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Earthquake Risk Assessment Methods of Unreinforced Masonry Structures: Hazard and Vulnerability

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Abstract

Seismic risk management of the built environment is integrated by two main stages, the assessment and the remedial measures to attain its reduction, representing both stages a complex task. The seismic risk of a certain structure located in a seismic zone is determined by the conjunct of the seismic hazard and its structural vulnerability. The hazard level mainly depends on the proximity of the site to a seismic source. On the other hand, the ground shaking depends on the seismic source, geology and topography of the site, but definitely on the inherent earthquake characteristics. Seismic hazard characterization of a site under study is suggested to be estimated by a combination of studies with the history of earthquakes. In this Paper, the most important methods of seismic vulnerability evaluation of buildings and their application are described. The selection of the most suitable method depends on different factors such as number of buildings, importance, available data and aim of the study. These approaches are classified in empirical, analytical, experimental and hybrid. For obtaining more reliable results, it is recommends applying a hybrid approach, which consists of a combination between methods depending on the case. Finally, a recommended approach depending on the building importance and aim of the study is described.

Keywords: *Earthquake hazard; structural vulnerability; seismic risk management; methods of assessment; historical and unreinforced masonry structures*

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1. General aspects on earthquake risk assessment

The risk management of existing buildings located in earthquake prone zones is integrated by two huge stages, the risk assessment and its reduction. Nowadays there is an enormous variety of methods to assess the seismic risk of buildings (Carreño et al. 2012) and exists a big confusion within the scientific community regarding which is the best procedure to follow for assessing this risk and the measures to take for its reduction. The application of risk management towards several disciplines has led to the development of a great diversity of definitions and methods. As a result, a unified approach to define and evaluate risk is indispensable for a rational quantification, comparison and treating (Sperbeck, 2009). Mena (2002) affirms that the seismic risk of buildings directly depends on the conjunct of the seismic hazard of the site and the structural vulnerability. It means that the seismic risk evaluation of a building or group of buildings located in a seismic hazard zone allows indicating the level of structural damage that could result by the action of an earthquake, depending on the vulnerability level of the structure. Analyzing the above mentioned, in general, it is worth noting that the seismic risk of buildings may be satisfactorily assessed by taking into account the seismic hazard of the site and the vulnerability of the structure. Next paragraphs present the definition of these terms commonly found in the literature of seismic protection of existing structures:

Seismic risk corresponds to the conjunct of the potential social, economic and cultural consequences in the built environment and persons due to earthquakes.

Seismic hazard is the probability of occurrence of a potential damaging earthquake, characterized for being an unavoidable event out of human control.

Seismic vulnerability represents the amount of damage that could be present in a building as a consequence of the occurrence of an earthquake of certain intensity.

Recent studies on earthquake engineering are oriented to the development, validation and application of techniques to assess the seismic vulnerability of existing buildings. (Carreño, et al., 2007; Sepe et al., 2008, Barbat, et al., 2008; Lantada, et al., 2009 and Pujades, 2012, Pujades 2012, Cao et al., 2014, Preciado et al., 2014 and 2015). The amount of identified damage in the seismic vulnerability assessment of buildings depends on many factors such as intensity of the seismic action, soil conditions, constructive materials, state of previous damages and structural elements. One more important aspect to consider is whether the structure was designed to resist earthquakes (nowadays buildings) or only to withstand their own self weight like most of historical constructions. The material degradation through time plays an important role in the structural vulnerability as well. Another classic definition of vulnerability is mentioned in the work of Sandi (1986), where the author defines it as an intrinsic property of the structure, a characteristic of its own behavior due to earthquakes, which could be described trough a law of *cause-effect*, where the

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cause is the seismic action and the effect is the damage. There is not a standardized measure of earthquake damage when assessing existing buildings, therefore the authors of this Paper may refer to local damage when the structure still stands and survived the earthquake motion. On the other hand, to global damage, when the complete structure collapses due to the formation of several mechanisms or also known in the relevant literature as failure modes.

2. Seismic hazard characterization

In general terms the seismic hazard level of a certain zone depends on its proximity to a seismic source with events of enough magnitude to generate significant seismic intensities at the zone under study. The earthquake source is mainly due to the released energy generated by the abrupt movements of the tectonic plates (see Fig. 1) of the earth´s crust, presented in the contact zone between plates (*interplate*), in geological faults inside of a plate (*intraplate*) or in the subducting slab beneath the contact between plates (*intraslab:* shallow 30–70 km, intermediate 70–300 km and deep>300 km). When the strain accumulated in the rock exceeds its capacity limit in the asperity, the *fault ruptures*, rock masses are abruptly displaced and seismic waves begin to radiate from the fault. As the rupture propagates, it successively releases the *strain energy* stored along the activated part of the fault. Therefore, each point of the rupture surface contributes, with a certain time of delay, to the total picture of *seismic waves*, which interfere with each other at a certain distance from the causative fault and give rise to a quite complicated wave train (Kulhanek, 1990).

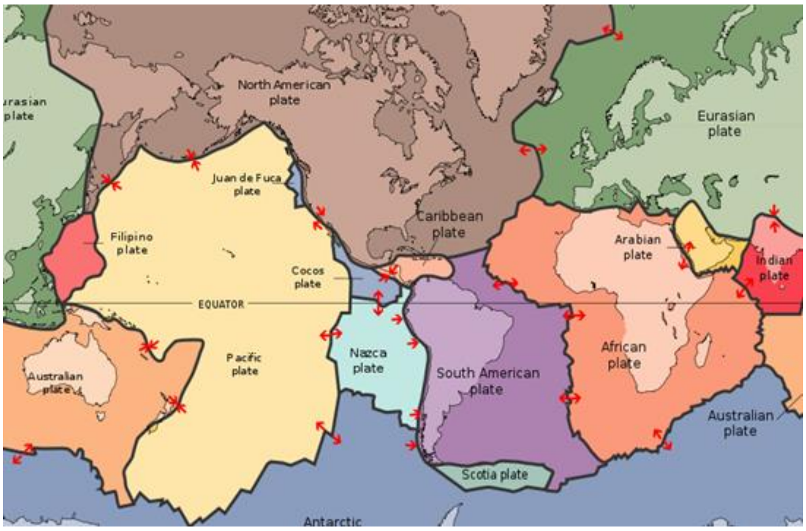

Fig. 1 Tectonic plates of the world (USGS, 2013)

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The seismic waves lose energy as they propagate through the earth along the travel path. The rate at which the earthquake ground motion decreases with the distance is a function of the *source*, *seismic wave types*, *regional geology*, *topography* and *inherent earthquake characteristics*. These major factors affect the severity of the ground shaking at the site. The attenuation varies depending on the source type (Gioncu and Mazzolani, 2011). Based on observations developed in different recorded accelerograms types, Filiatrault (1996) classifies the effects of the seismic wave types in function of the distance from the epicenter: *Near-source sites*, where all the wave types (body and surface) are present (P, S, L and R); for *intermediate-source sites*, the P-wave disappears due to the very important attenuation, being only present the S, L and R waves; and for *far-source sites*, only the surface waves remain (L and R). Mazzolani (2002) describes that there are four site classifications in function of the distance from the epicenter: *epicentral-site*, including the area around the epicenter (with a radius equal to the *source depth*); *near- source site* (near-field site), for an area within a distance of about 25-30 km from the epicenter; *intermediate-source site* (intermediate-field site), for an area within a distance of 150 km from the epicenter; *far-source site* (far-field site), an area located more than 150 km. Mena (2002) affirms that the ground shaking intensity and collateral effects mainly depend on the geology and topography of the site, but definitely on the inherent earthquake characteristics (e.g., hypocenter, mechanism, magnitude, intensity, duration and content of frequencies). Somerville (2000) describes that the first step in the evaluation of the seismic hazard of a zone is to characterize the seismic source to understand the inherent characteristics of earthquakes.

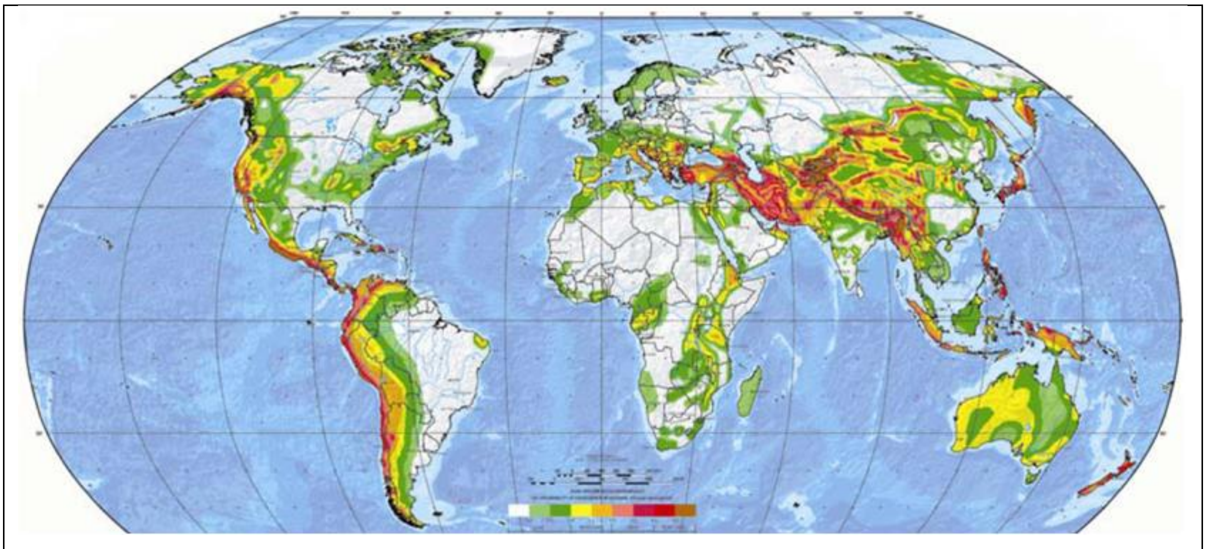

Fig. 2 Global seismic hazard map (GSHAP, 2013)

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Generally, simplified methods and models based in *statistical laws* are used to define the *probability of occurrence* in intervals of time for different intensities and expected maximum accelerations. However, these models involve many uncertainties that lead to the adaptation of other studies, resulting with this, in a rough representation of the real seismic hazard characteristics of the site under study. Woo (1992) and Mucciarelli and Magri (1992) describe that these uncertainties are even higher in areas with sporadic seismicity where previous studies are scarce (e.g., the seismicity of Italy). A good starting point towards the assessment of the seismic hazard of a site with these characteristics could be the study of *historical earthquakes and damages*. Due to the fact that this historical data is qualitative, the evaluation could be complemented with *probabilistic studies* and the opinion of experts (see Fig. 2).

(a) M7.5 Colima, Mexico in 2003

(b) M6.3 Canterbury, New Zealand in 2011

Fig. 3 Observed damage on URM buildings due to interplate earthquakes

Statistical seismology is a relatively new field, which applies statistical methods to earthquake data in an attempt to raise new questions about earthquake mechanisms and to make some progress towards earthquake characteristic prediction (Vere-Jones et al., 2005 and Vere-Jones, 2006). But the main question to be agreed is: can the physics of earthquakes be a statistical problem (Turcotte, 1999). Giovinazzi (2005) and Gonzalez-Drigo (2013) indicate that two universally recognized approaches exist for the seismic hazard assessment: the *deterministic* and the *probabilistic*. The deterministic considers each seismic source separately and determines the occurrence of an earthquake of specified size at a specified location. The probabilistic combines the contributions of all relevant sources and allows characterizing the rate at which earthquakes and particular levels of ground motions occur. Gioncu and Mazzolani (2011) describe that a seismic hazard analysis must

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be carried out on the basis of the earthquake type. For intraplate earthquakes, the major faults and sources are not well known (the epicenter positions are undetermined) and the hazard assessment is more difficult than for the interplate earthquakes (move along a well-defined fault). For this type is possible to use statistical approaches, which in contrast, are useless for intraplate earthquakes due to the absence of sufficient data on the same site, as in the case of the seismicity of Italy.

Fig. 4 Observed damage on URM buildings due to intraplate earthquakes after the M6.3 L'Aquila, Italy earthquake occurred in 2009

One good example of interplate earthquakes is the seismicity of Mexico and New Zealand, both interacting with the Pacific plate, also named the Ring of Fire (Circum-Pacific ring) due to the presence of very active volcanoes (see Fig. 1). Interplate earthquakes are characterized for having large magnitude and duration, being highly destructive for both compact and slender unreinforced masonry structures (URM) as shown in Figure 3. On the other hand, the Italian peninsula is characterized by intraplate seismic activity and the interaction between the Eurasian and African plates, with lower magnitudes and duration than interplate earthquakes but more damaging to compact URM structures due to the content of high frequencies (Fig. 4). Most of these earthquakes occur beneath the Apennines, which form the topographic "backbone" of the country. Analyzing all the aforementioned in this section, in general terms, the seismic hazard characterization of a certain zone under study is recommended to be estimated by considering a combination of the following:

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• Seismological and geophysical studies

• Geological and geotechnical investigations

• History of earthquakes and damages on buildings and infrastructure

• Opinion of experts

3. Methods of seismic vulnerability assessment

Seismic vulnerability assessment of buildings is an issue of most importance at present time and is a concept widely used in works related to the protection of buildings. Nevertheless, there is not a rigorous and widely accepted definition of it. In general terms, vulnerability measures the amount of damage caused by an earthquake of given intensity over a structure. However, “amount of damage” and “seismic intensity” are concepts without a clear and rigorous numerical definition (Orduña et al., 2008). The selection of a suitable method for the seismic vulnerability assessment of buildings mainly depends on the nature and objective of the study, as well as the reliability of the expected results. It means that is possible to evaluate the seismic vulnerability of a large group of buildings in a quite general manner (roughly) by following simple approaches (qualitative), or only evaluate one building in a detailed way by means of refined methods (quantitative). Qualitative approaches allow obtaining a qualification of the buildings or group of buildings in terms of seismic vulnerability that could range from low to high, whereas the quantitative ones in numerical terms (e.g., ultimate force, displacement capacity and failure mechanisms). Caicedo et al. (1994) describe that there is an extensive variety of methods proposed by different authors for the seismic vulnerability assessment of buildings. The selection of a certain method depends on the following aspects:

• Nature and objective of the study

• Available information

• Characteristics of the building or group of buildings under study

• Suitable method of assessment (qualitative or quantitative)

• Organization receiving the results and decision makers

Another interesting classification found in the relevant literature is proposed by Dolce (1994), who classifies the methods of vulnerability evaluation in four main groups depending on the available information: *empirical*, *analytical*, *experimental* and *hybrid* which represents a combination of methods.

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3.1. Empirical methods

These approaches are considered as qualitative and are widely used for the seismic vulnerability assessment of the built environment. Safina (2002) affirms that an especial characteristic of the empirical methods is that they are so subjective because are based on the acquired experience by observed earthquake damage on different types of buildings. These methods are used when the available information is limited and to perform a preliminary evaluation of a building or a large group of buildings at territorial scale in a fast way. These qualitative evaluations are commonly developed in-situ by means of a questionnaire of evaluation and visual inspections. The results give a grade of seismic vulnerability to every building ranging from low to high. The most used empirical methods are included by the vulnerability class and the vulnerability index.

Vulnerability class

These methods classify the buildings in vulnerability classes based on the seismic performance that similar typologies of buildings have shown after relevant earthquakes. The results are considered subjective and therefore the use of the vulnerability class methods is limited to preliminary assessments or to evaluate a large amount of buildings at territorial scale (seismic damage scenarios). One of the most famous methods commonly found in the relevant literature is the developed by the European Macroseismic Scale EMS-98 (Grünthal, 1998).

Table 1 Summary of the EMS-98 considering only masonry

Type of Structure		Vulnerability Class					
		A	B	C	D	E	F
MASONRY	Rubble stone, fieldstone.	X					
	Adobe (earth brick)	X	1				
	Simple stone	0	X				
	Massive stone		1	X	0		
	Manufactured units	0	X	0			
	With slabs of reinforced concrete		1	X	0		
	Reinforced or confined			0	X	1	

*X: most probable class; 1: probable range; 0: range of less probability, exceptional cases

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The EMS-98 approach classifies the seismic vulnerability of a building in six vulnerability classes ranging from A to F (A: high vulnerability and F: low vulnerability). It evaluates the materials used in walls and slabs, as well as the level of seismic design (see Table 1). If two groups of buildings are subjected to exactly the same earthquake shaking, and one group performs better than the other, then it can be said that the buildings that were less damaged had lower seismic vulnerability (more earthquake resistance) than the ones that were more damaged (Grünthal, 1998). Table 1 presents a resume of the classification of masonry structures in vulnerability classes of the EMS-98. During the visual inspections of the actual state of the structure the user can select the most probable vulnerability class, or the probable ranges mainly considering the structural engineering experience. Safina (2002) used the empirical method of the EMS-98 for the seismic vulnerability assessment of 64 hospitals located in Barcelona, Spain. With the results, the author elaborated a preliminary diagnostic, classifying the buildings in groups of less and more vulnerability. As a first stage the author collected all the specific information available of every one of the 64 hospitals, and in a subsequent stage applied the EMS-98 method to assign to each building a vulnerability class (low, medium or high).

Preciado (2007), Preciado et al. (2007) and Preciado and Orduña (2014) satisfactorily assessed the seismic vulnerability of 15 historical buildings (churches and museums) of the XIX century located in Colima, Mexico. This study was developed as a result of the high observed damage in most of the cultural patrimony after the M7.5 earthquake (SMIS and EERI, 2006) occurred on January, 21st, 2003 (see Fig. 3a). The EMS-98 was applied in the 15 buildings in order to obtain their vulnerability class. Additional information was considered for the evaluations, such as plans, characteristics of constructive materials, historical analysis, structural configuration and observed damage state. The results showed that eight of the buildings obtained a high vulnerability class, five an intermediate and the rest a low class. The most vulnerable historical constructions corresponded to churches as expected due to the conservation state and structural materials. Moreover, it was taken into account the lack of seismic design and other deficiencies related to local site effects such as poor soil conditions and topographic characteristics.

Vulnerability index

These methods are commonly used to identify and to characterize the potential seismic deficiencies of a building or group of buildings by means of a qualification by points to every significant component of the structure. This allows to the user the determination of a seismic vulnerability index. One of the most famous methods usually found in the relevant literature corresponds to the developed by Benedetti and Petrini (1984) and the GNDT (1990). This method has been widely used in Italy during the last years and has been upgraded as a result of the continuous experimentation and observed damage of certain types of structures (mainly URM) after earthquakes of different intensities, resulting in an extensive database of damage and vulnerability. The method is integrated by 11 parameters (Table 2) that were compiled in a

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questionnaire for the buildings assessment by visual inspections and desk work. As a result of its continuous use by many researchers around the world, the original questionnaire developed by the GNDT has suffered several changes, mainly based in past experiences or adaptations to structures of certain characteristics located in another places different to Italy. An example of this is the questionnaire of Aguiar et al. (1994) used to assess the seismic vulnerability of URM buildings in Spain.

The use of Table 2 is not a complicated task, during the visual inspections is selected for every one of the 11 parameters a vulnerability class A, B, C, or D, (A: low vulnerability, D: high vulnerability). Depending on the parameter and the selected class, the method assigns a numerical value (Ki) ranging from 0 to 45 that is affected for a coefficient of importance (Wi) between 0.25 and 1.5. This coefficient was assigned by the GNDT taking into account the opinion of experts and passed experience. It reflects the importance of each parameter in the evaluation of the seismic vulnerability of the structure. As a final stage the seismic vulnerability index (Iv) of the building could be obtained with the use of Eq. 1.

$$Iv = \sum_{i=1}^{11} Ki\, Wi \tag{1}$$

Analysing Eq. 1 and Table 2, it could be observed that the vulnerability index defines a scale of values ranging from 0 to the maximum reachable of 382.5 (100%), allowing to obtain a range in the order of 0 < Iv < 100. This range of vulnerability index could be used afterwards as a conclusion to determine a seismic vulnerability class (e.g., low Iv < 15, medium 15 ≤ Iv < 35 or high Iv ≥ 35) comparable to the empirical method of the EMS-98. Palencia et al. (2005) evaluated the seismic vulnerability of an educational building located in a high seismic zone by means of the GNDT method and the questionnaire developed by Aguiar et al. (1994). The authors found that the building presented an important vulnerability index (highly vulnerable), and concluded that as a consequence of a considerable earthquake the building could present important damages or collapse. Preciado (2007), Preciado et al. (2007) and Preciado and Orduña (2014) analysed the seismic vulnerability of the 15 aforementioned historical buildings located in Colima, Mexico as a second stage by the GNDT method. In this study, the base questionnaire developed by Aguiar et al. (1994) was modified and improved in order to assess historical masonry constructions located in high seismic zones of Mexico (e.g., churches, Cathedrals and Colonial buildings). The modified questionnaire was applied in 15 historical ancient masonry buildings by visual inspections in order to identify and characterize the potential structural deficiencies corresponding to the eleven parameters shown in Table 2. The field vulnerability evaluations were complemented with desk work and interpreted in terms of vulnerability classes. The results showed that 14 buildings (most of them churches) obtained a high vulnerability class and only one a medium vulnerability. Specifically, the parameters that contributed with their high vulnerability were the deficient conservation level, damage state, heavy and slender bell towers, vaulted roofs and heavy cupolas. The identified most vulnerable buildings by the empirical approaches (vulnerability class

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and index) were selected to be analysed by more refined and reliable methods such as the analytical and hybrid approaches, which are detailed in the following section.

3.2. Analytical methods

These approaches are mainly computerized numerical methods, which are based on the classical theories of elasticity and plasticity, and more recently on cracking and damage. The approaches that have gained more acceptance within the structural engineering community are integrated by the finite element method (FE) and the limit analysis (Preciado, 2015 and Preciado et al., 2015). These quantitative methods have the common characteristic of being more refined and require many parameters for modeling the real physical characteristics of the actual structure, representing with this more complexity and time consuming. Compared with the rough empirical methods that permit to evaluate a building or a large group of buildings at territorial scale in a fast way (preliminary evaluations); the quantitative methods are most commonly used to evaluate the seismic vulnerability of essential buildings that require especial attention. It could be the case of the seismic protection of historical buildings, hospitals, museums, schools and so on.

(a) FE model of a Medieval Italian tower

(b) limit analysis

Fig. 5 3D models of historical buildings

The analytical methods consist of developing as a first step a geometrical representation of the structure, mainly by the generation of a 3D model with computational tools. The model generation

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process depends on the selected method of analysis, FE or limit analysis as shown in Figure 5. Both models shown in Figure 5 were assessed by Preciado (2007 and 2011) and Preciado et al, (2015). The Cathedral depicted in Figure 5b was selected from the 15 buildings after the preliminary studies developed through empirical methods due to its imminent high vulnerability, strong observed damage after the Colima earthquake and the cultural importance of this 1889 historical building. After building the initial 3D FE or limit analysis model, the mechanical properties of materials constituting the structure and boundary conditions are assigned. Together with a suitable constitutive material model able to satisfactory represent the nonlinear behavior of URM, the model is statically or dynamically assessed. These evaluations are linear or nonlinear depending on the aim of the study and the action under analysis (e.g., self-weight, seismic loading and wind) in order to define levels of structural damage (vulnerability). The probabilistic methods for assessing the seismic vulnerability of existing structures are also gaining a lot of attention by the research community (e.g., Sperbeck, 2009, Rota et al., 2010 and Jinkoo and Donggeol, 2013). One of the most famous approaches based on probabilistic functions is the so called damage probability matrix by combining the structural fragility curves and the seismic demand. These matrixes of damage are used for assessing the seismic vulnerability of a large amount of existing buildings at territorial scale and for defining seismic damage scenarios (e.g. Moreno-Gonzalez and Bairan, 2010, Cattari et al., 2014 and Simoes et al., 2015).

3.3. Experimental methods

These methods consist of the implementation of tests with the purpose of determining the mechanical and dynamic characteristics of a certain existing structure. Generally, the mechanical properties of a structure are assessed in laboratory and in-situ, whereas the dynamic investigations are mainly developed in-situ. The mechanical tests (see Fig. 6a) aim to determine the characteristics of the building constructive materials (strengths, density, E modulus, Poisson´s ratio, etc.). Historical masonry is a very heterogeneous material and the assessment of its mechanical characteristics is always a complicated task. This is due to the structure was built following empirical rules and available materials, and mainly to the continuous modifications throughout its existence. Nowadays, with the continuous technological advances there is an enormous variety of equipment available for the development of non-destructive tests in the cultural heritage as shown in Figure 6a. By means of the mechanical characterization of structural properties is possible to determine its vulnerability by evaluating the materials quality. On the other hand, the main objective of the dynamic investigations (see Fig. 6b) is to obtain the natural frequencies by means of especial equipment (e.g., accelerometers) and ambient vibration (e.g., wind and traffic) as excitation. For the equipment selection is recommended to consider factors such as economy, simplicity and effectiveness. With this especial equipment is possible to evaluate the contributions in stiffness by horizontal constraints generated by neighbour buildings (boundary conditions) in the dynamic behavior of the building under study.

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(a) typical double flat-jack test (Bartoli et al., 2008)

(b) portable vibration analyzer

Fig. 6 Mechanical and dynamic characterization of URM buildings

The dynamic characterization of buildings allows the user to obtain relevant information of the actual damage state and vulnerability of a structure under study before or after the occurrence of an earthquake (damage scenario) (Safina, 2002). The normal procedure is to compare the different natural frequencies between the original structure and the damaged one, with special focus on the changes in stiffness (softening by cracking) and most of cases on mass due to collapsed structural elements. In the work of Abruzzese and Vari (2004) the authors affirm that the experimental methods represent a fundamental stage towards the seismic vulnerability assessment of constructions.

3.4. Hybrid methods

This last classification corresponds to a combination of methods for the seismic vulnerability evaluation of buildings (empirical, analytical and experimental). In the generation of an initial analytical model of a structure there are many assumptions and uncertainties regarding the determination of geometry, material properties, support and boundary conditions. All these issues and moreover considering the skills in numerical modeling and engineering experience of the user generate distrust about the reliability of the results. Thus, the initial analytical model has to be compared with the real physical characteristics (mechanical and dynamic) of the structure obtained by the experimental methods. It could be developed for example by comparing the natural frequencies of the initial analytical model with those obtained in the dynamic experimental

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campaigns. If the difference is satisfactory, the analytical model and the solution are assumed to be in agreement. If it is not the case, the model has to be calibrated or updated, obtaining with this an analytical model more reliable and representative of the real structure (analytical-experimental). Another possible use of the hybrid methods corresponds to the combination of the empirical, analytical and experimental approaches. It means that after assessing the seismic vulnerability of a group of buildings by the empirical methods, an organized list by level of vulnerability (low, medium and high) could be generated, selecting from it, the most vulnerable and important to analyse them by more refined methods such as the analytical-experimental e.g., Preciado (2007). In this way more reliable results towards the seismic vulnerability of the buildings could be obtained.

4. Recommended method depending on building importance

In section 3, the most important methods and applications for the seismic vulnerability evaluation of historical and URM buildings were described. Following paragraphs are aimed at summarizing the recommended method in dependency of the importance of the building:

• For the seismic vulnerability assessment of a complete city or large number of URM (non-cultural heritage) buildings is recommended to apply the empirical class method. The vulnerability class could be assigned during the visual inspection without the need of documentation such as plans, photographs or special equipment. As a proposal for reducing the seismic vulnerability may be designed a generic retrofitting (seismic strengthening) proposal that has shown good performance on similar structures subjected to past earthquakes

• For evaluating cultural heritage (churches, cathedrals, museums, etc.) buildings is recommended to collect all the possible information at a first instance such as photographic survey and visual inspections, identification of structural elements, state of damage, plans, historical analysis and restorations. Afterwards, to apply the empirical index method by evaluating the parameters that may be directly assessed during the field inspections and the ones that are evaluated with desk work. The buildings that obtained a low vulnerability may undertake a generic retrofitting proposal as in the case of simple URM buildings. The ones with medium to high vulnerability may be investigated in detail for seismic vulnerability assessment and strengthening proposals.

• Cultural heritage of great importance and the ones that obtained a medium to high vulnerability by the empirical index method may be investigated in detail by means of analytical approaches combined with experimental data (hybrid method). The same procedure is recommended for the seismic retrofitting proposals. The reader is referred to the research work of Preciado (2011), where the author developed a detailed research on seismic vulnerability assessment and most suitable retrofitting proposals (especially prestressing smart materials) by FE models of historical buildings of high cultural value in Italy and Mexico.

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5. Summary and discussion

Seismic risk management of the built environment is integrated by two main stages, the assessment and the remedial measures to attain its reduction, and represents a huge task its achievement. The seismic risk of a certain structure located in a seismic zone is determined by the conjunct of the seismic hazard and its structural vulnerability. The hazard level of the site mainly depends on its proximity to a seismic source. This may be due to a fault rupture when the strain accumulated in the rock exceeds its capacity limit at the contact zone between tectonic plates (interplate), in geological faults inside of a plate (intraplate) or in the subducting slab (intraslab). The ground shaking mainly depends on the seismic source, geology and topography of the site, but definitely on the inherent earthquake characteristics. The source of intraplate earthquakes is diffuse, being a quite complicated task its characterization. In the case of interplate earthquakes is possible to use statistical methods, which in contrast, are useless for intraplate faults due to the absence of sufficient recorded data at the same site. For fortune, low to moderate earthquakes occur in general in intraplate faults. The seismic hazard characterization of a site under study is suggested to be estimated by considering a combination of studies with the history of earthquakes.

In this Paper, the most important methods of seismic vulnerability evaluation of buildings were described in detail. The selection of the most suitable approach depends on different factors such as number of buildings, importance, available data and aim of the study. The empirical methods satisfactorily allow the vulnerability evaluation of a single building or a large group of buildings at territorial scale in a fast and qualitative way. These methods are used to determine seismic scenarios before or after the occurrence of an earthquake. For assessing the vulnerability of an essential building (e.g., a Cathedral, a hospital or a monument), the procedure is different and more in detail than using the qualitative evaluations by empirical methods. The literature recommends applying a hybrid approach, which considers a combination of the empirical, analytical and experimental methods to obtain more reliable and quantitative results. These detailed evaluations may serve to identify vulnerable parts at the structure and to propose several rehabilitation and strengthening measures to improve the seismic performance of the building by increasing its seismic energy dissipation capability. Other approaches which are gaining lot of attention by the research community for assessing the seismic vulnerability of buildings are the probabilistic based methods. One of the most famous approaches based on probabilistic functions is the so called damage probability matrix. These matrixes combine the structural fragility curves and the seismic demand of the site represented by the elastic response spectrum. The damage probability matrixes are used for assessing the seismic vulnerability of a large amount of existing buildings at territorial scale and for defining seismic damage scenarios.

Another method that combines the seismic demand of the site and the capacity curve of the structure converted into a bilinear system of one single degree of freedom is the so called Capacity Spectrum Method (CSM). This method is used for assessing the seismic vulnerability of essential buildings and the most recommended by the Authors of this Paper. This approach is one of the most used since recent years and it is in a continual improvement process.

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List of Figures

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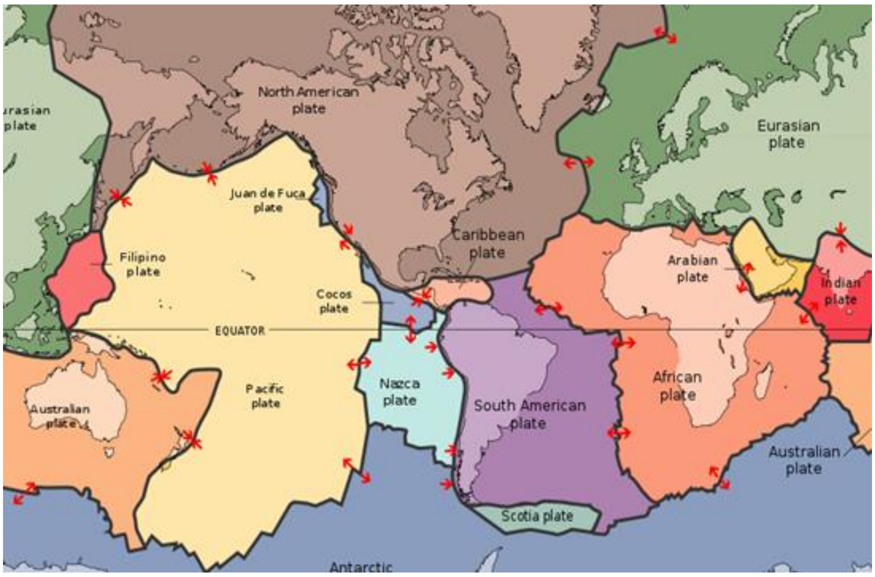

Fig. 1 Tectonic plates of the world (USGS, 2013)

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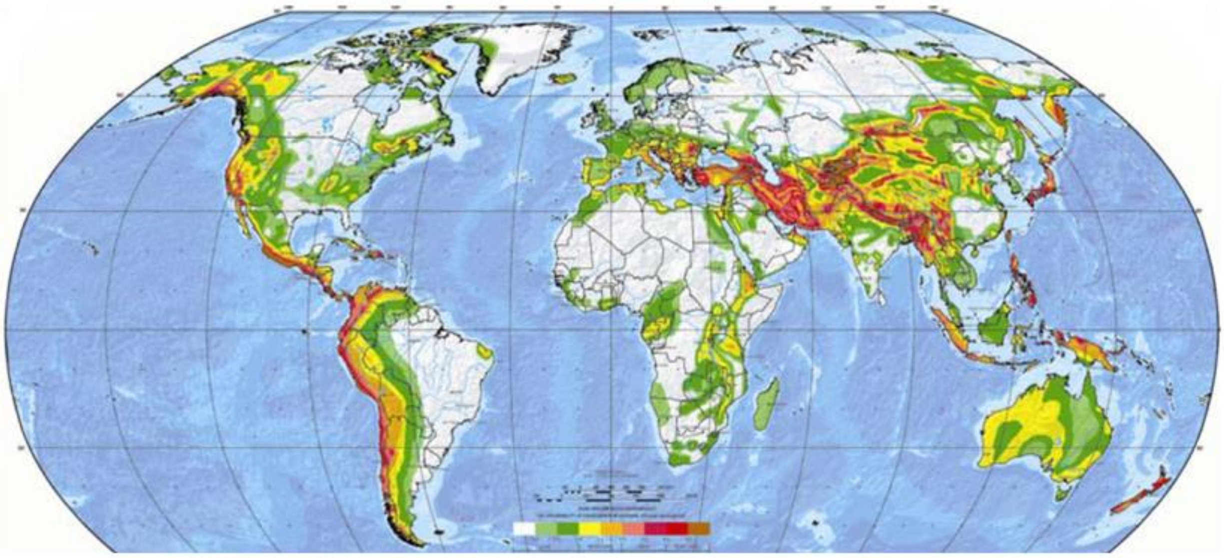

Fig. 2 Global seismic hazard map (GSHAP, 2013)

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(a) (b)

Fig. 3 Observed damage on URM buildings due to interplate earthquakes; (a) M7.5 Colima, Mexico in 2003 and (b) M6.3 Canterbury, New Zealand in 2011

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Fig. 4 Observed damage on URM buildings due to intraplate earthquakes after the M6.3 L'Aquila, Italy earthquake occurred in 2009

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(a) (b)

Fig. 5 3D models of historical buildings; (a) FE model of a Medieval Italian tower and (b) limit analysis model of the Cathedral of Colima, Mexico (Preciado, 2011)

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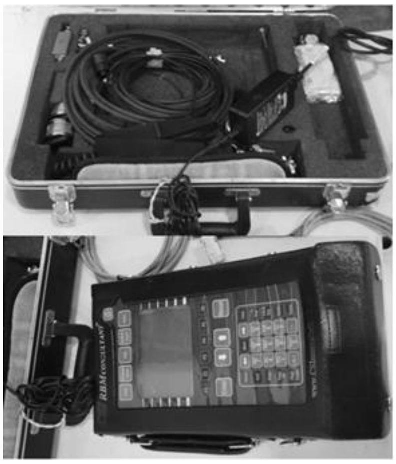

(a) (b)

Fig. 6 Mechanical and dynamic characterization of URM buildings; (a) typical double flat-jack test (Bartoli et al., 2008) and (b) portable vibration analyzer

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Table 1 Summary of the EMS-98 considering only masonry

Type of Structure		Vulnerability Class					
		A	**B**	**C**	**D**	**E**	**F**
MASONRY	Rubble stone, fieldstone.	X					
	Adobe (earth brick)	X	1				
	Simple stone	0	X				
	Massive stone		1	X	0		
	Manufactured units	0	X	0			
	With slabs of reinforced concrete		1	X	0		
	Reinforced or confined			0	X	1	

*X: most probable class; 1: probable range; 0: range of less probability, exceptional cases

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Table 2 Numerical scale of the vulnerability index (I_v) for URM buildings (Benedetti and Petrini, 1984)

i	**Parameter**	***Ki A***	***Ki B***	***Ki C***	***Ki D***	***Wi***
1	Organization of the resistant system	0	5	20	45	1.0
2	Quality of the resistant system	0	5	25	45	0.25
3	Conventional resistance	0	5	25	45	1.5
4	Position and foundation	0	5	25	45	0.75
5	Horizontal diaphragms	0	5	15	45	1.0
6	Floor configuration	0	5	25	45	0.5
7	Configuration of elevation	0	5	25	45	1.0
8	Maximum separation between walls	0	5	25	45	0.25
9	Typology of the roof	0	15	25	45	1.0
10	Nonstructural elements	0	0	25	45	0.25
11	Conservation level of the building	0	5	25	45	1.0

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