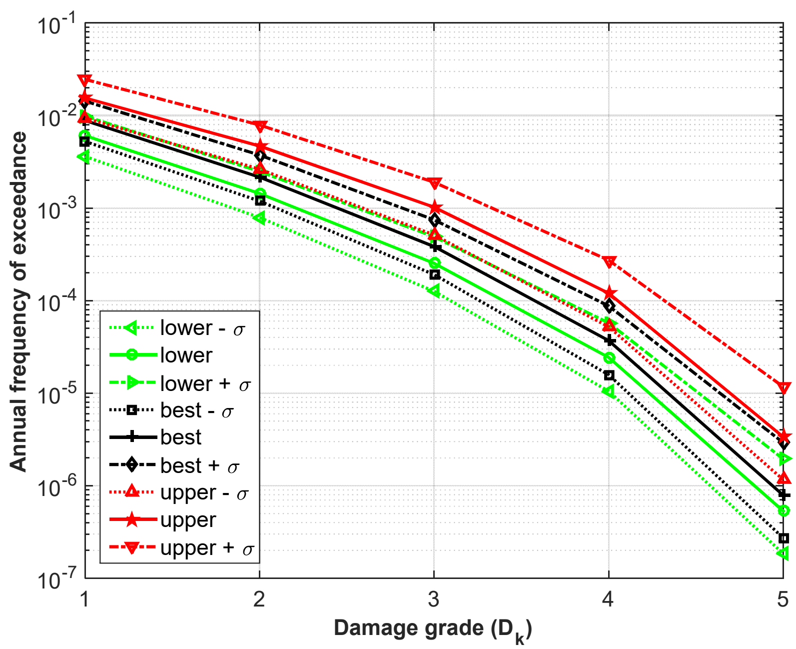


Figure 13. Seismic risk curves of building BCN1, which were computed considering the seismic vulnerability represented by curves of Figure 7a and considering the seismic hazard represented in Figure 12, but truncated to 475 years.

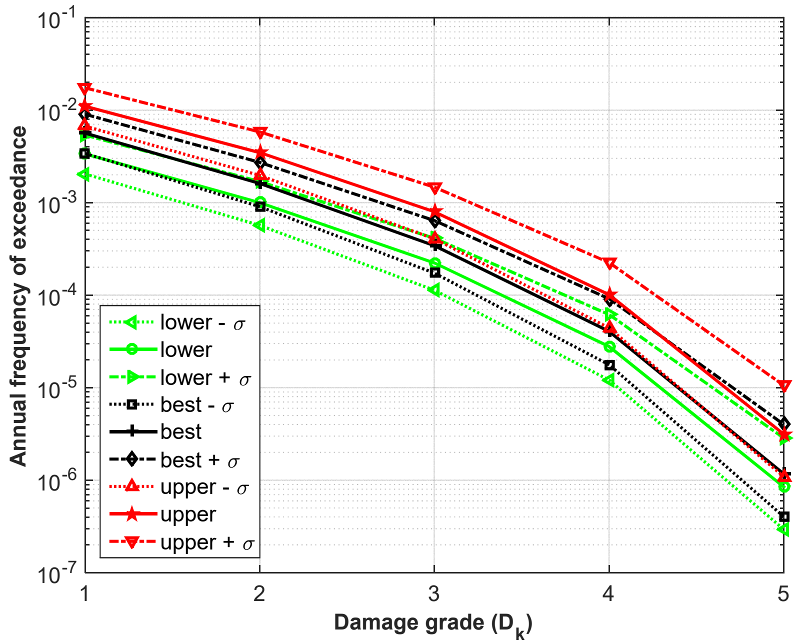


Figure 14. Seismic risk curves for building BCN2 that were computed considering the seismic vulnerability represented by curves of Figure 7b and considering the seismic hazard represented in Figure 12, but truncated to 475 years.

4 Application of the VIM_P method to assess the seismic risk of dwelling buildings of Barcelona

In the present section, we mentioned seismic risk results of Barcelona that were computed in previous works. Subsequently, we described the main steps that we applied to compute according to the VIM_P the seismic risk of 69982 dwelling buildings located in the ten districts of the city of Barcelona (Figure 15). Additionally, we highlighted the main results obtained during the application of the VIM_P to assess the seismic risk of the dwelling buildings of Barcelona.

4.1 Previous results of the seismic risk of Barcelona

The seismic risk of Barcelona has been assessed several times in the last years. These assessments have been done applying different methodologies (Barbat et al, 2010). For instance, seismic risk scenarios were computed applying the two methodologies (the VIM and the capacity spectrum) of the Risk-UE project (Lantada et al, 2010; Lantada et al 2009b; Mouroux and Le Brun, 2006). Recently, the seismic risk of Barcelona was assessed according to the CAPRA methodology (Marulanda et al, 2013). Particularly, Table 20 shows a summary of the main results of seismic risk of Barcelona that were computed by Lantada and collaborators (2010) when the VIM was applied to Barcelona. Additionally, Table 21 shows the average damage grade computed in the same work for each district (Figure 15) of Barcelona (Lantada et al, 2010).

Table 20. Main results of seismic risk of Barcelona according to the VIM (Lantada et al, 2010)

Seismic hazard	**Deterministic seismic scenario:** "The maximum intensity for a mean soil expected in the city of Barcelona varies from VII degrees to the north of the city to VI degrees in the southern area" (Lantada et al, 2010). **Probabilistic seismic scenario:** VI-VII for a return period of 500 years (Secanell et al, 2004)
Seismic vulnera-bility	**Masonry buildings:** Vulnerability index: 0.7-1.00 (mean value of 0.87) **Reinforced concrete buildings:** Vulnerability index: 0.40-0.85 (mean value of 0.65)
Seismic risk	**Deterministic seismic scenario:** Damage grade equal to 1.65 **Probabilistic seismic scenario:** Damage grade equal to 1.59 **Economic losses due to structural damage:** 10,000 million of euros

According to the results of seismic risk that were computed by Lantada and collaborators (2010), it is possible to identify that the district with the highest level of seismic risk is Ciutat Vella. This classification as the district with the higher seismic risk was obtained in two cases: i) when the deterministic hazard scenario was considered and ii) when the probabilistic hazard scenario was chosen. However, the district with the lowest seismic risk is Les Corts if the determinist seismic hazard scenario is considered. But if the probabilistic seismic hazard scenario is chosen, then the district with the lowest seismic risk is Horta-Guinardo. In the next section of this document, we describe the main data, the essential steps and the most important results of seismic risk of the dwelling buildings of Barcelona that we obtained during the application of the VIM_P.

Table 21. Average damage grade for the districts of Barcelona according to Lantada et al (2010)

No.	District	Seismic risk results considering a deterministic seismic hazard scenario	Seismic risk results considering a probabilistic seismic hazard scenario
1	Ciutat Vella	2.43	2.45
2	Eixample	2.00	2.03
3	Sants-Montjuïc	1.33	1.73
4	Les Corts	1.20	1.34
5	Sarrià-Sant Gervasi	1.37	1.37
6	Gràcia	1.61	1.61
7	Horta-Guinardó	1.31	1.16
8	Nou Barris	1.67	1.27
9	Sant Andreu	1.76	1.39
10	Sant Martí	1.73	1.70

Figure 15. Districts of Barcelona

4.2 Data of buildings of Barcelona

The database about buildings of Barcelona that we used in the present work is the result of more than 10 years of work of different institutions of Barcelona (Aguilar, 2011). Figure 16 shows a summary of the data available for the buildings of Barcelona. In the present work, we computed the seismic risk of 69982 buildings, because for these buildings we knew at least the data about their structural typology and their oldness.

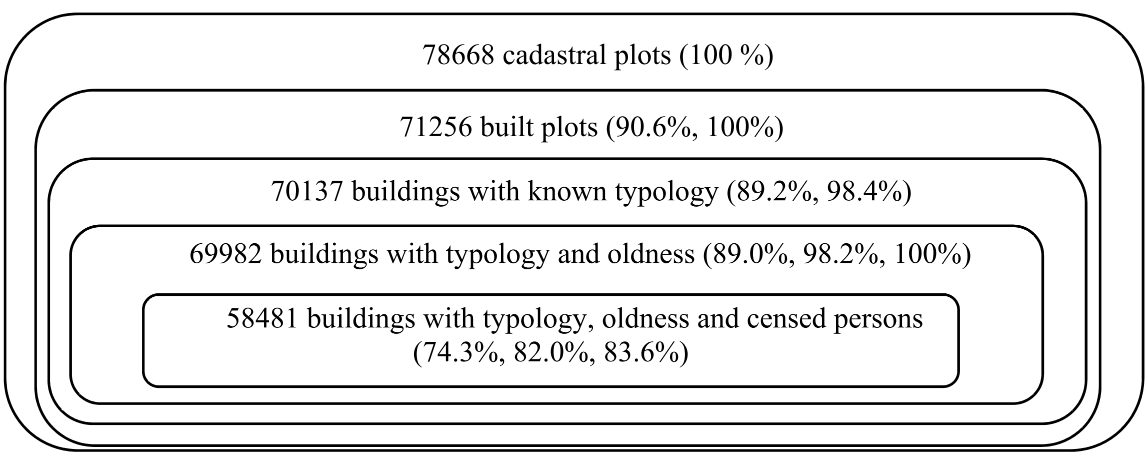


Figure 16. Summary of the database about the dwelling buildings of Barcelona that has been elaborated by *Ayuntamiento de Barcelona* and research group of the UPC from 1990 (Aguilar, 2011).

4.3 Probabilistic seismic hazard assessment of Barcelona

We perform a PSHA of Barcelona applying CRISIS2015 (Ordaz et al, 2015; Aguilar et al, 2017) directly in terms of macroseismic intensities. For this purpose, we considered the seismic sources of Figure 17 (Aguilar et al, 2013). Additionally, we use the Eq. 25 to model the occurrence of earthquakes in each seismic source.

$$\lambda(I)=\alpha\frac{e^{-\beta(I-I_{\min})}-e^{-\beta(I_{\max}-I_{\min})}}{1-e^{-\beta(I_{\max}-I_{\min})}} \tag{25}$$

where $\lambda(I)$ is the annual frequency of exceedance of the macroseismic intensity I, I_{min} is the minimum epicentral intensity considered, I_{max} is the maximum epicentral intensity possible in each seismic source, α is the annual frequency of exceedance of intensities greater or equal to I_{min}, and β is the slope associated to the Guttenberg-Richter relation (Goula *et al*, 1997; Ordaz *et al*, 2015). We used in the present work the main seismic parameters of each seismic source that are shown in Table 22. These parameters have been also used in recent studies about the seismic hazard of Barcelona and other regions of Catalonia (Irizarry et al, 2010; Secanell et al, 2004; Irizarry, 2004).

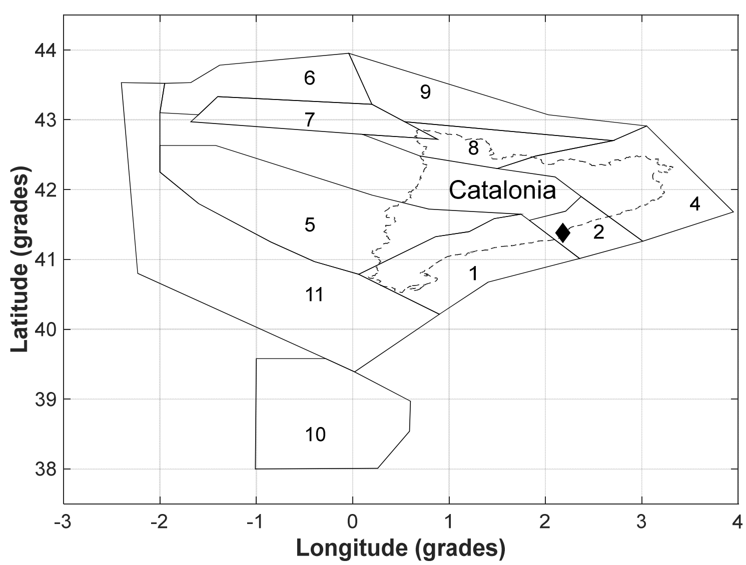


Figure 17. Geometry of seismic sources considered to estimate the seismic hazard of Barcelona (diamond symbol).

As a part of the PSHA, we applied two attenuation relationships proposed by López-Casado et al (2000). These attenuation relationships were mainly determined with catalogs of maps of isosist of the Iberian Peninsula. For this last reason, we considered valid its use in the assessment of the seismic hazard of Barcelona. These two attenuation relationships are represented by the general Eq. 26 and the values of Table 23. According to the specification of López Casado et al (2000), only the attenuation relationship for low attenuation must be applied to the seismic source that represents the seismicity in the Pirineus (Table 24). Therefore, we applied the relationship for high attenuation for the rest of the seismic sources (Table 24).

$$I = f\left(I_{epic}\right) - a_2 \ln \Delta - a_3 \Delta \qquad 26$$

where I is the macroseismic intensity to a focal distance Δ, $\Delta = \left(R^2 + R_0^2\right)^{1/2}$ where R is equal to the epicentral distance in km, and R_0 a value used to improve the fitting and means focal depth in km (Table 23); I_{epic} is the epicentral macroseismic intensity MSK; $f(I_{epic})$ is the value according to the Table 23; a_2 and a_3 are coefficients with the values shown in Table 23.

According to the seismic hazard curve of Barcelona (Figure 18) that we computed applying CRISIS2015, the macroseismic intensity that has a return period of 475 years corresponds to a value of VI. The total seismic hazard curve of Figure 18 is equal to the seismic hazard curve that was computed by Aguilar et al (2013) using CRISIS2012. On the other hand, according to the same seismic hazard results that are shown in Figure 18, it is possible to affirm, that the seismic source number 2 gives the most important contribution to the seismic hazard of Barcelona. At the same time, the seismic hazard results that we obtained in the present work have important coincidences with the results that were obtained in previous studies. For instance, Secanell et al (2004) obtained a mean value of 6.5 (VI-VII) for the macroseismic intensity corresponding to a return period of 475 years. A similar value was estimated by Goula et al (1997).

Table 22. Seismic parameters of the seismic sources, whose geometry is shown in Figure 17 (Secanell et al, 2004).

Seismic source	**α**	**β**	***Cv* (*β*)***	**I_{min}***	**$E(I_{max})$**	**Uncertainty interval of I_{max}**
1	0.100	1.864	0.3	V	VII	1
2	0.128	1.608	0.202	V	VIII	1
4	0.157	1.256	0.148	V	IX	1
5	0.040	1.319	0.283	V	VIII	1
6	0.099	1.977	0.324	V	VI	1
7	0.957	1.420	0.082	V	VIII	2
8	0.218	1.716	0.143	V	VIII	1
9	0.070	1.737	0.123	V	VII	1
10	0.635	1.201	0.069	V	X	1
11	0.060	0.886	0.273	V	VIII	1

* I_{min} is the minimum macroseismic intensity assigned to the seismic source; $Cv(\beta)$ is the variation coefficient of β; $E(I_{max})$ is the expected value of the maximum macroseismic intensity that in this case was considered equal to the I_{max} observed.

Table 23. Values of the two attenuations relationships that were applied to perform the PSHA for Barcelona and that were determined by López Casado et al (2000), for the Iberian Peninsula in terms of macroseismic intensities.

Attenuation relationship	$f(I_{epic})$	a_2	a_3	R_0	σ
1) For high attenuation (AR-HA)	$6.016+0.090\cdot I_{epic}+0.069\cdot I_{epic}^2$	1.477	0.01035	4	0.46
2) For low attenuation (AR-LA)	$5.557+0.902\cdot I_{epic}+0.014\cdot I_{epic}^2$	1.762	0.00207	2	0.59

σ is the standard deviation of the macroseismic intensity *I*.

Table 24. Attenuation relationships assigned to each seismic source

Seismic source	Attenuation relationships assigned
1,2,4,5,6, 8,9,10	AR-HA (López Casado et al, 2000)
7	AR-LA (López Casado et al, 2000)

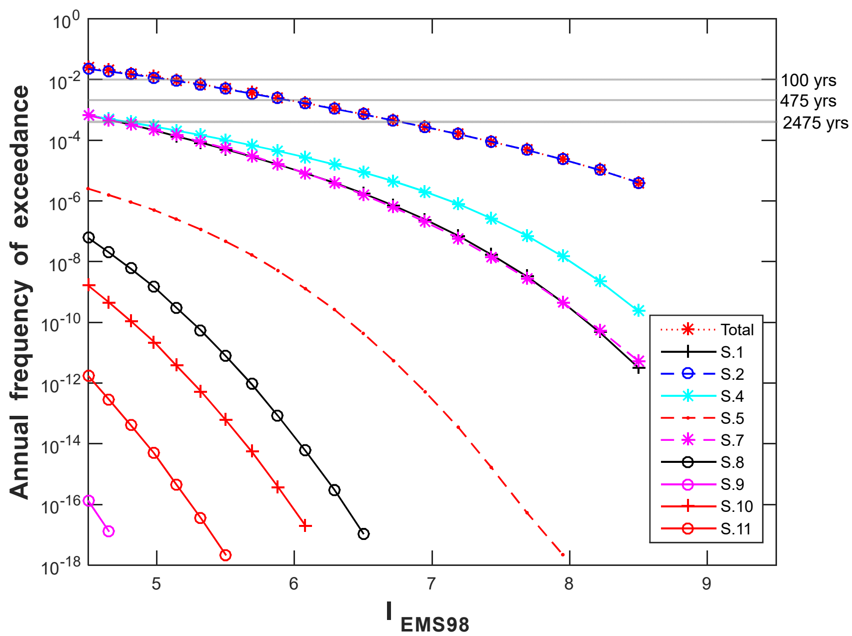


Figure 18. Seismic hazard curves at bedrock site of Barcelona in terms of annual frequency of exceedance versus macroseismic intensities (EMS-98). Total seismic hazard curve and single seismic hazard curves (S) for the 9 sources that contribute in major proportion to the total seismic hazard of Barcelona

4.4 Seismic vulnerability of the dwelling buildings of Barcelona according to the VIM_P

We applied the software USERISK2015 to compute the seismic vulnerability of dwelling buildings of Barcelona. Particularly, we use USERISK2015 to compute three seismic vulnerability curves for each one of the 69982 dwelling buildings of Barcelona. These results give us information about the seismic vulnerability of the studied buildings that can be used to compute seismic risk. On the other hand, these seismic vulnerability results allow doing a wide analysis of the seismic vulnerability of the dwelling buildings of Barcelona. For this purpose, we can use these vulnerability curves to generate representative seismic vulnerability for groups of buildings. For instance, Table 25 shows the values of α and β that define the three seismic vulnerability curves (Figure 19) that represent the seismic vulnerability of the 69982 dwelling buildings of Barcelona. We determined these last curves according to the procedure described in section 3 of this paper. According to these results of seismic vulnerability, the dwelling buildings of Barcelona have, on average, a probability between 42.71% and 70.78% with a mean value of 56.86% of that their vulnerability index is greater than 0.8 (Table 26). Similarly, the dwelling buildings of Barcelona have, on average, a probability between 6.21% and 22.61% with a mean value of 10.40% that their vulnerability index is greater than 1.0 (Table 26).

Table 25. Values that according to the VIM_P define the three curves that represent the seismic vulnerability of the dwelling buildings (69982) of Barcelona (adapted from Aguilar et al, in press)

Seismic vulnerability curve V_a=-0.04; V_b=1.04	***α***	***β***	***Mean***	***Standard deviation***
lower	2.76	1.18	0.72	0.22
best	3.73	1.10	0.79	0.19
upper	3.75	0.76	0.86	0.17

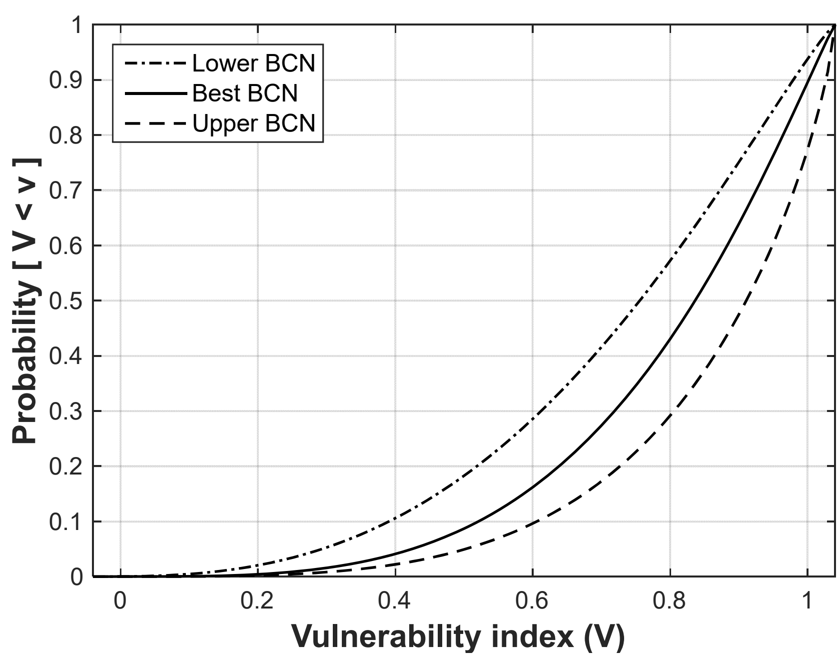


Figure 19. Representative curves of the seismic vulnerability of the 69982 dwelling buildings of Barcelona (Table 25) (Adapted from Aguilar et al, in press)

Table 26. Probabilities that the vulnerability index V is greater than 0.8, according to the curves of seismic vulnerability that represent the average vulnerability of 69982 dwelling buildings of Barcelona.

	lower	**best**	**upper**
P(V>0.8)	42.71%	56.86%	70.78%
P(V>1.0)	6.21%	10.40%	22.61%

Additionally, we computed the values of α and β (Table 27) that define the representative curves of best vulnerability (Figure 20) for each district of Barcelona. According to these curves, the district with the higher seismic vulnerability is Ciutat Vela and the district with the lower seismic vulnerability is Nou Barris (Figure 20). Particularly, according to the three seismic vulnerability curves of the dwelling buildings of the Eixample district (Table 27), these buildings have a probability between 21.05% and 38.67% with and mean value of 28.28% that their vulnerability index is greater than 1.0 (Table 28, Figure 21). Meanwhile, according to the three seismic vulnerability curves of the dwelling buildings of the Nou Barris District (Table 27) the buildings in this district have a probability between 1.32% and 11.15% with a mean value of 3.34% that their vulnerability index is a value greater than 1.0 (Table 29, Figure 22). Therefore, it is possible to conclude that, on average, the buildings in the Eixample district are significantly more seismically vulnerable than the buildings of the Nou Barris district. The seismic vulnerability results computed by USERISK2015 can be also used to generate maps as the ones shown in Figure 23.

Table 27. Values that define the representative curves of vulnerability of the dwelling buildings of each district of Barcelona (V_a=-0.04; V_b=1.04) (Adapted from Aguilar et al, in press)

		Low vulnerability curve				**Best vulnerability curve**				**High vulnerability curve**			
	District	α_L	β_L	$\overline{V_{I\_L}}$	σ_L	α_m	β_m	$\overline{V_I}$	$\sigma_{\overline{V}}$	α_U	β_U	$\overline{V_{I\_U}}$	σ_U
1	Ciutat Vella	3.85	0.63	0.89	0.16	5.62	0.64	0.93	0.12	5.65	0.49	0.95	0.11
2	Eixample	2.69	0.69	0.82	0.21	3.92	0.67	0.88	0.16	4.10	0.53	0.92	0.14
3	Sants-Montjuïc	2.70	1.04	0.74	0.22	3.84	1.01	0.82	0.18	3.83	0.68	0.88	0.16
4	Les Corts	2.12	1.26	0.64	0.25	2.78	1.12	0.73	0.22	2.89	0.75	0.82	0.20
5	Sarrià-S. G.	2.55	1.37	0.66	0.23	3.43	1.28	0.75	0.20	3.42	0.86	0.82	0.19
6	Gràcia	2.91	1.13	0.74	0.22	4.07	1.09	0.81	0.18	3.99	0.72	0.87	0.16
7	Horta-G.	2.94	1.79	0.63	0.22	3.67	1.60	0.71	0.20	3.65	1.08	0.79	0.19
8	Nou Barris	2.81	1.77	0.62	0.22	3.40	1.52	0.71	0.21	3.47	1.04	0.79	0.19
9	Sant Andreu	2.79	1.60	0.65	0.22	3.61	1.46	0.73	0.20	3.61	0.98	0.81	0.19
10	Sant Martí	2.30	1.04	0.70	0.24	3.19	0.98	0.79	0.20	3.15	0.63	0.86	0.18

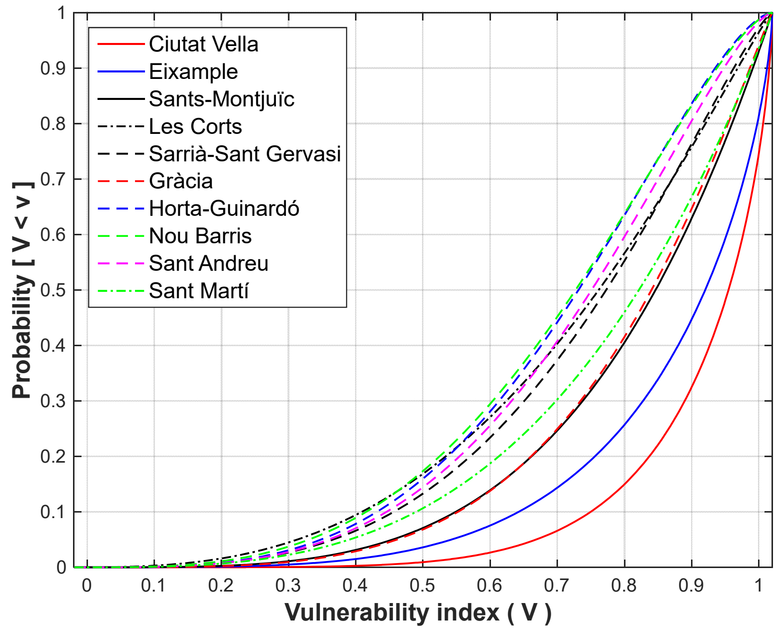


Figure 20. Representative curves of the best seismic vulnerability of the dwelling buildings of the 10 districts of Barcelona.

Table 28. Probabilities that the vulnerability index V is greater than 0.8, according to the curves of seismic vulnerability that represent the average vulnerability of 8723 dwelling buildings of Eixample district of Barcelona.

	lower	**best**	**upper**
P(V>0.8)	63.51%	75.82%	82.49%
P(V>1.0)	21.05%	28.28%	38.67%

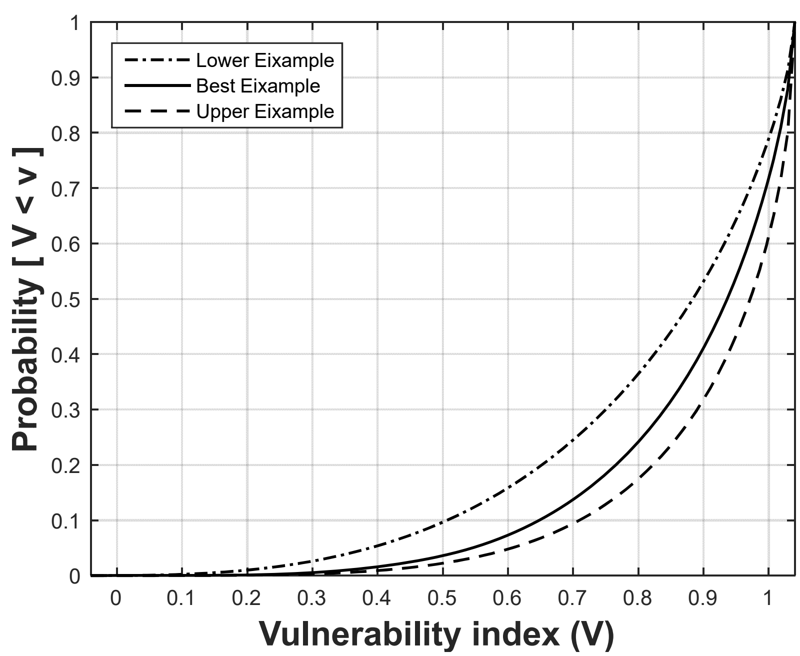


Figure 21. Representative curves of the seismic vulnerability of 8723 dwelling buildings of the Eixample district of Barcelona.

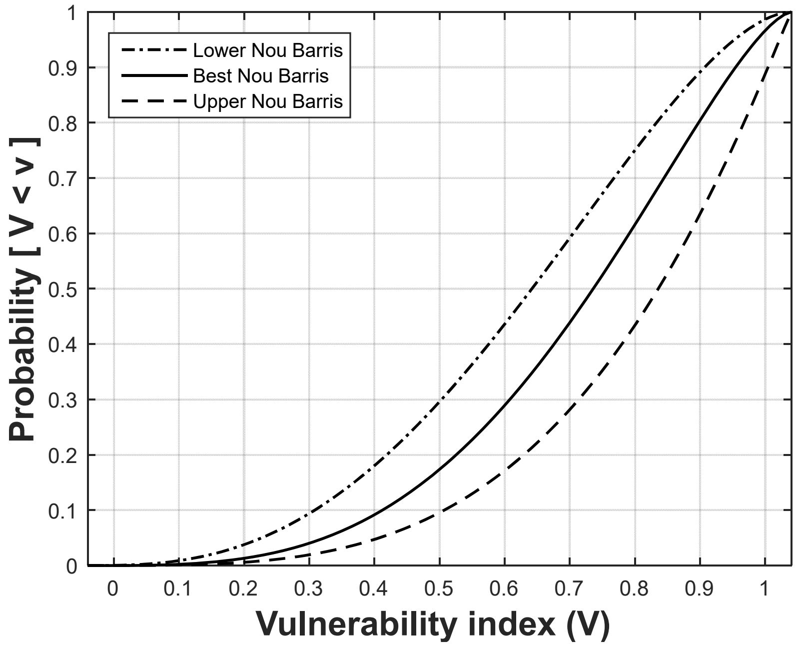


Figure 22. Representative curves of the seismic vulnerability of 6912 dwelling buildings of the Nou Barris district of Barcelona.

Table 29. Probabilities that the vulnerability index *V* is greater than 0.8, according to the curves of seismic vulnerability that represent the average vulnerability of 8723 dwelling buildings of Nou Barris district of Barcelona.

	lower	**best**	**upper**
P(*V*>0.8)	24.93%	38.36%	56.53%
P(*V*>1.0)	1.32%	3.34%	11.15%

The maps in Figure 23 allow identifying geographically the distribution of the seismic vulnerability of the Eixample district of Barcelona to a ground plot scale. It is also possible to observe in those maps (Figure 23) that in the district Eixample of Barcelona, there are dwelling buildings that have a probability lower than 20% of that their vulnerability index is greater than 0.8. But at the same time, there are buildings that have a probability greater than 80% that their vulnerability index is greater than 0.8. Particularly, in the Eixample district of Barcelona, the percentage of dwelling buildings that have a vulnerability index greater than 0.8 varies from 48.78% to 65.17%, with a mean value of 58.33%, according to the lower, best and upper curves, respectively.

Figure 23. Probability that the vulnerability index V is greater than 0.8 for the dwelling buildings of the Eixample district of Barcelona, according to the lower, best and upper vulnerability curves.

4.5 Seismic risk of the dwelling buildings of Barcelona

We applied the code USERISK2015 to assess according to the VIM_P, the seismic risk of the dwelling buildings of Barcelona. Particularly, we computed three seismic risk curves for each one of the 69982 dwelling buildings of Barcelona. We also use these individual seismic risk curves to compute representative curves of risk for the following groups: a) all the dwelling buildings (Figure 24, Table 30), and, b) for each group consisting of the dwelling buildings of each district of Barcelona (Figure 25, Table 31). As a reference value, it is possible to remember that according to McGuire (2004) dangers with an annual probability lower than $1x10^{-5}$ usually are ignored.

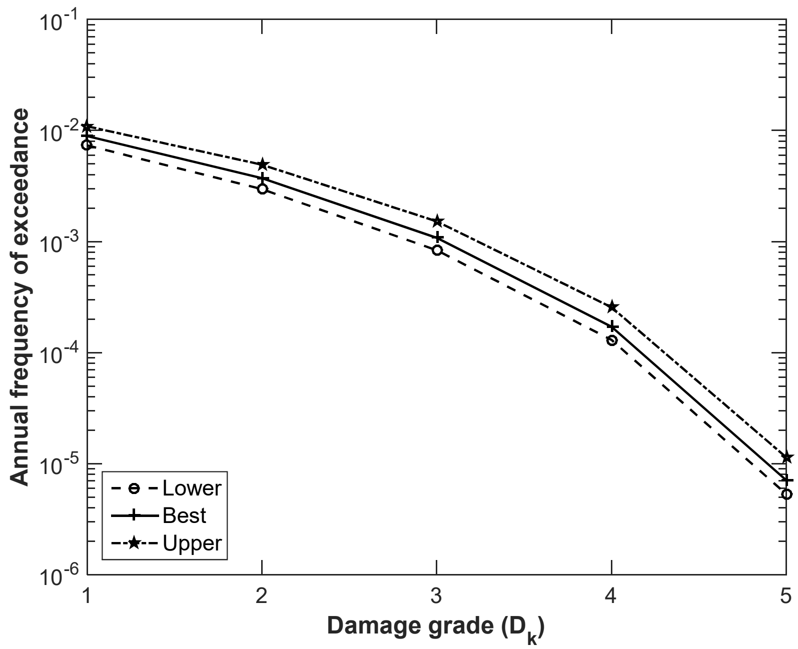


Figure 24. Average seismic risk curves of the dwelling buildings of Barcelona (Case 1).

According to the seismic risk results of the dwelling buildings of Barcelona, on average, the annual frequency of exceedance of the damage 5 (total collapse) are values lower than $1x10^{-5}$, because they range between $5.24x10^{-6}$ and $9.87x10^{-6}$ with a mean value of $6.72x10^{-6}$ (Table 30). Similarly, according to the seismic risk results of the dwelling buildings of each district of Barcelona, Ciutat Vella and Eixample are the districts with the highest levels of seismic risk and these levels exceed the value of $1x10^{-5}$ for the three cases of seismic risk: lower, best and upper. On the other hand, Horta-Guinardó and Nou Barris are the districts with the lower levels of seismic risk, and these levels are in average lower than $1x10^{-5}$ (Table 31).

Table 30. Annual frequencies of exceedance of damage state of the dwelling buildings of Barcelona (Case 1).

Seismic risk curve	**ν (D≥D1)**	**ν (D≥D2)**	**ν (D≥D3)**	**ν (D≥D4)**	**ν (D=D5)**
			[1/years]		
Low	7.05E-03	2.83E-03	8.01E-04	1.26E-04	5.24E-06
Best.	8.47E-03	3.50E-03	1.01E-03	1.61E-04	6.72E-06
High	1.02E-02	4.48E-03	1.35E-03	2.25E-04	9.87E-06

*Value lower than 1.00E-05

The seismic risk results that we computed applying USERISK2015 allows generating seismic risk maps as the maps of Figure 28 and Figure 29. These maps show the geographic distribution of the seismic risk of the Eixample district to a ground plot scale. According to the maps of Figure 28, the values of the annual frequency of exceedance of damage 4 in the dwelling buildings of the Eixample districts range between 0 and $5x10^{-4}$. Meanwhile, according to the maps of Figure 29 the values of the annual frequency of exceedance of damage 5 in the dwelling buildings of the Eixample district range from 0 to $2.3x10^{-5}$.

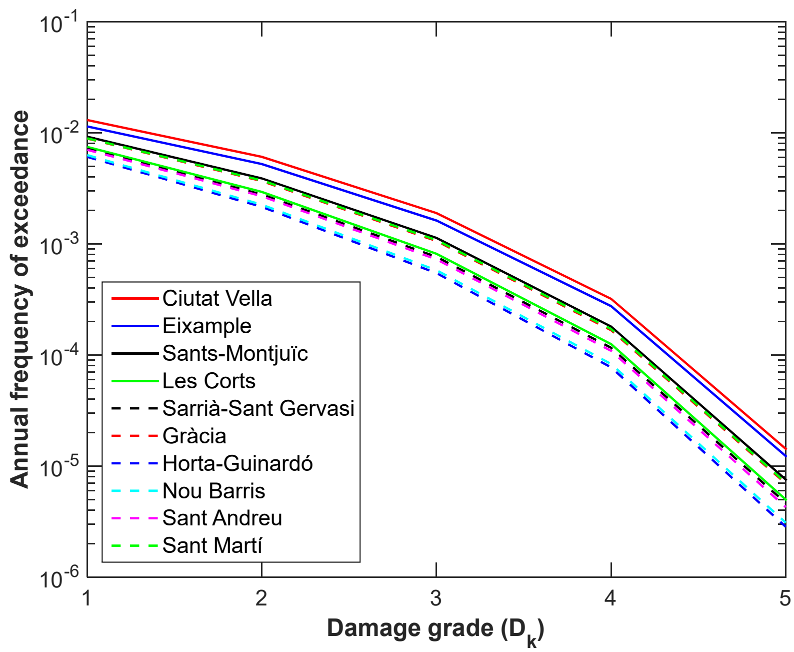


Figure 25.Average seismic risk curves (best) of dwelling buildings of the districts of Barcelona.

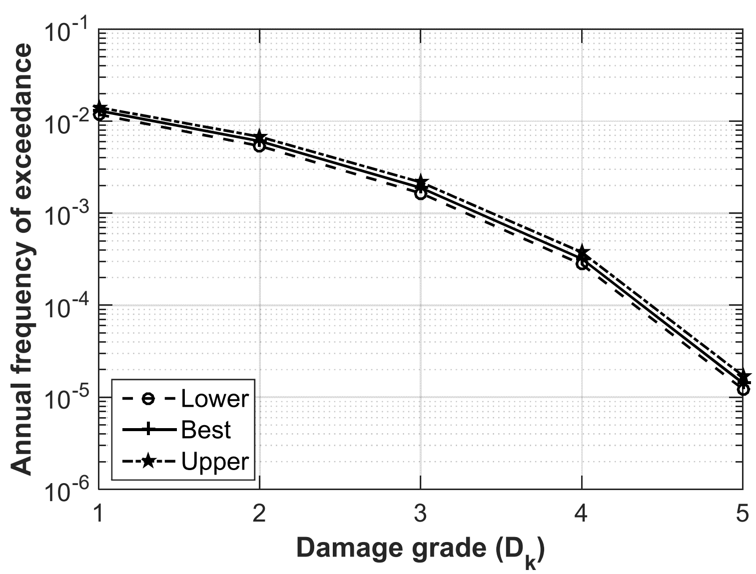


Figure 26. Average values of the annual frequencies of exceedance of the damage grades of the dwelling buildings of the Eixample District.

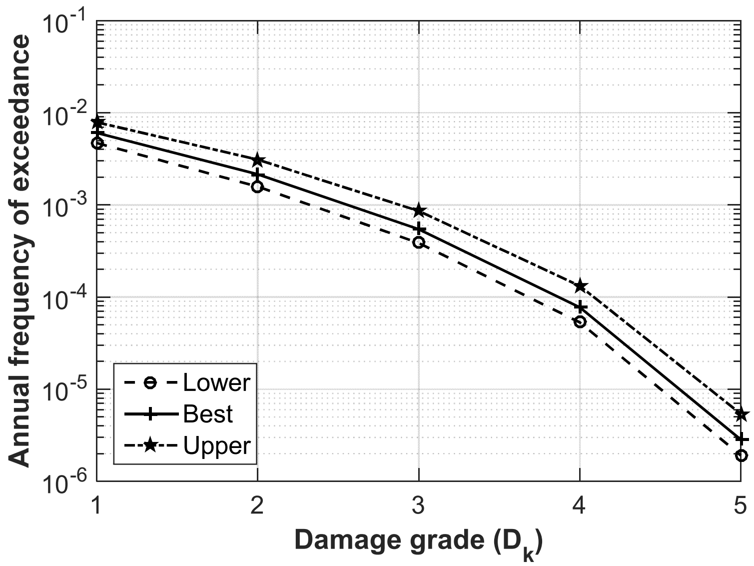


Figure 27. Average values of the annual frequencies of exceedance of the damage grades of the dwelling buildings of the Nou Barris District.

The seismic risk results related to the damage state 4 are relevant because in this damage state partial collapse can occur. Therefore, according to the seismic risk maps of Figure 28, the seismic risk of the dwelling buildings of the Eixample district must not be ignored. On the other hand, the percentage of dwelling buildings of the Eixample district that have a frequency of occurrence of the damage 5 greater than 1x10-5 varies from 52.68% to 70.07% with a mean value of 56.55%, if the lower, upper and best results are considered, respectively. Therefore, according to these results, the seismic risk of the dwelling building of Barcelona cannot be ignored.

The seismic risk results that we computed in the present work were also used to determine economic losses. For this last assessment and for comparative purposes we consider that the value of the total dwelling buildings of Barcelona (69982) corresponds to the 31522.8 million of euros considered by Marulanda et al (2013). Additionally, to obtain the losses curve that it is shown in Figure 30 we considered: a) the damage factors that were proposed by Dolce et al in 2006 (Table 32) and; b) the results of seismic risk in terms of frequencies of exceedance of damage grades, that we computed in the present work. These seismic risk results were assessed for two cases: considering regional modifiers of the vulnerability and without considering regional modifiers of the vulnerability.

Table 31. Annual frequencies of exceedance of damage state of the dwelling buildings by district of Barcelona

	District		ν (D≥D1)	ν (D≥D2)	ν (D≥D3) [1/years]	ν (D≥D4)	ν (D=D5)
1	Ciutat Vella	Low	1.18E-02	5.37E-03	1.65E-03	2.78E-04	1.23E-05
		Best	1.30E-02	6.06E-03	1.89E-03	3.20E-04	1.43E-05
		Upper	1.41E-02	6.77E-03	2.17E-03	3.76E-04	1.72E-05
2	Eixample	Low	9.92E-03	4.45E-03	1.36E-03	2.29E-04	1.02E-05
		Best	1.14E-02	5.22E-03	1.62E-03	2.75E-04	1.23E-05
		Upper	1.26E-02	5.93E-03	1.87E-03	3.22E-04	1.46E-05
3	Sants-Montjuïc	Low	7.81E-03	3.19E-03	9.13E-04	1.44E-04	5.99E-06
		Best	9.22E-03	3.88E-03	1.13E-03	1.80E-04	7.55E-06
		Upper	1.09E-02	4.91E-03	1.50E-03	2.51E-04	1.11E-05
4	Les Corts	Low	5.83E-03	2.17E-03	5.79E-04	8.59E-05	3.33E-06
		Best	7.45E-03	2.93E-03	8.13E-04	1.25E-04	4.99E-06
		Upper	9.56E-03	4.12E-03	1.23E-03	2.02E-04	8.78E-06
5	Sarrià-Sant Gervasi	Low	5.78E-03	2.17E-03	5.81E-04	8.71E-05	3.43E-06
		Best	7.15E-03	2.78E-03	7.64E-04	1.16E-04	4.65E-06
		Upper	8.95E-03	3.77E-03	1.10E-03	1.79E-04	7.67E-06
6	Gràcia	Low	7.47E-03	3.01E-03	8.51E-04	1.33E-04	5.50E-06
		Best	8.86E-03	3.67E-03	1.06E-03	1.67E-04	6.95E-06
		Upper	1.06E-02	4.68E-03	1.42E-03	2.36E-04	1.04E-05
7	Horta-Guinardó	Low	4.70E-03	1.58E-03	3.86E-04	5.31E-05	1.91E-06
		Best	6.06E-03	2.15E-03	5.45E-04	7.73E-05	2.84E-06
		Upper	7.90E-03	3.10E-03	8.59E-04	1.32E-04	5.40E-06
8	Nou Barris	Low	4.76E-03	1.59E-03	3.89E-04	5.35E-05	1.92E-06
		Best	6.28E-03	2.25E-03	5.78E-04	8.29E-05	3.09E-06
		Upper	8.29E-03	3.31E-03	9.34E-04	1.47E-04	6.08E-06
9	Sant Andreu	Low	5.57E-03	2.03E-03	5.34E-04	7.85E-05	3.01E-06
		Best	7.02E-03	2.68E-03	7.25E-04	1.09E-04	4.27E-06
		Upper	8.92E-03	3.75E-03	1.10E-03	1.79E-04	7.74E-06
10	Sant Martí	Low	7.34E-03	2.96E-03	8.35E-04	1.30E-04	5.32E-06
		Best	8.90E-03	3.72E-03	1.08E-03	1.71E-04	7.09E-06
		Upper	1.09E-02	4.92E-03	1.52E-03	2.56E-04	1.14E-05

Figure 30 shows the economic losses computed by Marulanda et al (2013) for Barcelona and the economic losses that we computed in the present work. It is possible to observe the important agreement of the best curve without regional modifiers, and the curve of Marulanda et al (2013), especially, for return periods lower or equal to 500 years. On the other hand, the economic losses computed in the present work can be considered as reasonable values if they are also compared with the 10,000 million of euros that Lantada et al (2010) computed for a seismic scenario with a return period of 475 years (Table 20).

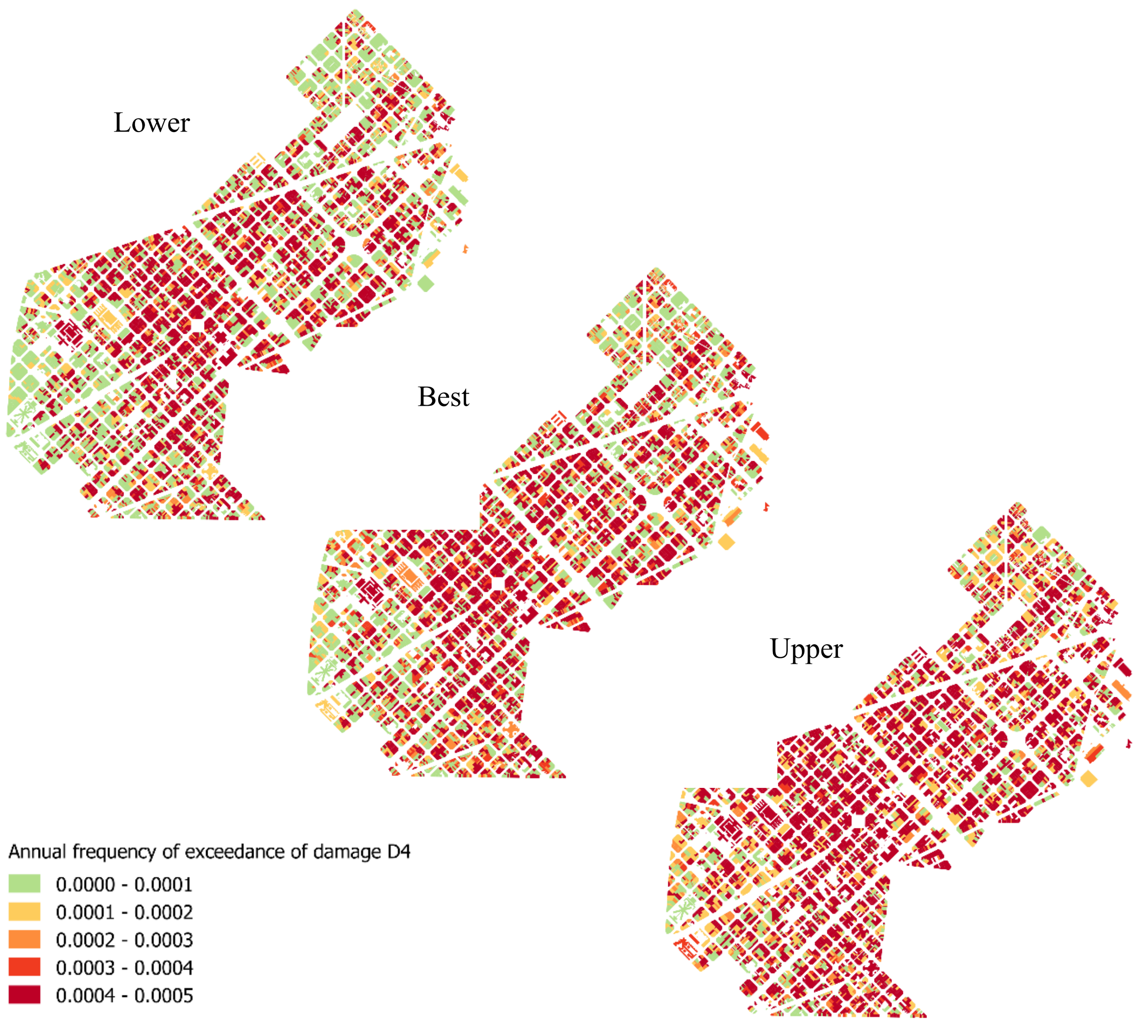


Figure 28. Seismic risk maps of the Eixample District of Barcelona, which were generated considering 5 ranges of values of the occurrence rate of the damage state 4 and the three seismic risk results for this damage state (lower, best and upper).

Figure 29. Seismic risk maps of the Eixample District of Barcelona, which were generated considering 5 ranges of values of the occurrence rate of the damage state 5 and the three seismic risk results for this damage state (lower, best and upper).

Table 32. Damage factor proposed by Dolce et al (2006)

Damage state	Damage factor
1	0.035
2	0.145
3	0.305
4	0.800
5	1.000

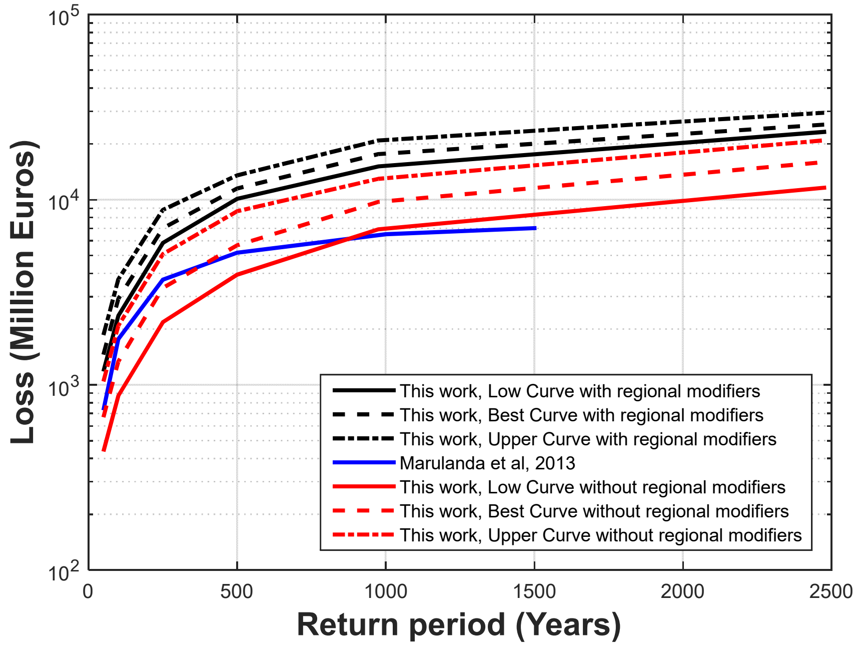


Figure 30. Curves of seismic losses for the dwelling buildings of Barcelona.

5 Conclusions

The methods VIM and VIM_P allow obtaining reasonable results of seismic risk of buildings in urban areas. The results of both methods are complementary results. At the same time, it is possible to highlight that the VIM_P is very helpful to model the important uncertainty related to the assessment of the seismic vulnerability of the buildings. This last characteristic is an important difference of the VIM_P respect to the VIM method. The seismic risk results that can be computed by the VIM method can be considered in a big proportion as deterministic results, otherwise, the seismic risk results computed by VIM_P can be considered with a high content of probabilistic base. Therefore, we can conclude that the seismic risk results of both methods are complementary results.

The VIM_P is a robust methodology to determine the seismic vulnerability and the seismic risk of buildings in urban zones. The VIM_P is based on a probabilistic approach, which allows considering uncertainty in the three following basic elements: a) the seismic hazard; b) the seismic vulnerability and; c) the seismic risk. Particularly, the VIM_P requires a seismic hazard curve that must be computed according to a PSHA. This curve will be used to compute seismic risk. Additionally, in the VIM_P the seismic vulnerability of each building is represented by a probability density function beta type, which describes the probable variation of the vulnerability index, that represents the seismic vulnerability of buildings. At the same time, according to the VIM_P, the seismic risk is expressed in terms of frequencies of exceedance of damage states. The VIM_P can be considered as a versatile methodology because it is also possible to generate probability density functions that represent the seismic vulnerability of a group of buildings, for instance, it is possible to generate a single curve that represents the best seismic vulnerability of a group of buildings located in the same district of a city. For this purpose, procedures were specified in the VIM_P. On the other hand, the representation of the seismic vulnerability of buildings through *pdf* contributes to highlight that there is an important uncertainty in the determination of this seismic vulnerability and therefore the uncertainty in the seismic risk results it is also important. Therefore, the VIM_P contributes to do appropriate interpretations of the results of seismic vulnerability and seismic risk computed through this method. The VIM_P can be appropriately implemented with the support of software CRISIS2015 and USERISK2015, to assess seismic hazard, seismic vulnerability and seismic risk of buildings in urban areas.

About the semi-empirical seismic damage function that is used in the VIM_P, it is important to highlight that it is convenient to improve the present semi-empirical damage function to incorporate more probabilistic elements in the assessment of the seismic damage. For this purpose, we recommended considering previous works as the Vargas and colleagues work of 2013.

In the case of the seismic hazard of Barcelona, it is possible to mention that the results of the present work agree with results determined in previous works. However, it is important also to highlight that the major proportion of the total seismic hazard in Barcelona is due to the seismic source 2, where Barcelona is included. Therefore, according to the present work, the major ground motion in Barcelona could due to an earthquake that could occur in the seismic source number 2 (Figure 17).

The results computed in the present work according to the VIM_P show that Ciutat Vela is the district of Barcelona whose buildings have in average the major levels of seismic vulnerability in the city. Similarly, Horta-Guinardó and Nou Barris are the districts with the lowest levels of seismic vulnerability. Additionally, according to the results of seismic risk, Ciutat Vella is the district that has, on average, the buildings with the highest levels of seismic risk in the city. Similarly, Horta-Guinardó is the district that has, on average, the buildings with the lowest levels of seismic risk in Barcelona. These results agree with the values of seismic risk that were determined by Lantada et al (2010), considering a probabilistic seismic hazard scenario (Table 21).

According to the results of seismic risk in Table 30, on average, the annual frequency of occurrence of the damage 5 in the dwelling buildings of Barcelona is a value lower than $1x10^{-5}$. On the other hand, according to the results of seismic risk of table Table 31, on average, in the dwelling buildings of the Eixample and Ciutat Vella, the annual frequency of occurrence of the damage state 5 are higher than $1x10^{-5}$. Similarly, on average, in the dwelling buildings of the Les Corts, Sarría-Sant Gervasi, Horta-Guninardó, Nou Barris and Sant Andreú, the annual frequency of occurrence of the damage state 5 are values lower than $1x10^{-5}$ (Table 31).

On the other side, according to the individual seismic risk results of each building of the Eixample district that were used to generate the maps of Figure 29, the 52.68% of the total dwelling buildings of the Eixample district have a frequency of occurrence of the damage 5, greater than $1x10^{-5}$ if the lower seismic risk results are considered. Therefore, to take decisions, we recommend the use of the results of seismic vulnerability and seismic risk in the different scales available, for instance: city, districts and single buildings.

To assess economic losses, we considered two cases: seismic risk results computed considering regional modifiers and seismic risk results without considering regional modifiers. The significant difference between the results of both cases highlights the importance of the election of the values of the regional vulnerability modifiers to be considered in each project.

In relation to the economic losses computed in the present work for Barcelona, it is possible to affirm that are reasonable results, because they are in general slightly higher than the economic losses computed by Marulanda et al (2013) and they are similar to the losses computed by Lantada et al (2010). Therefore, it is possible to affirm that the VIM_P is a valid method to assess seismic risk of buildings in urban areas in terms of economic losses. At the same time, the difference between the loses computed considering regional modifiers of the vulnerability and the losses computed without considering regional modifiers of the vulnerability, suggest the important to execute sensitivity analysis about the regional modifiers of the vulnerability that must be considered in each project.

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Appendix 1. Case of criteria II to determine the seismic vulnerability curves

A) Curve of best seismic vulnerability.

Determination of the curve of the best seismic vulnerability
Step 1. Computation of mean vulnerability index.

The mean vulnerability index, $\overline{V_I}$, it is determined according to the same procedure described for Criteria I. Then, for the example of buildings BCN1 and BCN2, the values of $\overline{V_I}$ for these buildings are 0.67 and 0.42, respectively (Table 9).

Step 2. Determination of values of V_c and V_d

According to the criteria II, it is considered that V_I^{min} and V_I^{max} (Table 4) are references values to determine V_c and V_d, for each building. In this case, the values of V_c and V_d will be estimated for each building using equations (27) and (28), respectively. According to this criterion the values of V_c and V_d that define the confidence interval of 90%, can be different for each building, even for buildings that are part of the same structural typology.

$$V_c = V_I^{\min} + \Delta V_R + \Delta V_m \tag{27}$$

$$V_d = V_I^{\max} + \Delta V_R + \Delta V_m \tag{28}$$

If the criteria II is selected, then the pair of values (V_c, V_d) computed for buildings BCN1 and BCN2 will be (0.426, 0.986), and (-0.042, 0.918), respectively.

Step 3. Determination of values of V_a and V_b

According to criteria II in order to determine the values of V_a and V_b it is possible to assess the values of V_c and V_d of all the buildings, and then to choose a value of V_a and a value of V_b according to Eq.29, and Eq. 30, respectively.

$$V_a \leq \min\left[\min\left(V_c\right) - 0.02, -0.04\right] \quad 29$$

where min(V_c) is the minimum value of V_c between all the values of V_c of all the studied buildings.

$$V_b \geq \max\left[\max\left(V_d\right) + 0.02, 1.04\right] \quad 30$$

where max(V_d) is the maximum value of V_d between all the values of V_d of all the studied buildings.

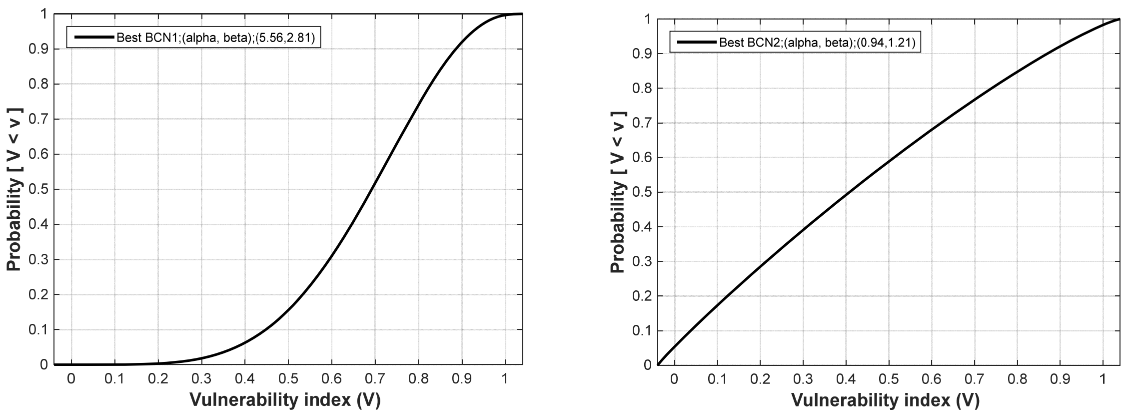
For instance, if buildings BCN1 and BCN2 are the total buildings of a study, then, it will be possible to observe that the minimum value of V_c from both buildings is -0.042, if the criteria II is selected. Similarly, the maximum value of V_d of both buildings is 0.986 according to the same criteria. Therefore, applying the Eq. 16 and 17, the values of V_a and V_b are equal to -0.062 and 1.04, respectively.

Step 4. Determination of values of α_m and β_m

This step is the same than in the case of the procedure described for Criteria I, but using the values of of V_a , V_b , V_c and V_d that were determined according to the previous steps. Therefore, if this criterion is considered then it is possible to obtain the seismic vulnerability curves defined by the values of Table 33 and the curves that are shown in Figure 31.

Table 33. Results of seismic vulnerability of buildings BCN1 and BCN2. Values of α_m and β_m that define the best seismic vulnerability curve for each building according to the criteria II available to assess values of V_c and V_d

	Criterion II V_a = -0.062; V_b = 1.04			
Building	α_m	β_m	***Mean***	***Standard deviation***
BCN1	5.56	2.81	0.67	0.17
BCN2	0.94	1.21	0.42	0.31



(a) (b)

Figure 31. Results of seismic vulnerability of buildings BCN1 and BCN2. Cumulative density function (CDF) beta type, which represent the best curve of the seismic vulnerability of buildings BCN1 (a) and BCN2 (b), respectively. These seismic vulnerability curves were computed considering the criteria II, and the values of V_a and V_b are equal to -0.062 and 1.04, respectively.

B) Curves of lower and upper seismic vulnerability.

To determine these seismic vulnerability curves, it is necessary to do the following considerations:

- The mean values V_I for each seismic vulnerability curves are determined according to the same equations applied for the criteria I (Eq. 21 and Eq. 22).

- For the assessment of the lower seismic vulnerability curve, the value of V_c or V_{c_L} is determined according to Eq. 31, and the value of V_d or V_{d_L} is determined substituting V_I^{min} by V_I^{max} in Eq. 31. Similarly, the value of V_c or V_{c_U} for the upper seismic vulnerability curve is determined according to Eq.32 and the value of V_d or V_{d_U} is determined substituting V_I^{min} by V_I^{max} in Eq. 32.

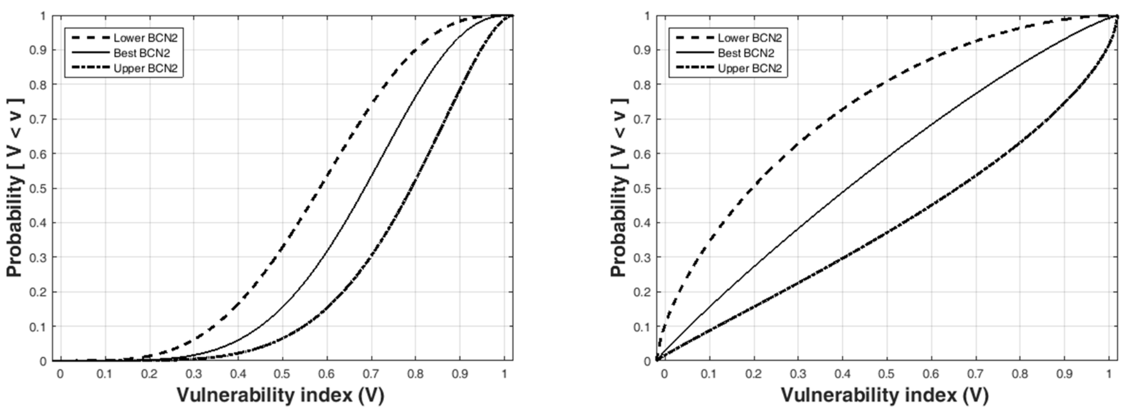
$$V_{c\_L} = \left(V_I^{\min} - \frac{I_f - f}{I_f} \cdot \phi \cdot \sigma_{\overline{V}} \right) + \Delta V_R + \Delta V_m \quad 31$$

$$V_{c\_U} = \left(V_I^{\min} + \frac{I_f - f}{I_f} \cdot \phi \cdot \sigma_{\overline{V}} \right) + \Delta V_R + \Delta V_m \quad 32$$

Finally, with these previous values, it is applied the same procedure than for the best vulnerability curve to determine the values of α and β that define the lower and upper curves.

Table 34. Results of seismic vulnerability of buildings BCN1 and BCN2. Values of α_m and β_m that define the lower and upper seismic vulnerability curves for each building according to the criteria II available to assess values of V_c and V_d

		Criterion II V_a = -0.062; V_b = 1.04			
Building		α_m	β_m	***Mean***	***Standard deviation***
BCN1	(lower)	4.59	3.41	0.57	0.18
	(upper)	5.58	1.81	0.77	0.16
BCN2	(lower)	0.68	1.81	0.24	0.26
	(upper)	0.92	0.61	0.60	0.34



(a) (b)

Figure 32. Results of seismic vulnerability of buildings BCN1 and BCN2. Cumulative density functions (CDF) beta type, which represent the three curves of the seismic vulnerability of buildings BCN1 (a) and BCN2 (b), respectively. These seismic vulnerability curves were computed considering the criteria II, and the values of V_a and V_b are equal to -0.062 and 1.04, respectively.