Analytically Derived Fragility Curves and Damage Assessment of Masonrybuildings

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Abstract. The latest earthquake disasters have highlighted, once again, poor functioning of the existing masonry structures, and the need to intervene all these structures which have been designed with old regulatory criteria, inadequate or those that have been built before the emergence of design codes. The significant progress made in new criteria of earthquake resistant design, should be extended to all the existing structures, it is therefore essential to identify the degree of seismic performance. Unreinforced masonry (URM) buildings represent a significant portion of the residential structures in Algeria, accounting for more than 60% of existing buildings. In addition to significant population, the brittle nature of URM buildings further supports a thorough consideration of seismic response given the susceptibility to severe failure modes. Currently, there is a pressing need for analytically based fragility curves for URM buildings. In order to improve the estimation of damage state probabilities through the development of simulation-based masonry fragilities, an extensive literature survey is conducted on pushover analysis of URM structures. Structural response is evaluated using an advanced capacity spectrum method. Capacity, demand, and response are thus derived analytically and response data is used to generate an improved and uniform set of fragility curves for use in risk assessment. Seismic fragility curves are expressed in multiple forms for wide range of use in loss-assessment applications. Results are discussed and compared with other relationships developed in the literature.

1 Introduction

Fragility curves are important for estimating the risk from potential earthquakes and for predicting the economical impact for future earthquakes. They can be used for emergency response and disaster planning by national agencies and by insurance companies to estimate the overall loss after an earthquake event. Fragility curves can be used to mitigate risk by improving the seismic codes. Seismic assessment and evaluation of the existing building stock has become a recognized priority after damage and collapse of many unreinforced masonry buildings structures during recent earthquakes ((Irizarry 2004); Askan and Yuceman 2010). Algeria is frequently exposed to destructive earthquakes. Besides, it is one of several countries in which earthquakes cause loss of human lives even though with moderate earthquake due the fact that 60 percent of the buildings stock are URM structures built without any seismic regulations. It is known

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that major part of the north of the country where 80 percent of population is concentrated is under high seismic risk (Benouar 2008). Considerable heavy damages have happened because of earthquakes events during the last 10 years (ATC 13 1985). URM buildings built before the appearance of modern codes have either collapsed or sustained extensive damage during the past earthquakes because of low quality of the material. Damage occurrence to stone masonry buildings is attributed to inadequate structural integrity and lack of connection between stone walls and wooden floors and roofs. The ensuing inadequate structural resistance results in typical shear cracking and disintegration of stone walls and partial or total collapse of buildings (Tomaževic 1999). Seismic risk assessment of stone masonry buildings is therefore the first step in the risk mitigation process, providing adequate planning for retrofit and preservation of historical urban centers.

Fragility analysis is a key component in seismic risk assessment and more specifically in regional seismic risk assessment (Coburn and Spence 2002). Performed over a population of structures with similar characteristics such as material, height and design code level, it leads to the estimation of earthquake damage for a number of structures present within a specific geographical area. With this, it provides valuable information for generating pre-disaster mitigation and emergency response plans. To overcome the absence of information and consider the uncertainties in the structural parameters, the methodology developed for this area of high seismicity, uses the technique of the statistical simulation method and unpublished simplified algorithms for the evaluation of damage. As a first step toward the assessment of the vulnerability and the seismic performance of existing buildings, URM buildings have been chosen (Freeman 2004). On the basis of the development of these methodologies, simplified expressions are proposed for the evaluation of damage of the typology analyzed, consistent with the way of defining the seismic hazard in the regions where are located the structures. These expressions are used for the generation of seismic hazard maps for different scenarios, which enable them to identify potential sources of concentration of damage and can be used directly to develop plans for disaster prevention and response in urban environments.

2 Organization Methodology and Process of Analytical Fragility Assessment

Figure 1 summarizes the different steps needed in the methodology for analytical fragility assessment of masonry buildings (GEM), by way of a schematic roadmap for the calculation of fragility functions. The first step of the process is to define the structural type of the buildings, in terms of structural system, material characteristics and so on. Depending on the scope of the work and available resources, the analyst will be required to choose the analysis type, model type and define a set of damage states in a consistent framework of complexity and accuracy (R.P.A 99/Version 2003).

To overcome the absence of information and consider the uncertainties in the structural parameters, the methodology developed for this area of moderate to high seismicity, uses the technique of the statistical simulation method and unpublished simplified algorithms for the evaluation of damage. As a first step toward the

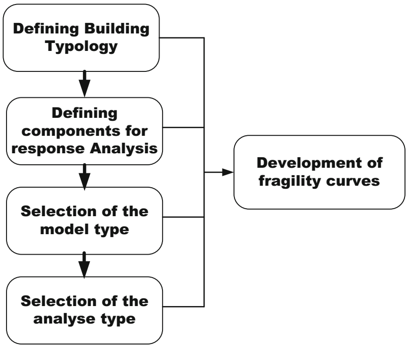

Fig. 1. Flow chart of the methodology

assessment of the vulnerability and the seismic performance of existing buildings URM buildings have been chosen. Simplified expressions are proposed for the evaluation of damage of the typologies analyzed, consistent with the way of defining the seismic hazard in the regions where are located the structures.

3 Buildings Typology Considered

The work presented herein refers mainly to unreinforced masonry buildings with brick slab vaults, which are by far the most common types in the north part of the country, as well as in the rest of Algerian cities. This main category is further subdivided into two-storey, three to four-story and five to six-story buildings; the specific buildings analysed within the present study are described in the Fig. 2.

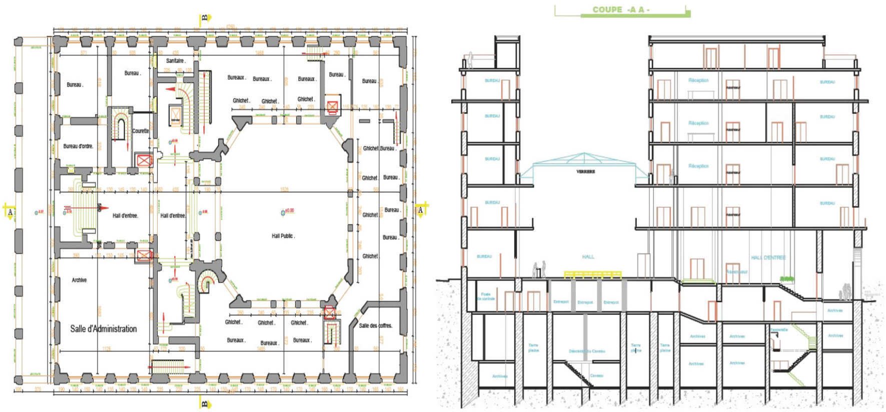

Fig. 2. Exemple of URM building type in Algeria

Three models of URM typology building have been considered. The seismic performance of a building can be characterized by its capacity spectrum obtained by means of a pushover analysis (Yogendra 2012), modeled in its bilinear form.

4 Capacity Curves

A pushover curve is a plot of a building's lateral load resistance as a function of the lateral displacement. It is commonly presented as a plot of base shear versus building displacement at roof level. Two control points that define a bilinearised pushover curve correspond to the "Yield Capacity" and the "Ultimate Capacity".

Pushover curves can be converted to so-called capacity curves, based on the equivalent SDOF system approach (see e.g. FEMA 1997); capacity curves are constructed based on estimates of engineering properties that affect the design, yield and ultimate capacities of each model building type.

The calculation of prototype pushover and capacity curves is achieved through a series of nonlinear static (pushover) analyses with several variations in the material properties and the building geometry in order to establish an adequate level of confidence in the results (Remki and Benouar 2014).

The method adopted herein for the pushover analysis of URM buildings uses equivalent frame models and concentrated non-linearity at the ends of the structural elements, with a view to simplifying this otherwise cumbersome (for URM buildings) procedure. The capacity spectrum method which has been developed by Freeman (2004) (ATC 13 1985), by using a graphical procedure; take into account the assimilation of the capacity of a structure with the demands of earthquake ground motion on the structure (Fig. 3). The graphical presentation makes possible a visual evaluation of how the structure will perform when subjected to earthquake ground motion.

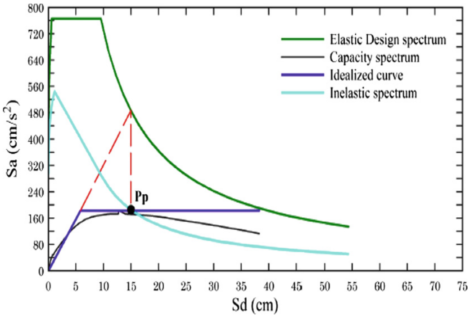

Fig. 3. Capacity spectrum method

The capacity of the structure is represented by a force displacement curve, obtained by non-linear static (pushover) analysis. The base shear forces and roof displacements are converted to the spectral accelerations and spectral displacements of an equivalent Single Degree-Of-Freedom (SDOF) system, respectively. These spectral values define the capacity spectrum. The demands of the earthquake ground motion are defined by highly damped elastic spectra (5% in our case). The Acceleration Displacement Response Spectrum (ADRS) format is used, in which spectral accelerations are plotted against spectral displacements, with the periods represented by radial lines (Fig. 4). The intersection of the capacity spectrum and the demand spectrum provides an estimate of the inelastic acceleration (strength) and displacement demand (Yogendra 2012). A probabilistic hazard scenario is considered.

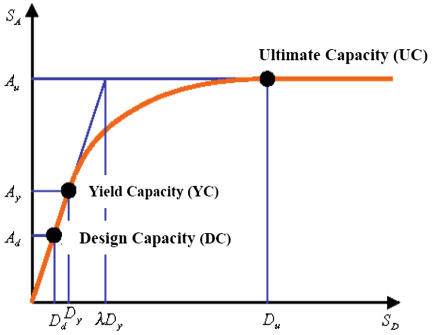

Fig. 4. Building capacity spectrum (RISK-EU)

Structural models have been used to estimate the capacity curves for URM buildings. An equivalent frame modeling of masonry walls has been used successfully in many previous studies (Lagomarsino and Cattari 2014) for the assessment of global behavior of masonry buildings. In this method, multistory masonry walls are modeled as equivalent frames made of vertical (pier) and horizontal (spandrels) elements with rigid intersecting joint elements (Milutinovic and Trendafiloski 2000). The equivalent frame model which has been used in this study is shown in Fig. 5(a) and (b), for a typical URM masonry wall. This model has been implemented on the computer program Sap2000 code (Computers and Structures 2014). The nonlinear behavior of piers and spandrels is modeled by inserting elasto-plastic hinges at pre-defined locations in the frame elements.

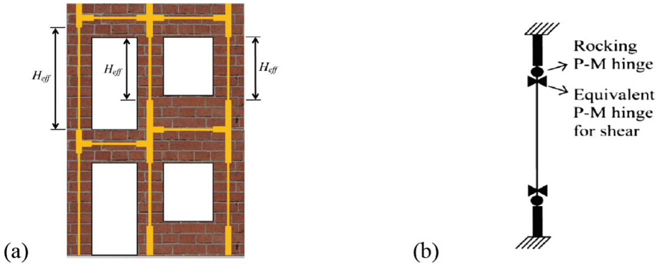

Fig. 5. (a) Equivalent frame model of a typical multistory URM wall with openings (b) Interactive plastic hinges for simulating rocking and shear behavior

To assess the expected damage of existing URM buildings, the computer program SAP2000 has been used, by taking into account the assumption of rigid diaphragm. Curves will be implemented in their bilinear form defined by two important points (Fig. 6), the yielding point (D_y, A_y) and the ultimate point (D_u, A_u).

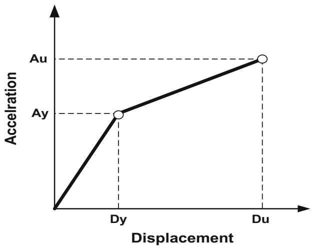

Fig. 6. Bilinear representation

Five damage states have been considered to analyze the seismic damage of masonry buildings: none, slight, moderate, severe and complete. Those states of damage are similar to the ones used in HAZUS and they are given in Table 1 (Barbat et al. 2008).

Table 1. Damage states vs. damage index (Park & Ang)

Damage degree (DI)	Damage Index	State of the Building
No damage	$DI \leq 0.10$	Safe
Slight	$0.10 < DI \leq 0.25$	Apparition of cracks
Moderate	$0.25 < DI \leq 0.40$	No structural damage
Severe	$0.40 < DI \leq 1.00$	Structural damage
Complete	$DI \geq 1.00$	Collapse

5 Fragility Curves

Fragility curves represent the probability that a structure exceeds a given state of damage as a function of a parameter that defines the seismic intensity. These curves are used to estimate the seismic risk of groups of buildings with similar structural features. Fragility curves can be generated from field observations, based on the opinion of experts and using analytical methods. Where there is insufficient information in the field, the fragility curves can be generated analytically by means of simulation. In our case, the parameter that defines the seismic intensity is the spectral displacement S_d. According to RISK-UE, fragility curves follow a lognormal probability distribution; define by two important parameters, the mean spectral displacement $\overline{S}_{d,ds}$ and the standard deviation β_{ds}. For a given damage state d_s, the fragility curve is given by:

$$P[\mathrm{d_s}/\mathrm{S_d}] = \Phi\left[\frac{1}{\beta_{\mathrm{ds}}}\ln\left(\frac{\mathrm{S_d}}{\overline{\mathrm{S}}_{\mathrm{d,ds}}}\right)\right] \tag{1}$$

Where, $\overline{S}_{\mathrm{d,ds}}$: The median value of spectral displacement at which the building reaches a certain threshold of the damage state $\mathrm{d_s}$, β_{ds}. The standard deviation of this spectral displacement, Φ: The standard normal cumulative distribution function and Sd: The spectral displacement.

According to the European macroseismic scale (1998), the seismic damage of existing building follow a binomial probability distribution (Beta distribution) used to calculate the continuous damage probability matrix for every vulnerability class. The approach assumes that the probability of each damage state at its spectral displacement is the 50% and the probability of the other damage states follows the Beta distribution. Table 2 summarized the probability distribution for each damage state.

Table 2. Probabilities by beta distribution

Condition	$P_\beta(1)$	$P_\beta(2)$	$P_\beta(3)$	$P_\beta(4)$
$P_\beta(1)$	0.500	0.119	0.012	0.00
$P_\beta(2)$	0.896	0.500	0.135	0.008
$P_\beta(3)$	0.992	0.866	0.500	0.104
$P_\beta(4)$	1.000	0.988	0.881	0.500

Fragility curves will be obtained, starting from a bilinear representation of the capacity curves. Figure 7 shows the values of the thresholds $\overline{\mathrm{S}}_{\mathrm{d,ds}}$ (Magenes et al. 2000), and their values are given in the following equation:

$$\begin{cases} \overline{S}_{\mathrm{d1}} = 0.7\,\mathrm{D_y} \\ \overline{S}_{\mathrm{d2}} = D_y \\ \overline{S}_{\mathrm{d3}} = D_y + 0.25(D_u - D_y) \\ \overline{S}_{\mathrm{d4}} = D_u \end{cases} \tag{2}$$

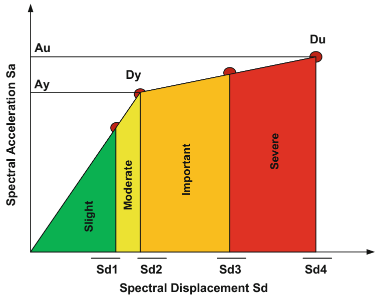

Fig. 7. Median value of spectral displacement

6 Case Study

6.1 Structural Capacity of the Studied Buildings

A simplified building typology has been adopted with only three models. The seismic performance of a building is characterized by its capacity spectrum obtained by means of a pushover analysis, modeled in its bilinear form. On the other way, three unreinforced masonry buildings of the city of Algiers have been modeled. The analyzed unreinforced masonry models correspond to two storeys (low-rise), four storeys (mid-rise) and five storeys (high-rise) buildings. Both the mid- and high-rise buildings have the same floor size (12 × 12 m) but different height (12 m and 15 m). The low-rise building has a (7 m × 8 m) in floor and is 6 m tall (Fig. 8). The structural analyses have been performed using the frame equivalent element in the SAP 2000 computer program in 2D model. The out-of-plane response was not included in the analysis because its effect on the global building response was not considered. Table 3 shows the mechanical properties of masonry.

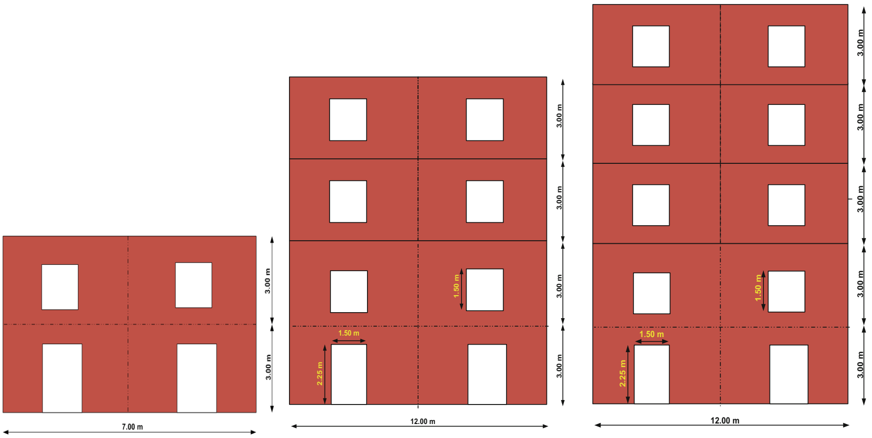

Fig. 8. URM buildings considered in this study

Table 4 shows the fundamental period and the yield and ultimate capacity points defining the bilinear capacity spectra for the modeled reinforced concrete and masonry buildings.

Figure 9 shows the bilinear capacity spectra for unreinforced masonry buildings in ADRS format for the probabilistic scenario, for typical buildings considered compared to those developed in the RISK-EU program. The capacity spectrum for low-rise

Table 3. Mechanical properties

Compressive strength fc_{28}	Steel strength Fe	Elastic modulus E	Shear modulus G
25 Mpa	500 Mpa	20 Gpa	12 Gpa

Table 4. Yield and ultimate capacity for reinforced concrete (RC) and unreinforced masonry buildings (L: low, M: Moderate and H: High)

Building class	Nbre of stories	Period of vibration (s)	Yield capacity		Ultimate capacity	
			D_y (cm)	A_y (g)	D_u (cm)	A_u (g)
URM-L	1-3	0.17	0.58	0.32	3.18	0.32
URM-M	3-5	0.37	0.73	0.15	2.85	0.13
URM-H	6+	0.48	0.72	0.13	2.91	0.11

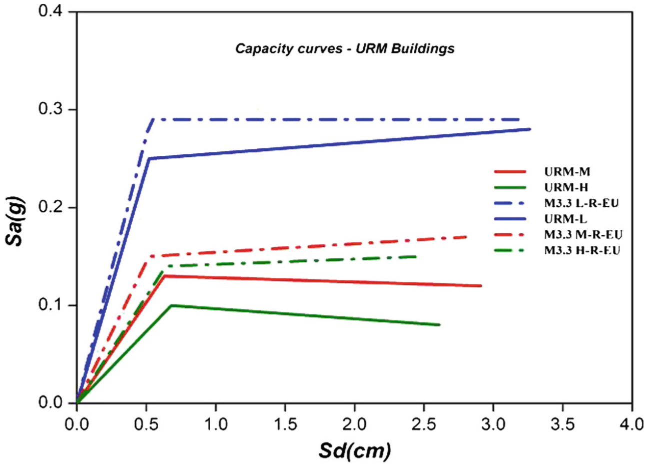

Fig. 9. Bilinear capacity curves for URM buildings (URM-L, URM-M and URM-H)

masonry buildings shows high stiffness and strength. In fact, this type of building, representative for a number of one-family houses, mainly located in the residential districts of the city, is completely different from the mid- and high-rise masonry buildings.

It is clear that the capacity curves adopted by Risk-EU are different in comparison with the curves developed herein, especially those for the low-rise building type. The large discrepancy between Risk-EU and the proposed curves lies not in spectral displacements, which are similar, but in spectral accelerations, which are substantially lower in the present analysis.

6.2 Fragility Curves of the Studied Buildings

In order to develop seismic fragility curves that describe more accurately the expected damage to URM existing buildings for several excitation intensities, an analytical approach has been used herein. More specifically, the capacity spectrum method that has been described before, combined with the different damage states proposed

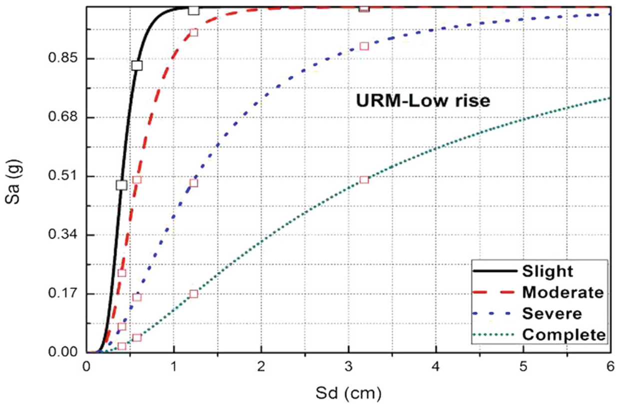

Fig. 10. Fragility curves for low rise URM buildings

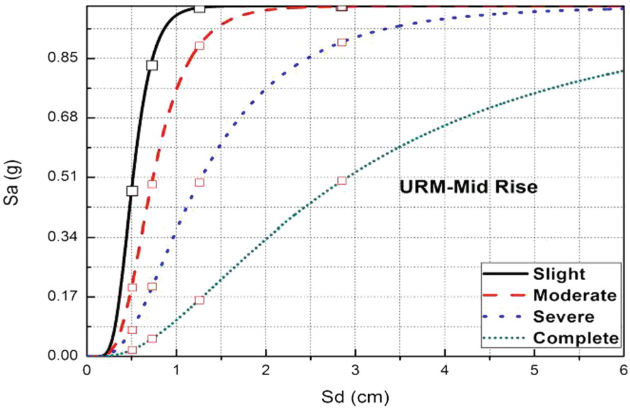

Fig. 11. Fragility curves for mid rise URM buildings

previously have been implemented to develop fragility curves. It is well documented in the current literature that such curves can be described by normal, lognormal, beta or other distribution, provided that sufficient data is available.

Fragility curves were then derived by fitting the lognormal cumulative distribution function. The parameters of the lognormal distribution functions were calculated for each building type and damage state. Using these parameters, the fragility curves shown in Figs. 10, 11 and 12 are plotted. Table 5 shows the corresponding obtained parameters, namely S_{di} and β_{sdi} which define the corresponding cumulative lognormal distribution and the fragility curves corresponding to reinforced concrete RC frames and URM building classes.

The results show that URM buildings present non ductile behavior at all, providing a poor seismic performance. As an example, for mid-rise URM buildings in Fig. 11, in case of a 2 cm spectral displacement, the expected probability for the complete damage

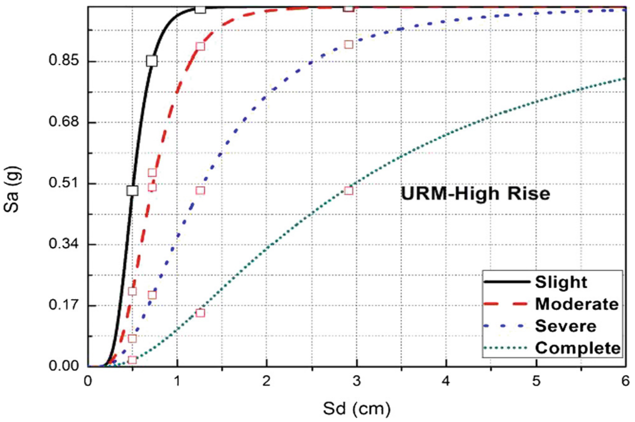

Fig. 12. Fragility curves for high rise URM buildings

Table 5. Mean values and standard deviations of the fragility curves of the buildings considered

Building class	Damage states							
	Slight		Moderate		Severe		Collapse	
	S_{d1}	β_{sd1}	S_{d2}	β_{sd2}	S_{d3}	β_{sd3}	S_{d4}	β_{sd4}
URM-L	0.40	0.37	0.58	0.51	1.23	0.80	3.18	1.0
URM-M	0.51	0.37	0.73	0.47	1.26	0.71	2.85	0.91
URM-H	0.50	0.33	0.72	0.42	1.26	0.59	2.91	0.76

Units of the spectral displacement are cm

state is about 35%, but it is more than 42% for severe damage state. The analyses clearly point out the very high vulnerability of the buildings and, consequently, a significant probability of damage even in the case of a not too severe earthquake. It is somewhat surprising that the obtained results show high expected seismic damage for relatively low spectral displacements.

7 Conclusions

The methodology adopted for the development of analytical fragility curves of URM buildings has been presented herein. The work included two independent phases; the definition of capacity curves by means of pushover analysis for URM building typologies very common in Algeria, and the definition of fragility curves correlating the spectral displacement S_d to the probability of a building type to exceed a particular damage state, using a spectral acceleration S_a. Considering various uncertainties, seismic damage evaluation had been carried out within probabilistic framework, by considering seismic hazard evaluation, damage and risk estimation. The vulnerability of the different building classes is characterized by bilinear capacity spectra obtained by using CMS methods. The basic seismic hazard in the studied area is defined by 5%

elastic response spectra starting from which demand spectra are obtained. Starting from capacity spectra, fragility curves are also estimated in a simplified way for each considered building type. Fragility curves are used to characterize the expected structural damage in a probabilistic way. The adopted method has been applied to URM buildings in the city of Algiers, located in a moderate seismic hazard area. One of the most important results, which have been obtained, is the seismic vulnerability of the buildings. Reliable capacity curves have been obtained, which show a wide vulnerability range.

Capacity and fragility curves have been developed for about 60% of the residential building of the city, which has been represented by three building classes. Significant damage is obtained for mid-rise and high-rise masonry buildings, due to the slow strength of these buildings.

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