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A PROBABILISTIC MODEL FOR THE SEISMIC RISK OF BUILDINGS. APPLICATION TO ASSESS THE SEISMIC RISK OF BUILDINGS IN URBAN AREAS

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ABSTRACT

A probabilistic model to estimate the seismic risk of buildings is evaluated. For this purpose a specific methodology is proposed. The developed methodology allows explicitly consider important uncertainties that are present in the main elements, that are used to estimate the seismic risk of buildings. One of these elements is the seismic vulnerability of each building, which is mainly represented in the proposed methodology through probability density functions that describe the variation of a vulnerability index. In the developed methodology, the seismic vulnerability is considered as a property that is changing through the time. Therefore, it is possible to estimate seismic vulnerability curves for different stages on the future life of a building. The methodology was used to estimate the seismic risk of 59,905 buildings of Barcelona. According to the results, in average, 53,152 buildings have a probability lower than 5% of suffer some kind of collapse during the next 50 years. If the government of Barcelona conducts a program to do a seismic rehabilitation of buildings, then the first buildings that could be evaluated for rehabilitation purposes could correspond to the 1,317 buildings, which were identified in this work as the buildings with the highest seismic vulnerability.

Introduction

The significant damage related to the 2008 Sichuan earthquake and the 2010 Haiti earthquake, corroborates the importance of improving the activities related to the mitigation of the seismic risk of buildings. In these earthquakes the damaged buildings were most of the times the buildings that had not been designed, built or retrofitted, according to the existing advanced seismic codes. In spite of the existence of these codes, which describe the procedures to reduce significantly the seismic vulnerability of buildings, there are in the world many buildings that have a high level of seismic vulnerability. Nowadays the number of buildings with a high seismic

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vulnerability is important. Some reasons that explain the existence of buildings with a high seismic vulnerability are: 1) many buildings were designed or built without take into account some seismic code; 2) there are not enough economic resources to retrofit all the buildings that have a high seismic vulnerability; 3) we do not know the level of the seismic vulnerability of many existing buildings; 4) we do not know the size of the seismic risk of many existing buildings. Therefore, the knowledge of the vulnerability and the seismic risk of existing buildings is essential to increase the effectiveness of the activities related to the mitigation of the seismic risk. In this context, a probabilistic approach is considered in order to develop a simplified methodology to estimate the seismic risk of buildings in urban areas.

Probabilistic model

It is widely accepted that there are important epistemic and aleatory uncertainties in the main elements that are used to compute the seismic risk of buildings (McGuire 2004). For this reason, the application of probabilistic models to compute the seismic risk is frequently considered more appropriate than the deterministic ones. In the present model, the seismic vulnerability of a building is defined as a property of the building, which describes the level of the weakness of this building to resist properly the effects triggered by earthquakes. This seismic vulnerability can be also considered as an opposite property to the seismic strength. For instance, a building that has a low seismic vulnerability is at the same time a building that has a high capacity to resist properly, the shaking in the building that is produced during the occurrence of seismic ground motions. The seismic hazard, the seismic vulnerability and the earthquake damage are the three main elements considered in the present model to estimate the seismic risk. The way in that these three elements are taken into account to estimate the seismic risk is summarized in Eq. 1. This equation is used to compute the annual probability that the damage *d* will be exceeded.

$$P[D > d] \approx \iint P[D > d \mid I, V] \gamma'[I] P[V] dV dI \tag{1}$$

where $\gamma'[I]$ is the frequency of occurrence of the seismic intensity, which can be expressed in terms of pseudo-acceleration, macroseismic intensity, etc. $P[V]$ is the probability of occurrence of the seismic vulnerability. P $[D > d \mid I, V]$ is the probability of that the damage *d* will be exceeded given that a seismic intensity *I*, and a seismic vulnerability *V* have occurred. In the Eq. 1 the total probability theorem is applied and the intensity *I* and the vulnerability *V* are considered as independent random variables (Aguilar 2008).

The probabilistic approach to compute seismic risk that is summarized in Eq.1 can be implemented in different kind of methodologies. In this work the mentioned probabilistic approach is considered to develop a methodology to estimate the seismic risk of buildings in urban areas. This methodology has as starting point the vulnerability index method of the Risk-UE project (Giovinazzi 2005; Milutinovic 2003) and also it is a refinement of the proposed method by Aguilar and colleagues (Aguilar 2009). For identification purposes this new methodology is named LM1_P method. The seismic risk computed with the LM1_P method for each building is mainly represented by curves of annual probability of occurrence versus damage states. The main steps of the LM1_P method are: 1) Probabilistic analysis of the seismic vulnerability; 2) Probabilistic seismic hazard assessment (PSHA); 3) Estimation of the seismic risk. In the following sections more details about the LM1_P method are included.

Probabilistic analysis of the seismic vulnerability

The level of the seismic vulnerability of a building depends on many factors. According to the experience, a building with a low seismic vulnerability is generally a building that fulfills the following conditions: 1) it was designed according to advanced seismic codes; 2) it was built or retrofitted using high quality standards; 3) it has respected the conditions of service that were considered during the structural design stage; 4) it has had adequate maintenance programs during its life.

The seismic vulnerability can be divided into two parts: intrinsic seismic vulnerability and extrinsic seismic vulnerability. The intrinsic seismic vulnerability depends mainly on the characteristics of the building and its contents. For instance, the presence of a soft story is a factor that increases the intrinsic seismic vulnerability of a building. On the other hand, the extrinsic seismic vulnerability depends mainly on the possible interaction of the studied building with other buildings, or with other specific external factors. This interaction can mainly happen during the occurrence of an earthquake. For instance, the presence of a neighboring building that can pound to the studied building during the occurrence of an earthquake is an example of a factor, which increases the extrinsic vulnerability.

Data

The quality and the quantity of the data have significant influence in the results of seismic vulnerability. For this reason, the process to obtain the data and the preliminary analysis of this information is considered, as a fundamental step in the LM1_P method. Most of the times the information related to the buildings in a city or urban zone is obtained from different sources, and frequently, this information has different levels of confidence. For this last reason in the LM1_P method, the confidence in the main data related to the buildings is mainly represented trough a confidence factor. This factor is a value between 0 and 10. Values close to cero mean low confidence in the data, and values close to 10 mean high confidence in the data. Examples of the data used to estimate the seismic vulnerability in the LM1_P method are: a) geometric properties of the building (area, perimeter, height, etc); b) main characteristics of the materials of the building; c) age of the building; d) uses of the building; e) structural typology; f) conservation state of the building.

Intrinsic seismic vulnerability

In the LM1_P method, the classification of each studied building into some structural type previously defined is a critical decision. Therefore, this stage requires significant efforts in order to obtain reasonable results about the seismic vulnerability of the studied buildings. Most of the buildings can be classified into some of the existing structural typologies. However, a new structural typology can be proposed if the studied building cannot be easily classified into the existing structural typologies. Table 1 shows some examples of common building typologies that can be used in the LM1_P methodology.

Table 1. Examples of building typologies used in the LM1_P method.

Typology code	Brief description
M3.4.1	Unreinforced masonry bearing walls with reinforced slabs– without or low earthquake resistant design (E.R.D).
S1.2	Steel moment frames – with moderate E.R.D.

The structural type chosen to represent the main structural characteristics of a building has much influence, in the magnitude of the results of seismic risk and in the confidence related to these results. For this reason in the LM1_P method, a confidence factor must be assigned to the datum of the structural typology. Table 2 shows an example of the criteria that can be used to determine the confidence value that can be assigned, to the datum of the structural type.

Table 2. Example of the criteria used to determine the confidence value for the structural typology datum, when this datum has been determined during a field study.

Process used to determine the structural typology	Academic and experience levels of the person that did the survey	Age of the data in years	Confidence value
Rapid field survey	High	5-10	8-9.5
		More than 10	7-8.5
	Moderate	5-10	7-8.5
		More than 10	6-7.5

In the LM1_P methodology, it is considered that the seismic vulnerability of a building can be mainly represented, by probability density functions that describe the probable variation of a vulnerability index V_I. When only the intrinsic seismic vulnerability is considered, then the possible values of V_I are only values between 0 and 1. In order to estimate the pdf's it is necessary to estimate the mean index $\overline{V_I}$ of the intrinsic seismic vulnerability according to Eq. 2.

$$\overline{V_I} = \left(F_R.V_T\right) + \sum Vm_j \quad ;0 < \overline{V_I} < 1 \tag{2}$$

where V_T is the most probable value of the vulnerability index V_I , if only the datum of the structural typology of the studied building is considered (Table 3); F_R is a regional factor that modifies to the V_T; *Vm* are modifiers of the seismic vulnerability.

Table 3. Examples of structural typologies with its corresponding representative values of the intrinsic seismic vulnerability, which is expressed in terms of a vulnerability index (Giovinazzi 2005 and Milutinovic 2003).

Typology	Representative values of the vulnerability*				
	V^{min}	V^{-}	V_T	V^{+}	V^{max}
M3.4.1	0.30	0.50	0.62	0.80	0.86
S1.2	0.06	0.16	0.30	0.54	0.76

* V^{-} and V^{+} delimit the range of probable values of the vulnerability index for the corresponding typology. V^{min} and V^{max} delimit the range of less probable values of the vulnerability index for the corresponding typology.

In Eq. 2 the factor F_R allows considering regional characteristics of the buildings that belong to the same structural typology. For instance, this factor allows taking into account, the differences between the buildings that have been classified into the same typology, but that are located in different cities or countries. Vm_j is the sum of j-esim modifiers of the intrinsic vulnerability and it is calculated using Eq. 3.

$$\sum Vm_j = \sum^{NVm_{DV}} (Vm < 0) + \left(\sum^{NVm_{IV}} (Vm > 0) \right) F_V \tag{3}$$

where NVm_{IV} is the number of modifiers that increase the intrinsic seismic vulnerability of the studied building. These modifiers are values greater than cero. NVm_{DV} is the number of modifiers that decrease the intrinsic seismic vulnerability of the studied building. These modifiers are values lower than cero. F_V is a factor that considers that the increment of the seismic vulnerability, due to the addition of diverse modifiers is an increment that does not have a lineal behavior. In other words, this factor allows considering, for instance, that the adverse effect that produce the simultaneous presence of a soft story and a bad preservation state, will be greater than the sum of the effects that each one of this adverse effects can produce in isolated form. In the Table 4 are shown examples of the expressions that are used to estimate the value of F_V.

Table 4. Example of the expressions used to compute the factor that amplifies the effect of the intrinsic vulnerability, in function of the number of modifiers that increase the vulnerability.

NVm_{IV}	F_V
1	1
2-5	$1+0.01\,e\left(\dfrac{NVm_{IV}}{2}\right)$

The vulnerability modifiers Vm allow distinguishing if the studied building is more or less vulnerable, than the average of the buildings that belong to the same structural typology. Examples of the scores related to a vulnerability modifier are shown in Table 5.

Table 5. Scores related to the state of preservation in masonry buildings.

Intrinsic vulnerability modifier	**Score**		
State of preservation in masonry buildings	Pre or low ERD*	Moderate ERD	High ERD
Good	-0.04	-0.03	-0.02
Regular	0	0	0
Bad	0.04	0.04	0.04
Ruinous	0.06	0.06	0.06

*Earthquake Resistant Design (ERD)

For each studied building, the most probable range, of values of the vulnerability index, is estimated. In order to estimate this range, three main elements are considered: 1) The probable range of values of the vulnerability index delimited by the values of V^- and V^+ for the structural typology of the studied building (Table 3); 2) The exceptional range of values of the vulnerability delimited by the values of V^{max} and V^{min} for the structural typology of the studied building (Table 3); 3) The quantity and quality of the data available to compute the seismic vulnerability of the studied building. The quality of the data considered is mainly estimated through the confidence values assigned to each one of the main data, used to compute the mean vulnerability index ($\overline{V_I}$).

The mean vulnerability index, the most probable range of values of the vulnerability index, and the uncertainty related to the data used to estimate the mean vulnerability index, are used to obtain probability density functions (pdf's) that represent the variation of the vulnerability index, for each studied building. In the LM1_P method, these pdf's are considered beta type. The general form of a beta pdf that describes the variation of the vulnerability index (V_I) is shown in the Eq. 4.

$$f(V_I;\alpha,\beta,0,1)=\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\left(V_I\right)^{\alpha-1}\left(1-V_I\right)^{\beta-1} \qquad 0\le V_I\le 1 \qquad (4)$$

In the LM1_P method the parameters α and β are obtained for each one of the three probability density functions (lower, mean and upper) that represent the main seismic vulnerability of each studied building. Table 6 shows an example of the α and β values that can define seismic vulnerability curves.

Table 6. Parameters that define the intrinsic vulnerability curves of a specific building.

Intrinsic vulnerability curves	**Parameters of probability density functions beta type that describe the variation of the vulnerability index V_I**	
	α	***β***
Lower	11.48	30.81
Mean	46.07	94.81
Upper	59.66	96.31

Due to the fact that the seismic vulnerability is a property that is changing through the time, in the LM1_P methodology is possible to estimate, the seismic vulnerability of a building related to different dates in its future life. For instance, it is possible to estimate the present seismic vulnerability of a building, and also the seismic vulnerability that this building will have 50 years later.

Seismic hazard

In the LM1_P method, the estimation of the seismic hazard is mainly based on the Cornell-Esteva approach (Esteva 1970). Specifically, in the LM1_P method it is recommend the use of the CRISIS2007 computer code (Ordaz 2007). This software allows obtaining the seismic hazard expressed in terms of exceedance rates of an intensity parameter (pseudo-acceleration, macroseismic intensity, etc).

Seismic risk

In the LM1_P methodology, the seismic risk is estimated using the approach that is summarized in the Eq. 1. Specifically, the LM1_P method allows computing annual probability of occurrence of different damage states (Table 7). For this purpose, the following elements are integrated: 1) the seismic vulnerability curves for each studied building; 2) the seismic hazard for each studied building, which is expressed in terms of exceedance rate of an intensity parameter; 3) the damage function represented by the Eq. 5.

Table 7. Description of the main damage states considered in the LM1_P method.

Damage grade (*k*)		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	

A damage function that can be used in the LM1_P method is the expression proposed by Bernardini and colleagues in 2007 (Eq. 5).

$$\mu_D = \left[2.5 + 3\tanh\left(\frac{I_a + 6.25V_I - 12.7}{3}\right)\right].f\left(V_I, I_a\right) \qquad ; 0 \le \mu_D \le 5 \tag{5}$$

where μ_D is the mean damage grade, I_a is a macroseismic intensity that considers the possible amplification of the soil where the studied building is located, V_I is the seismic vulnerability index, $f\,(V_I, I_a)$ is a function that depends on the vulnerability index V_I and the intensity I_a. The value of this function is determined according to the Eq. 6.

$$f(V_I, I_a) = \begin{cases} e^{\frac{V_I}{2}.(I_a - 7)} & I_a \le 7 \\ 1 & I_a > 7 \end{cases} \tag{6}$$

Application to Barcelona

In order to validate the LM1_P methodology, the seismic risk of 59,905 buildings in Barcelona was estimated. The data used to estimate the seismic risk of those buildings were obtained from different sources; however a fundamental database was proportionate by the City Council of Barcelona with data updated until the 2007 year. An important proportion of the buildings of Barcelona can be classified as unreinforced masonry buildings. Another common typology in Barcelona is the reinforced concrete building.

Seismic vulnerability

According to the results of the seismic vulnerability analysis, in average, there is a 50% of probability that the vulnerability index (V_I) of the 59,905 studied buildings, will be a value greater than v_i. v_i range between 0.68 and 0.90, with a mean value of 0.8 (Fig. 1). In order to estimate quickly the meaning of this level of seismic vulnerability, it is convenient to remember that a value of V_I equal to 0.8 is a value 30% greater than, the most probable value of the vulnerability index related to the buildings that are represented by a M3.4.1 typology (Table 3). Therefore, it is possible to conclude that, in average, the seismic vulnerability of the existing buildings that were studied in Barcelona is high.

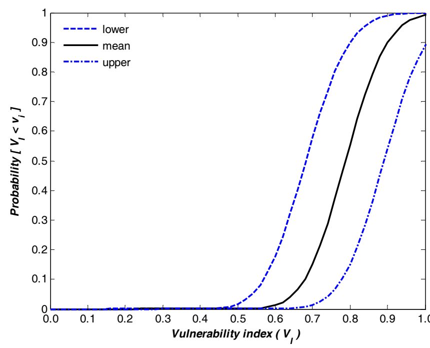

Figure 1. Average curves of the intrinsic seismic vulnerability for the 59,905 studied buildings in Barcelona. v_i is a value between 0 and 1 for the intrinsic vulnerability.

Seismic Hazard

Barcelona is located in a moderate seismic zone (Cid 1999). The seismic hazard used in this work was estimated by Secanell and colleagues in 2004. Fig. 2 shows seismic hazard curves for the city of Barcelona, which were applied in the present work to estimate the seismic risk.

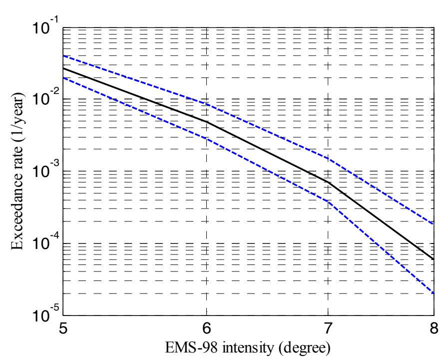

Figure 2. Seismic hazard curves for the city of Barcelona (mean values and one standard deviation) adapted from Secanell, 2004.

In order to appreciate the level of seismic hazard that exists in Barcelona, it is possible identify, for instance, that the intensity of VI will occur, in average, one time every R years. R, evaluated in years, range between 118 and 357, with a mean value of 208 (Fig. 2).

Seismic Risk

According to the results in the 59,905 studied buildings, the moderate damage grade will occur, in average, one time every R years. R, evaluated in years, range between 245 and 653, with a mean value of 369 (Fig. 3). In other words, the probability that the moderate damage grade will occur in the studied buildings in the next 50 years, is a value between 7.37% and 18.5%, with a mean value of 12.7%. According to the results, the number of studied buildings that could suffer total or partial collapse during the next 50 years is a value that range between 466 and 2,847, with a mean value of 1,317. Therefore, in order to guarantee that the buildings in Barcelona are complying with the collapse prevention level (FEMA 1997), it is convenient to do a more detailed estimation of the seismic risk of at least the 1,317 buildings, which were identified in the present study as the buildings with the highest seismic vulnerability.

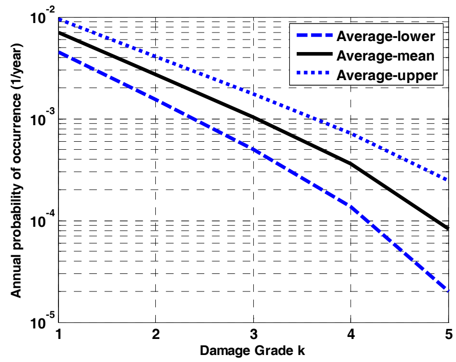

Figure 3. Average curves of the seismic risk of 59,905 buildings in Barcelona.

Conclusions

The LM1_P method based on a probabilistic approach allows obtaining reasonable results of the seismic risk of buildings in urban areas. On the other hand, this methodology allows taking advantage of the heterogeneous information (data in different quantities with diverse qualities), that usually is available to estimate the seismic risk of buildings in urban areas. The proposed methodology also allows representing uncertainty related to the seismic risk results. According to the seismic risk results of the 59,905 buildings located in Barcelona, it is possible to conclude that there is an important quantity of buildings in Barcelona that have a high level of seismic vulnerability. It is important to notice that this last conclusion is in agreement with the results obtained in previous studies (Barbat 2008; Lantada 2008). Therefore, it is convenient to establish a rehabilitation program that considers the detailed analysis of the 1,317 buildings, which were identified in the present work as buildings with a high probability of not satisfy with the collapse prevention level, in the next 50 years.

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