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Methodologies for the evaluation of seismic vulnerability in masonry structures

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ABSTRACT

For the evaluation seismic risk, there are evermore complex and elaborate procedures, the functions of fragility and vulnerability a fundamental tool. In the last 30 years, various methods have been developed for the analysis of seismic vulnerability in masonry structures. In this article, some of the most common empirical and analytical methodologies have been revised and are explained in a concise manner, which will help other investigators in the field to decide which method is the most suitable, depending on the available information in the study that is being carried out.

Keywords: *Vulnerability; Masonry; Seismic engineering; Structural analysis*

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Metodologías para la evaluación de la vulnerabilidad sísmica en estructuras de mampostería

RESUMEN

Para la evaluación del riesgo sísmico existen procedimientos cada vez más complejos y elaborados para su cálculo, siendo una herramienta fundamental las funciones de fragilidad y vulnerabilidad. En los últimos 30 años se han desarrollado varios métodos para el análisis de vulnerabilidad sísmica en estructuras de mampostería. En este artículo se han revisado algunas de las metodologías empíricas y analíticas más comunes y se explican de una manera concisa, lo que ayudara a decidir a otros investigadores del área a elegir cual es el método más adecuado dependiendo de la información disponible en el estudio que se está realizando

Palabras clave: *Vulnerabilidad; Mampostería; Ingenería Sísmica; Análisis estructural*

1.introduction

Human victims and economic losses caused by natural disasters have drastically increased in the last two decades. Among these natural disasters, earthquakes have been the most catastrophic phenomenon, in which more than 750,000 people have lost their life, and the economic losses total more than 787 billion dollars(CRED, 2015)(Wallemacq and Below, 2018). The vast majority of the economic and human losses due to earthquakes are the result of the bad results of man-made constructions (Imjai et al., 2020) (Rodríguez Valenzuela et al., 2020). In this context, accurate studies into the evaluation of vulnerabilities provide an essential tool in understanding both the geographical distribution of seismic risk and the development and implementation of risk mitigation strategies (for example, through the adjustment of structures considered to be excessively vulnerable)(Martins and Silva, 2018).

In the great variety of methodologies regarding risk evaluation, to the damage or loss for a determined building classification (Silva et al., 2014)(Yamin et al., 2017) is its drawback. Generally two different focuses are employed: fragility and vulnerability functions. The fragility functions express the probability of exceeding a damage state, for a predetermined value of the intensity measures (IM), generally represented by the PGA or the spectral displacements (Chieffo et al., 2019).

The damage states are normally defined in qualitative and descriptive terms (Park, Ang and Ween, 1987) (for example S: slight, M: moderate, E: extensive, C: collapse). The formulation of the fragility functions requires the consideration of N different damage states, for a structural system. Thus, the probability of reaching or exceeding the ith damage state given a danger intensity is normally estimated through a normal logarithmic probability distribution function with different parameters for each damage state.

The vulnerability functions provide all the necessary information to calculate the probability of reaching or surpassing a loss value, given the selected intensity of the ground motion (Borzi, Crowley and Pinho, 2008). The formulation of vulnerability functions requires the definition of the loss as a random variable. In this case, the vulnerability function describes the variation of the statistical moments of loss (average and variance) for different values of threat intensity. Loss is defined using numeric scales in place of qualitative scales as for the damage states (for example, the relationship between the cost of repairs and the value of replacing the component, also known as the Mean Damage Ratio (MDR), which allows its direct use in probabilistic risk and loss calculations. Generally, it is supposed that a Beta probability distribution function for the loss calculation is used (Yamin et al., 2017). It is possible to obtain the vulnerability function through the formulation of fragility of any given component once an expected loss value is assigned to each damage state (Silva et al., 2014).

2. Vulnerability methods: empirical and analytical

For the development of fragility and vulnerability functions, we will focus on the following methods: empirical and analytical (Figure 1). Empirical methods are based on the results of laboratory tests or the compiled information of earthquake damage evaluation reports (Yamin *et al.*, 2017). They can have some disadvantages, such as the subjectivity of the assignment of a damage state for each building, or a lack of accuracy in the determination of ground motion which affects a region (Kassem, Mohamed Nazri and Noroozinejad Farsangi, 2020). In order to overcome these limits, analytical methods can be employed for a single structure which is believed to represent a class of buildings, or for a combination of buildings generated randomly, modeled through structural analysis techniques and subject to lateral load patterns or specific accelerograms (Silva *et al.*, 2014).

2.1 Empirical Methods

Pioneering empirical methods of the 70's and 80's, as well as some of those from the past 15 years, used for the evaluation of seismic vulnerability of masonry structures are presented by way of summary in Table 1, although only some of those are described hereunder.

2.1.1 Vulnerability Index Methods

In the Italian method (Benedetti, Benzoni and Parisi, 1988), the vulnerability of a building is defined through a vulnerability index (*Iv*), which is obtained through the evaluation and deliberation of different parameters related to structural and non-structural components, which have an important role in the seismic behaviour of the building. Basically, the method consists of the evaluation of 11 parameters through fieldwork. For unreinforced masonry structures, there are categories A, B, C, and D, which go respectively from favourable to unfavourable conditions and their evaluation allows the assignment of numeric value (K_i), which varies from 0 to 45. The weight (W_i) of the parameters varies between 0.25 and 1.0. The vulnerability index is obtained through the equation 1, which is the deliberated sum of the numeric values which express the quality of each one of the eleven parameters. The bigger the vulnerability index, the worse the resistant capacity of the building (Lantada, 2007).

$$Iv = \sum_{i=I}^{11} K_i W_i \qquad \text{Eq. 1}$$

The macroseismic method (Lagomarsino and Giovinazzi, 2006) allows the evaluation of vulnerability for a group of buildings, up to the evaluation of vulnerability of a single building. The vulnerability is measured in terms of an index of vulnerability (V) and an index of ductility (Q), with both evaluations taking into account the typology of the building and their constructive characteristics. This index varies between 0 and 1; the closer to 1, the more vulnerable the building. The danger is described in terms of macroseismic intensity, according to the European Macroseismic Scale EMS-98 (EMS, 1998), which is considered, in the framework of macroseismic focus, as a continuously evaluated parameter regarding the condition of rigid ground; the possible effects of amplification owing to the different conditions of the ground are within the parameter of V. For physical damage to the building, the EMS-98 damage grades are used, describing the observed damage for structural and non-structural components. Five grades of damage (*Dk*) (*k* = 0/5) are identified: D1 light, D2 moderate, D3 heavy, D4 very heavy, D5 destruction, plus the absence of damage, D0 no damage (Bernardini and Lagomarsino, 2008) .

Some current studies carried out in residential buildings allowed the estimation of damages by seismic phenomenon, such as that by (Serrano-Lanzarote and Temes-Córdovez, 2015), who presented a study on the seismic vulnerability in the Valencian Community, Spain, for the assignment of vulnerability to each type of building. They carried it out according to the opinion of experts and contrasted said information through the application of the vulnerability index method. (Pavel *et al.*, 2018) utilised the microseismic method for housing in Bucharest, the capital of Romania. They compared the evaluation of seismic damages and losses using the KOERILoss software, with the results of a previous study based in the Hazard of United State (HAZUS) manual.

The results of the analysis demonstrated that the economic loss and the average damage grade are smaller than those obtained using HAZUS methodology. However, the number of people affected in this study is higher.

The Vulnerability Index Method (VIM) has been simplified in order to evaluate the seismic vulnerability in masonry building facades, like the work carried out by (Ferreira *et al.*, 2017) on the Azores archipelago, Portugal; additionally VIM has been adapted with a total of fourteen parameters by (Vicente *et al.*, 2011) and utilised by (Catulo *et al.*, 2018) for the seismic evaluation of buildings in Pombalino in the city of Lisbon.

2.1.2 Rapid Visual Screening, Rvs

Rapid visual screening is a qualitative evaluation procedure used in the evaluation of the seismic vulnerability of buildings. The procedure can be implemented with relative speed in a large inventory of buildings in order to identify potentially dangerous structures without the high costs of detailed seismic analysis of individual buildings. The RVS method involves a curbside survey which is used in order to compile information on the main parameters which influence the seismic vulnerability of the buildings (FEMA P-155, 2015).

The Federal Emergency Management Agency (FEMA) developed a number of directives for the evaluation and rehabilitation of the seismic risk of buildings. FEMA 310 provides a process of tree levels for the seismic evaluation of existing buildings in any seismic zone. In accordance with FEMA 310, before using the three provided methodologies in the guidelines, a Rapid visual screening of the building should be carried out in order to decide if a seismic evaluation is necessary (FEMA 310, 1998).

The RVS procedure proposed in FEMA 154, utilises a scoring system which requires that the user identify the primary structure resistant to the lateral load and the building's attributes which modify the expected seismic behaviour. The results are recorded in a data collection form according to the seismicity of the region in question. The method assigns a basic structural score based on the structural typology and uses score modifiers in order to consider the effect of the number of floors, the type of ground, the vertical and floor irregularities, and details of the previous or subsequent code to the reference code (FEMA P-155, 2015).

In Egypt, (El-Betar, 2018), with the RVS procedure FEMA P-154, evaluated the seismic vulnerability of school buildings from the 1960's and schools built after the 1990's, designed in accordance with the country's code, and they determined the capacity functions with a pushover analysis, using the IDARC version 6 software. They concluded that buildings from the 60's tend to be more vulnerable under high seismic loads, while those designed in accordance with the code have a large capacity to resist earthquakes. Some authors present other alternatives to the RVS method, such as (Achs and Adam, 2012) in Vienna, Austria, who carried out the seismic evaluation of historic brick masonry buildings, the RVS methodology proposal evaluates the physical and socio-economic vulnerability, which generated result maps for damage scenarios which afford useful information for the planning of emergencies and evacuations, as well as the identification of critical objects vulnerable to seismic loads. In India, (Rajarathnam and Santhakumar, 2015) evaluate the seismic safety of buildings in Chennai using the RVS technique. They used aerial photographs in order to identify irregularities in the buildings with a Geographic Information System (GIS). (Ajay Kumar *et al.*, 2017) propose a new format modified in order to carry out Rapid visual screening (RVS) in the state of Himachal, Pradesh. With the RVS scores, they obtained damage distribution curves for each typology of housing in order to understand the building distribution in the state.

2.2 Analytical Methods

Currently as we can observe in Table 2**,** there exists a great variety of methods which carry out an analytical evaluation. In this article, we focus on the program packet RMTK (Risk Modellers' Toolkit) by OpenQuake, developed by GEM (Global Earthquake Model), in which different cutting-edge methods for deriving solid analytical seismic vulnerability and fragility functions for individual structures or buildings (Figure 2).

2.2.1 Direct Nonlinear Static Procedures

The evaluation studies of the nonlinear structural response has been integrated into three direct nonlinear static procedures: (Ruiz-García and Miranda, 2007), (Vamvatsikos and Cornell, 2005) and (Dolšek and Fajfar, 2004) (Table 3). These are based on the use of capacity functions, resulting from nonlinear static Pushover analysis, in order to directly determine the average seismic intensity values corresponding to the acquisition of a certain threshold of damage state (limit state) and the corresponding dispersion of the seismic intensity value.

These parameters are used to represent a fragility curve as the probability of the limit state capacity (*C*) is exceeded by the demand (*D*), both expressed in terms of intensity levels ($S_{a,ds}$ and S_a respectively), as shown in the equation 2 (Silva *et al.*, 2015):

$$P_{LS}(S_a) = P(C < D \mid S_a) = \Phi\left(\frac{InS_a - In\hat{S}_a, ds}{\beta_{S_a}}\right) \qquad \text{Eq. 2}$$

The implemented methodologies allow the consideration of different shapes of the Pushover curve (multilinear and bilinear), entry to entry dispersion, and dispersion of the thresholds of damage state, in a systematic and coordinated way.

2.2.2 Static Nonlinear Procedures Based On Registries

Static nonlinear procedures described hereafter allow the calculation of the seismic response of various structures (Table 4) (in terms of the maximum displacement of the system equivalent to a single degree of freedom (SDOF)), considering a group of registries of ground movement. The development of these methods involves the numerical analysis of systems with particular dynamic and structural properties (for example, periods of vibration, viscous damping, hysteretic behaviour, among others) and accelerograms selected for specific regions of the world (for example, California, Southern Europe). For these reasons, their applicability to other types of structures and different ground movement registries requires adequate care (Silva *et al.*, 2015).

The main results of each of these methodologies is a Probability Damage Matrix (which is to say, a section of assets by damage state for each ground movement registry, represented by the variable PDM), and the Spectral Displacement (which is to say, the maximum expected displacement of the equivalent SDOF system, represented by the variable Sd) for ground movement registries (Silva *et al.*, 2015).

2.2.3 Nonlinear Time-History Analysis In Oscillators With A Degree Of Freedom

This methodology carries out a series of nonlinear time-history analyses (NLTHA) on one or various systems to a single degree of freedom (SDOF) (Table 5). In order to determine the structural capacity of the systems to multiple degrees of freedom (MDOF) under analysis, it is necessary to identify the relationship between the shear force and the roof displacement (which is to say, the PushOver curve). This curve should later convert into the capacity curve of an equivalent SDOF oscillator.

For buildings of low and medium height, it is typically assumed that the fundamental manner of vibration corresponds to the predominant response of the structure. Under this hypothesis, the SDOF oscillator represents the first response mode of the structure. This is usually valid for building with fundamental periods of vibration of up to approximately 1.0 s. On the contrary, they need to take into account the superior modes (Silva *et al.*, 2015).

In this methodology, the demand is represented by a group of ground movement registries. The response of each structure comes from the solution of the movement equation 3 for an inelastic SDOF under seismic excitement:

$$m\ddot{u}(t)+c\dot{u}(t)+ku(t)=p(t) \qquad \text{Eq. 3}$$

Nonlinear time-history analysis is carried out using the open code software for structural analysis OpenSees (Mazzoni *et al.*, 2006).

3. Previous Studies That Used The Rmtk Program

(Acevedo *et al.*, 2017), (Martins and Silva, 2018) and (Villar-Vega *et al.*, 2017), are researchers who developed fragility and vulnerability functions for distinct classes of buildings, obtaining good results through nonlinear time-history analysis (analytical method), using the risk modelling program GEM (GEM's Risk Modeller's Toolkit), the latest version of the program is available on the open archive GitHub: (https://github.com/GEMScienceTools/rmtk).

In the city of Antioquia, Colombia, they carried out a study of seismic risk on non-reinforced masonry buildings, for which they developed an exposition model based on the available land register information, survey data, and the opinion of experts. If the information was not accessible, they turned to a virtual survey carried out by Google Street View. They calculated the capacity functions through a pushover analysis, in order to subsequently develop the fragility functions for each building. The considered scenarios that could take place in the region of interest were carried out with the OpenQuake software. The results they obtained indicate that around 20% of the total property of the non-reinforced masonry structures would suffer big damages to the point of collapse, with the structures with four to six stories being the most vulnerable (Acevedo *et al.*, 2017).

Through an analytical focus, fragility and vulnerability functions were developed for the majority of the types of common buildings in the world. Obtained from a global survey (50 countries), close to two hundred types of buildings were considered. The fragility models were developed for different tectonic environments. Two model groups were considered, one for the active surface crust, and the other for subduction. After having tested and calibrated the fragility models in order to provide viable seismic risk estimations, it is believed that the resulting database could be used as a standard for the comparison of existing models or as a starting point for the analysis of seismic risk for regions where there are other available models (Martins and Silva, 2018).

In the Andes region (Argentina, Bolivia, Chile, Colombia, Ecuador, Peru and Venezuela) (Villar-Vega *et al.*, 2017) a uniform fragility model was carried out for 54 types of representative buildings for risk analysis on a grand scale. All the fragility functions are publicly available through the GEM vulnerability database on the OpenQuake platform (http://platform.openquake.org). Despite the usefulness of these models, it is important to recognise their limitations and their range of application. These fragility functions do not capture the specific characteristics of the building inventory on a local level. For the loss evaluation of earthquakes on a local scale, the models derived from using a more detailed methodology, and considering the local characteristics of the building inventory, should be considered.

4. Derivation Of Fragility And Vulnerability Functions

For the seismic vulnerability analyses of structures, the empirical method currently used are: Vulnerability Index Method (VIM), the macroseismic method by (Lagomarsino and Giovinazzi, 2006), and rapid visual screening (RVS) (FEMA P-155, 2015).

The main advantage of these methods is that they offer a more realistic vulnerability upon displaying the observed damages during the event. Some disadvantages could be the lack and weakness of data, not having a clear vision for investigating damage, depending mainly on the decisions of experts with differing opinions. In the diagram of Figure 3, the empirical methodology for the development of fragility functions is described (Kassem, Mohamed Nazri and Noroozinejad Farsangi, 2020).

The recent computational advances and the consequent improvement and refinement in the numerical modelling of relatively complex structures, using static or dynamic methods, have facilitated a greater exploitation of analytical methods for the evaluation of vulnerability (D'Ayala, 2013).

The analytical method is the most accurate and can be used to consider all kinds of uncertainties. One of the main disadvantages of the analytical derivation of vulnerability functions is that the procedure is extremely intense from a computational perspective, and thus requires a lot of time. As such, vulnerability functions cannot be easily developed for different areas or countries with diverse building characteristics (Calvi *et al.*, 2006) (Kassem, Mohamed Nazri and Noroozinejad Farsangi, 2020).

In the RMTK program OpenQuake, a probability damage matrix is used to derive a fragility function (which is to say, the probability of exceeding a number of damage states for a group of intensity level measurements), which can later be converted into a vulnerability function (which is to say, the loss index distribution for a group of intensity level measurements), using a consequence model. In this process, the portion of buildings in each damage state is multiplied by the associated damage index (from the consequence model) in order to obtain a loss index distribution for each type of intensity measurement (Silva *et al.*, 2015). For the derivation of the vulnerability functions, the general process of the analytical methodologies of the RMTK program is described in (Figure 4).

5.TABLES, FIGURE

Table 1. Summary of empirical procedures for masonry structures (D'Ayala, 2013).

Method	Data requirement	Method Highlight	Intensity Measure	Form	Reference
DPM (Damage probability matrix)	Typological description	Vulnerability assessment	Macro-seismic intensity	N/A	(Whitman, Reed and Hong, 1974)
VIM (Vulnerability index method)	Typological description	Fragility and vulnerability functions	Macro-seismic intensity, PGA	N/A	(Benedetti, Benzoni and Parisi, 1988) (Lagomarsino and Giovinazzi, 2006)
AeDES (Agibilità e Danno nell'Emergenza Sismica)	Typological description	Damage state	Macro-seismic intensity	Damage level form	(Baggio *et al.*, 2009)
RVS (Rapid Visual Screening)	Typological description	Damage state	Response spectrum	Data collections form of FEMA -154	(FEMA P-155, 2015)

Table 2. Summary of analytical procedures for the evaluation of seismic vulnerability of masonry structures (D'Ayala, 2013).

Method	Data requirement	Method Highlight	Intensity Measure	Software	Reference
FaMIVE (Failure Mechanism Identification and Vulnerability Evaluation)	Geometry, material parameters, structural details	Fragility functions, Vulnerability assessment	PGA Response spectrum	FaMIVE	(D'Ayala and Speranza, 2003) (D'Ayala, 2005)
SP-BELA (Simplified Pushover-Based Earthquake Loss Assessment)	Structural description	Vulnerability functions	PGA Response spectrum	SP-BELA	(Borzi, Crowley and Pinho, 2008)
CSBM (Capacity Spectrum Based Methods)	Structural description	Fragility functions, Damage in structural and economic terms	PGA Response spectrum	N/A	(Kappos, Panagopoulos and Penelis, 2008)
SELENA (SEismic Loss EstimatioN using a logic tree Approach)	Typological description, Structural description	Damage in structural and economic terms, and number of casualties	PGA Response spectrum	SELENA	(Molina, Lang and Lindholm, 2010)
HAZUS (HAZard U.S)	Typological description,	Fragility functions, Damage in structural and	PGA Response spectrum	HAZUS-MH	(FEMA, 2012)

	Structural description	economic terms			
RMTK (Risk Modellers' Toolkit)	Typological description, Structural description	Fragility and vulnerability functions, and Seismic Risk	PGA Response spectrum	OpenQuake RMTK	(Silva *et al.*, 2015)

Table 3. Summary of direct nonlinear static analytical methods from the RMTK program (Silva et al., 2015).

Method	Requirements	Result
SPO2IDA (Vamvatsikos and Cornell, 2005) (Dolšek and Fajfar, 2004) (Ruiz-García and Miranda, 2007)	1.Capacity curves 2.Pushover curve: Base Shear vs Roof Displacement , or Base Shear vs Floor Displacements 3.The capacity curves idealised: Bilinear, Quadrilinear or Multilinear 4.The inter-storey drift based damage model 5. Monte Carlo sampling 6.Spectran ratio variable (Sa_ratios)	Calculate the parameter of the fragility model, median and dispersion

Table 4. Summary of static nonlinear analytical methods based on registries from the RMTK program (Silva et al., 2015).

Method	Requirements	Result
(Vidic, Fajfar and Fischinger, 1994)	1.Capacity curves 2.Ground motion records 3. Damage model 4. Damping Ratio 5.Type of hysteresis: Q or Bilinear 6.Damping Model: Mass or Stiffness	Calculate the distribution of structures across the set of damage states for each ground motion record. Where PDM represents a matrix with the number of structures in each damage state per ground motion record, and Sd represents a matrix with the maximum displacement (of the equivalent SDOF) of each structure per ground motion record. The variable PDM can then be used to calculate the mean fragility model.
(Lin and Miranda, 2008) (Miranda, 2000) for Firm Soils N2 (CEN, 2004) Capacity Spectrum Method (FEMA 440, 2005)	1. Capacity curves 2. Ground motion records 3. Damage model 4. Damping Ratio	
DBELA (Silva *et al.*, 2013)	1.Assess the capacity displacement of one or multiple assets, following the DBELA approach. 2. Ground motion records 3. Damage model 4. Type of structures that are being evaluated: bare frame and infilled frame	

Table 5. Summary of nonlinear time-history analysis methods in oscillators with a degree of freedom from the RMTK program (Silva et al., 2015) .

<table>
<tr><th>Method</th><th>Input requirement</th><th>Ground motion record requirement</th><th>Result</th></tr>
<tr><td>Unscaled Record</td><td rowspan="2">1.One or multiple capacity curves
2.The capacity curves idealised by five relevant Sd-Sa points
3.Damping Ratio
4.Period of the structure
5.The degree of degradation in the cyclic rule
6.Damage model
7.The response of each SDOF system in terms of displacement</td><td>Unscaled ground motion records</td><td>Calculate the PDM that represents the number of structures in each damage state per each ground motion record intensity.
Spectral displacements Sd that represents a vector with the maximum displacement of each structure per ground motion record .
The variable PDM can then be used to calculate the mean fragility</td></tr>
<tr><td>Multiple Stripe Analysis (MSA) (Jalayer, 2003)</td><td>Set of ground motion records that are scaled to multiple levels of intensity measure</td><td>The response of the SDOF system to each ground motion record is used to determine theProbability Damage Matrix (PDM). In this case the PDM represents the number of records leading the structure to each damage state for the intensity measure of each "stripe" of responses.
With MSA it is possible to derive fragility curves also for a single structure. Alternatively more capacity curves can be input and the PDMs of the corresponding SDOF systems are summed up to get a unique PDM for the building class.</td></tr>
</table>

Figure 1. Empirical and analytical methods for the evaluation of seismic vulnerability.

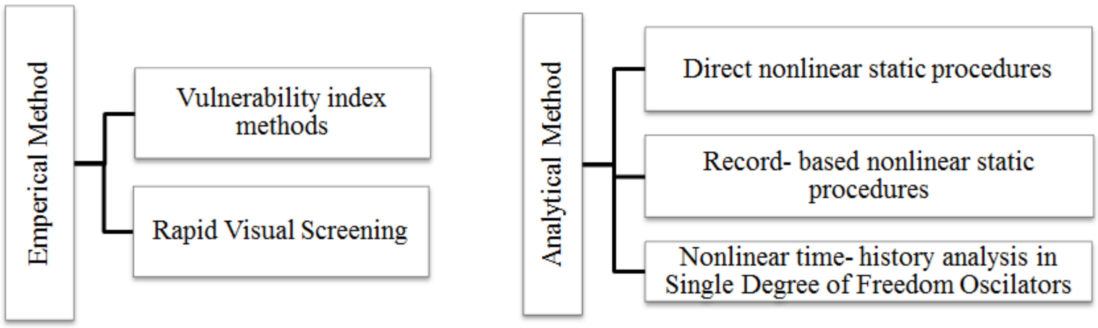


Figure 2. Analytical methods from the RMTK program for the evaluation of seismic vulnerabilities (Silva et al., 2015).

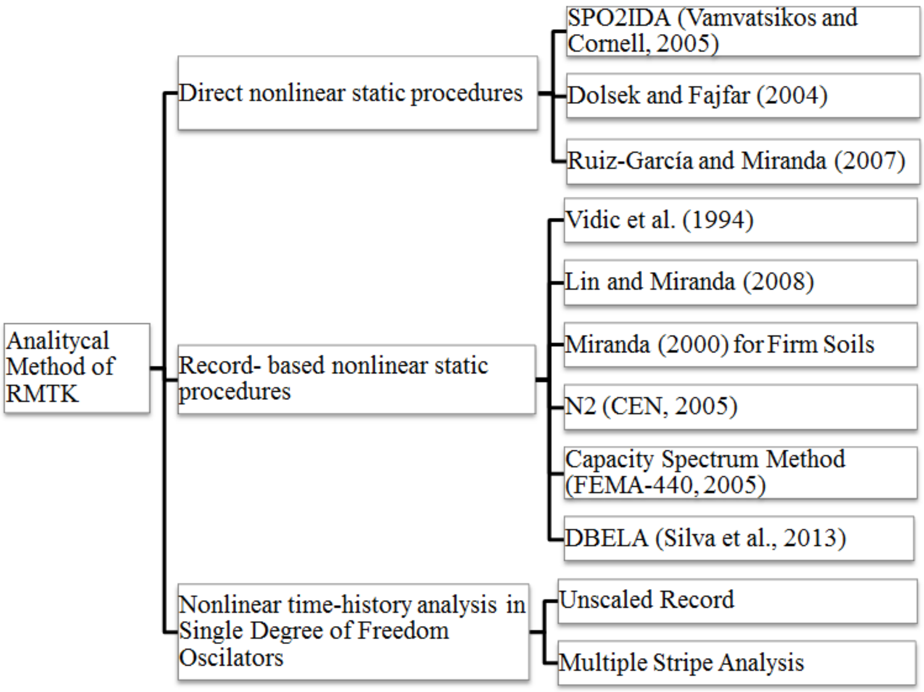


Figure 3. Methodology and steps of the development of fragility curves (Kassem, Mohamed Nazri and Noroozinejad Farsangi, 2020).

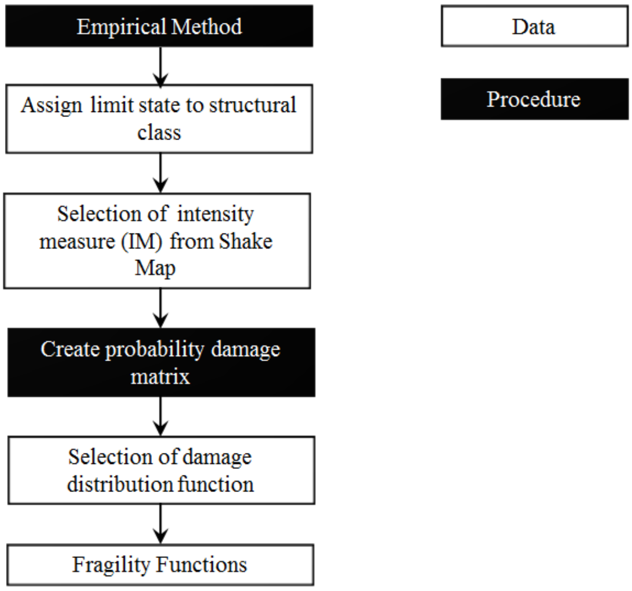
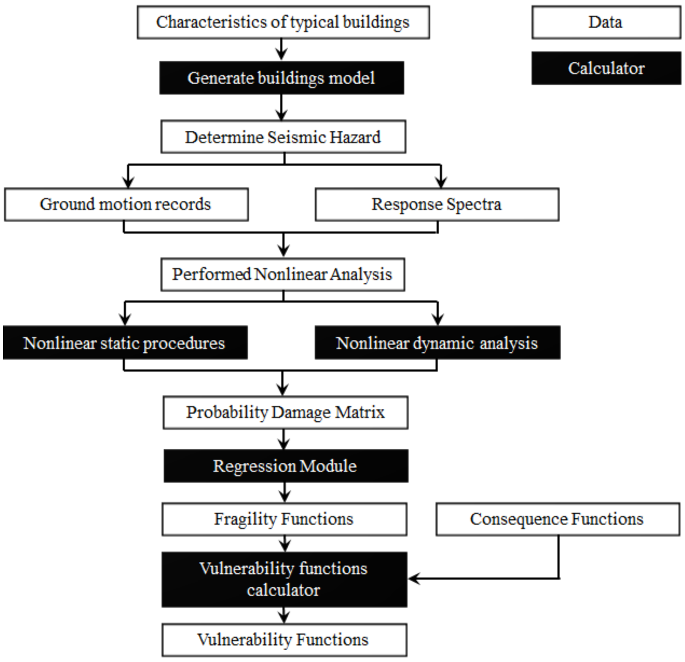


Figure 4. Steps to obtain vulnerability functions with analytical methods from the RMTK program (Adaptation by (Silva et al., 2014)).



6. CONCLUSIONS

In the previous descriptions, both empirical and analytical methods have been presented, along with their advantages and disadvantages, describing the inherent characteristics of each one. The choice of the most optimal or ideal vulnerability evaluation method will depend largely on the information available on the region in question.

If we wish to encompass the characteristics of each method, we could note that: The results of empirical methods are largely contributed by the judgement of experts, the definition of vulnerability is based on the characteristics of the building and the damage data of previous earthquakes. Damage data are used to calibrate the vulnerability functions, relating to the vulnerability index of global damages observed for buildings of the same typology, and extending the application in regions that have experienced the same level of macroseismic intensity or PGA.

Analytical methods, with the great variety of free access programs that currently exist appear to be a viable option to determine the vulnerability functions. Before choosing any of them, one must research their limitations and necessary characteristics so that they can be easily adapted to different types of buildings around the world.

The employment of two or more different methods which can complement and verify each-other will remain the choice of the investigator who wishes to obtain less uncertainty in the vulnerability evaluation.

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REFERENCES

Acevedo, A. B. et al. (2017) Evaluation of the seismic risk of the unreinforced masonry building stock in Antioquia, Colombia. Natural Hazards 86:31–54, doi: 10.1007/s11069-016-2647-8.

Achs, G. and Adam, C. (2012) Rapid seismic evaluation of historic brick-masonry buildings in Vienna (Austria) based on visual screening. Bulletin of Earthquake Engineering 10(6):1833–1856. doi: 10.1007/s10518-012-9376-5.

Ajay Kumar, S. et al. (2017) Rapid visual screening of different housing typologies in Himachal Pradesh, India. Natural Hazards. 85(3):1851–1875. doi: 10.1007/s11069-016-2668-3.

Baggio, C. et al. (2009) Manuale per la compilazione della scheda di primo livello di rilevamento danno, pronto intervento e agibilità per edifici ordinari nell'emergenza post-sismica (AEDES). Editrice Italiani nel Mondo srl. Roma, Italy.

Benedetti, D., Benzoni, G. and Parisi, M. A. (1988) Seismic vulnerability and risk evaluation for old urban nuclei. Earthquake Engineering and Structural Dynamics 16:183–201. doi: doi.org/10.1002/eqe.4290160203.

Bernardini, A. and Lagomarsino, S. (2008) The seismic vulnerability of architectural heritage, Proceedings of the Institution of Civil Engineers: Structures and Buildings 161(4):171–181. doi: 10.1680/stbu.2008.161.4.171.

Borzi, B., Crowley, H. and Pinho, R. (2008) Simplified pushover-based earthquake loss assessment (SP-BELA) method for masonry buildings. International Journal of Architectural Heritage 2(4):353–376. doi: 10.1080/15583050701828178.

Calvi, G. M. et al. (2006) Development of seismic vulnerability assessment methodologies over the past 30 years. ISET Journal of Earthquake Technology 43(3):75–104.

Catulo, R. et al. (2018) Simplified evaluation of seismic vulnerability of Lisbon Heritage City Centre based on a 3DGIS-based methodology. Journal of Cultural Heritage. 32. doi: 10.1016/j.culher.2017.11.014.

CEN (2004) Eurocode 8 - Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, Technical report EN 1998-2. Brussels, Belgium.

Chieffo, N. et al. (2019) Comparative fragility methods for seismic assessment of masonry buildings located in Muccia (Italy). Journal of Building Engineering 25(May). doi:10.1016/j.jobe.2019.100813.

CRED (Centre for Research on the Epidemiology of Disasters) (2015) The Human Cost of Natural Disaters 2015: Global Perspective.Brussels, Belgium.

D'Ayala, D. (2005) Force and displacement based vulnerability assessment for traditional buildings. Bulletin of Earthquake Engineering 3(3):235–265. doi: 10.1007/s10518-005-1239-x.

D'Ayala, D. (2013) Assessing the seismic vulnerability of masonry buildings, Handbook of Seismic Risk Analysis and Management of Civil Infrastructure Systems. doi: 10.1533/9780857098986.3.334.

D'Ayala, D. and Speranza, E. (2003) Definition of Collapse Mechanisms and Seismic Vulnerability of Historic Masonry Buildings. Earthquake Spectra 19(3):479–509. doi: 10.1193/1.1599896.

Dolšek, M. and Fajfar, P. (2004) Inelastic spectra for infilled reinforced concrete frames. Earthquake Engineering and Structural Dynamics 33(15):1395–1416. doi: 10.1002/eqe.410.

El-Betar, S. A. (2018) Seismic vulnerability evaluation of existing R.C. buildings. HBRC Journal. Housing and Building National Research Center 14(2):189–197. doi: 10.1016/j.hbrcj.2016.09.002.

FEMA (2012) Hazus–MH 2.1: Technical Manual, Federal Emergency Management Agency, Washington DC, USA.

FEMA 310 (1998) Handbook for the Seismic Evaluation of Buildings: A Prestandard, Fema 310, Federal Emergency Management Agency, Washington DC, USA.

FEMA 440 (2005) Improvement of Nonlinear Static Seismic Analysis Procedures, FEMA 440, Federal Emergency Management Agency, Washington DC, USA.

FEMA P-155 (2015) FEMA-155: Rapid Visual Screening of Buildings for Potential Seismic Hazards : Supporting Documentation, Federal Emergency Management Agency, Washington DC, USA. doi: 10.4231/D3M90238V.

Ferreira, T. M. et al. (2017) Seismic vulnerability assessment of stone masonry façade walls: Calibration using fragility-based results and observed damage. Soil Dynamics and Earthquake Engineering 103(January):21–37. doi: 10.1016/j.soildyn.2017.09.006.

EMS (1998) European Macroseismic Scale, EMS - 98. Conseil de L'Europe Cahiers du Centre Européen de Géodynamique et de Séismologie. G. Grünthal, Luxembourg.

Imjai, T. et al. (2020) Seismic strengthening of low strength concrete columns using high ductile metal strap confinement: A case study of kindergarten school in Northern Thailand. Walailak Journal of Science and Technology 17(12):1335–1347. doi: 10.48048/wjst.2020.10738.

Jalayer, F. (2003) Direct Probabilistic Seismic Analysis : Implementing Non-Linear Dynamic Assessments. Stanford.

Kappos, A. J., Panagopoulos, G. and Penelis, G. G. (2008) Development of a seismic damage and loss scenario for contemporary and historical buildings in Thessaloniki, Greece. Soil Dynamics and Earthquake Engineering 28(10–11):836–850. doi: 10.1016/j.soildyn.2007.10.017.

Kassem, M. M., Mohamed Nazri, F. and Noroozinejad Farsangi, E. (2020) The seismic vulnerability assessment methodologies: A state-of-the-art review. Ain Shams Engineering Journal 11(4):849-864. doi: 10.1016/j.asej.2020.04.001.

Lagomarsino, S. and Giovinazzi, S. (2006) Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. Bulletin of Earthquake Engineering 4(4): 415–443. doi: 10.1007/s10518-006-9024-z.

Lantada, M. N. (2007) Evaluación Del Riesgo Sísmico Mediante Métodos Avanzados Y Técnicas Gis. Universidad Politécnica De Cataluña.

Lin, Y. Y. and Miranda, E. (2008) Noniterative equivalent linear method for evaluation of existing structures. Journal of Structural Engineering 134(11): 1685–1695. doi: 10.1061/(ASCE)0733-9445(2008)134:11(1685).

Martins, L. and Silva, V. (2018) A global database of vulnerability models for seismic risk assessment. Proceedings of the 16th European Conference on Earthquake Engineering. Thessaloniki, 18-21 June.

Mazzoni, S. et al. (2006) Opensees command language manual. Pacific Earthquake Engineering Research(PEER) Center.

Miranda, E. (2000) Inelastic displacement ratios for structures on firm sites. Journal of Structural Engineering 126(October):1150–1159.

Molina, S., Lang, D. H. and Lindholm, C. D. (2010) SELENA - An open-source tool for seismic risk and loss assessment using a logic tree computation procedure. Computers and Geosciences. 36(3):257–269. doi: 10.1016/j.cageo.2009.07.006.

Park, Y. J., Ang, A. H.-S. and Ween, Y. K. (1987) Damage-Limiting Aseismic Design of Buildings. Earthquake Spectra 3(1):1–26. doi: doi:10.1193/1.1585416.

Pavel, F. et al. (2018) Assessment of seismic risk scenarios for Bucharest, Romania. Natural Hazards. 93(122):25–37. doi: 10.1007/s11069-017-2991-3.

Rajarathnam, S. and Santhakumar, A. R. (2015) Assessment of seismic building vulnerability based on rapid visual screening technique aided by aerial photographs on a GIS platform. Natural Hazards. 78(2):779–802. doi: 10.1007/s11069-014-1382-2.

Rodríguez Valenzuela, L. M. et al. (2020) Structural damage to housing and effects on users due to seismic risk: a case study. Proceedings of the Institution of Civil Engineers - Municipal Engineer 1–47. doi: 10.1680/jmuen.18.00025.

Ruiz-García, J. and Miranda, E. (2007) Probabilistic estimation of maximum inelastic displacement demands for performance-based design. Earthquake Engineering and Structural Dynamics 36(9): 1235–1254. doi: 10.1002/eqe.680.

Serrano-Lanzarote, B. and Temes-Córdovez, R. (2015) Vulnerabilidad y riesgo sísmico de los edificios residenciales estudiados dentro del Plan Especial de evaluación del riesgo sísmico en la Comunidad Valenciana. Informes de la Construccion 67(539). doi: 10.3989/ic.13.182.

Silva, V. et al. (2013) Extending displacement-based earthquake loss assessment (DBELA) for the computation of fragility curves. Engineering Structures 56:343–356. doi: 10.1016/j.engstruct.2013.04.023.

Silva, V. et al. (2014) Evaluation of analytical methodologies used to derive vulnerability functions. Earthquake Engineering and Structural Dynamics 43(2):181–204. doi: 10.1002/eqe.2337.

Silva, V. et al. (2015) OpenQuake Risk Modeller's Toolkit - User Guide. Global Earthquake Model (GEM). Technical Report 2015-09. doi: 10.13117/GEM.OPENQUAKE.MAN.RMTK.1.0/02, 97 pages.

Vamvatsikos, D. and Cornell, C. A. (2005) Direct estimation of the seismic demand and capacity of oscillators with multi-linear static pushovers through IDA. Earthquake Engineering and Structural Dynamics 35(9):1097–1117. doi: 10.1002/eqe.573.

Vicente, R. et al. (2011) Seismic vulnerability and risk assessment: Case study of the historic city centre of Coimbra, Portugal. Bulletin of Earthquake Engineering 9(4):1067–1096. doi: 10.1007/s10518-010-9233-3.

Vidic, T., Fajfar, P. and Fischinger, M. (1994) Consistent inelastic design spectra: Strength and displacement. Earthquake Engineering & Structural Dynamics 23(5):507–521. doi: doi.org/10.1002/eqe.4290230504.

Villar-Vega, M. et al. (2017) Development of a fragility model for the residential building stock in South America. Earthquake Spectra 33(2):581–604. doi: 10.1193/010716EQS005M.

Wallemacq, P. and Below, R. (2018) Natural disasters in 2017: Lower mortality, higher cost. Centre for Research on the Epidemiology of Disasters (CRED) (50):2. doi: 10.13140/RG.2.2.27820.92808.

Whitman, R. V., Reed, J. W. and Hong, S.-T. (1974) Earthquake Damage Probability Matrices. Proceedings of the Fifth World Conference on Earthquake Engineering. Rome, Italy, pp. 2531–2540.

Yamin, L. E. et al. (2017) Probabilistic seismic vulnerability assessment of buildings in terms of economic losses. Engineering Structures 138:308–323. doi: 10.1016/j.engstruct.2017.02.013.