Seismic Vulnerability Analysis of RC Buildings: Case Study of Ibn Khaldoun Area in Boumerdes City, Algeria

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ABSTRACT

This study focuses on empirical assessment of vulnerability and fragility curves of existing reinforced concrete (RC) buildings in Ibn Khaldoun area of Boumerdes city (Algeria). In this area, existing RC buildings experienced significant damage during the 2003 Boumerdes earthquake. Currently, the area includes existing non-damaged buildings, strengthened buildings and new RC buildings constructed in place of those demolished. The proposed seismic vulnerability assessment method combines the GNDT (Gruppo Nazionale per la Difesa dai Terremoti) II level method and the macroseismic method by means of correlation between the peak ground acceleration PGA and the macroseismic intensity I. For this purpose, data was collected by investigating buildings within the area. Structural and non-structural building characteristics were identified and statistical analysis was performed. Resulting vulnerability curves obtained using the macroseismic method were expressed as a function of macroseismic intensity and the vulnerability index obtained using the GNDT II level method. Fragility curves, obtained by using correlation between the peak ground acceleration PGA and the macroseismic intensity I, showed that the highest probability to reach or exceed a very heavy damage grade is obtained for the highest values of I and vulnerability index V.

KEYWORDS: Boumerdes, Damage, Vulnerability assessment, Fragility curve.

INTRODUCTION

During last Algerian earthquakes, existing RC frame buildings behaved poorly against seismic action, contrary to RC wall buildings. RC frame system was adopted in Algeria from the 1950s, but after the Boumerdes 2003 earthquake, it was completely banned for mid-rise and high-rise buildings. In fact, a significant number of existing RC frame buildings was constructed before the introduction of the first Algerian seismic code in 1981, RPA81 (CTC, 1981), thus considered as having a low level of earthquake-resistant design (ERD), due to their structural system which consisted of columns and beams supporting only vertical loads. Post-earthquake observations revealed that seismic vulnerability of RC frame structures is directly related to their structural deficiencies (undersized structural elements, insufficient ductility,…), but is also influenced by other non-structural factors, such as the state of preservation or site conditions.

Assessing vulnerability of existing buildings is an important step towards seismic risk reduction. Vulnerability refers to the probability of a structure to experience a certain level of damage when exposed to an earthquake with a given intensity (Lang, 2002; Lang and Bachmann, 2003). Methods to assess vulnerability are numerous; they can be classified into different categories depending on the scale of application and the available data (Vicente et al., 2005; Vicente et al., 2011). Generally, vulnerability assessment methods can be classified into empirical and analytical (or numerical) methods (Calvi et al., 2006). Empirical methods are essentially based on observing and recording damage after earthquakes (Whitman et al., 1974; ATC-13). Some of these techniques include the determination of a vulnerability index firstly and then establishing the relationships between damage and seismic intensity, such as the widely applied methodology developed by GNDT (Gruppo Nazionale per la Difesa dai Terremoti) in Italy based on

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post-earthquake observations (GNDT, 1994). Analytical methods are based on structural analysis, detailed analysis or using simplified models (ATC-40, 1996; Fajfar, 1999; FEMA, 1999 (HAZUS-99 earthquake loss estimation)). Empirical and analytical methods can be combined to assess seismic vulnerability of buildings, such as the macroseismic approach (Giovinazzi and Lagomarsino, 2004; Giovinazzi, 2005) which uses vulnerability classes defined in the European Macroseismic Scale EMS-98 (Grünthal, 1998) and a vulnerability index.

This study focuses on assessing vulnerability and fragility curves of existing buildings in Ibn Khaldoun area of Boumerdes city. This area experienced a large concentration of damage during the 2003 earthquake. Currently, the area includes new RC shear-wall buildings constructed in place of those demolished, strengthened RC frame buildings and the non-damaged RC frame buildings (non-strengthened). The proposed method to assess vulnerability and fragility combines the vulnerability index GNDT II level method and the macroseismic method, by means of correlation between the peak ground acceleration PGA and the macroseismic intensity I (Azizi-Bondarabadi at al., 2016). For this purpose, data was collected by investigating buildings within the area. The database obtained includes the number of investigated buildings, the types of structures and their structural and non-structural characteristics.

Brief Overview of Boumerdes City

Boumerdes city is located in the central part of Algeria on the Mediterranean Sea, at about 45 km east of Algiers, the capital of Algeria (see Fig. 1). The city extends on a surface of 19.08 m² and had a population of 41 685 inhabitants according to the last census of 2008. Boumerdes was shaken by a violent earthquake on May 21, 2003 with a magnitude of 6.8 and an intensity of X according to EMS-98 (Harbi et al., 2007). It was the most violent earthquake that occurred in northern Algeria after the 1980 El Asnam earthquake, but remains the most disastrous in terms of human victims, with more than 1,000 deaths and 3000 injures (EERI, 2003), in addition to property losses.

According to the available data of the Boumerdes Department of Housing (DLEP, 2004) and the Construction Technology Control (CTC), about 67% of the buildings in the city suffered damage grade 1, while 14% suffered damage grade 2. Damage grades 3, 4 and 5 were concentrated in zones A and D (Fig. 1), with respectively 8%, 8% and 2%. According to the EMS-98 classification (Grünthal, 1998), grade 1 corresponds to no damage to structural elements; grade 2 corresponds to slight damage to structural elements; grade 3 corresponds to moderate damage to structural elements; grade 4 corresponds to heavy damage to structural elements; and grade 5 corresponds to very heavy structural damage, partial or total collapse.

In zones A and B, there are mainly mid-rise (four to five stories) residential buildings, built in the period of 1959-1970, with RC frame system. In zone C, there are mid-rise residential buildings built in the early 1980s, with RC wall bearing system. In zone D, there are RC frame buildings, built in the 1990s.

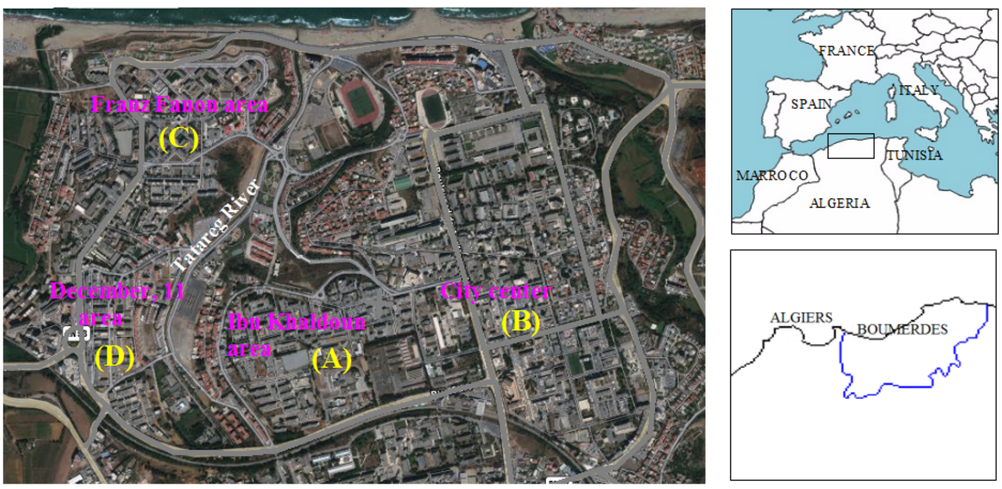

Figure (1): Location and urbanization of the city of Boumerdes (Satellite image captured by satellite.pro)

Study Area and Structural Features of the Existing Buildings

This study did not extend over the entire city, but was limited to the residential area Ibn Khaldoun (zone A). In this area, located on hilltops along the southwest Tatarreg River valley, the highest rate of damage during the 2003 earthquake was recorded, with about 60% severely damaged and collapsed buildings. At present, existing buildings in the area are; (i) new mid-rise residential buildings, composed of RC wall structure, constructed in 2009-2010, in place of those demolished, (ii) strengthened existing RC frame buildings and (iii) non-strengthened (non-damaged) existing RC frame buildings. Fig. 2(a) shows the new mid-rise residential buildings (two adjacent blocks) with semi-buried basement. The block on the left shows an irregular plan form. Fig. 2(b) shows the existing mid-rise RC frame buildings. Column strengthening was performed using classical jacketing technique (Fig. 2(c)), in which the section of central columns was not enlarged over the height of the building. As shown in the plan view (Fig. 2(d)), RC frame structural system is oriented in the transverse direction only. Structural dimensions (in cm) are: (20×40) for columns, except central columns (20×50), and (20×40) for beams. Such RC building structures, designed prior to the integration of the seismic code regulations in 1981, RPA81, commonly present structural deficiencies; load bearing system in one direction, undersized or non-ductile columns…, which made them exposed to seismic damage.

It is worth noting that after the 2003 earthquake, under the decision of the Provençal authorities, buildings severely damaged (suffering damage grades 4 and 5) were demolished and reconstructed. Moderately damaged buildings (suffering damage grade 3) were strengthened in order to increase their structural capacity and slightly damaged buildings were just repaired.

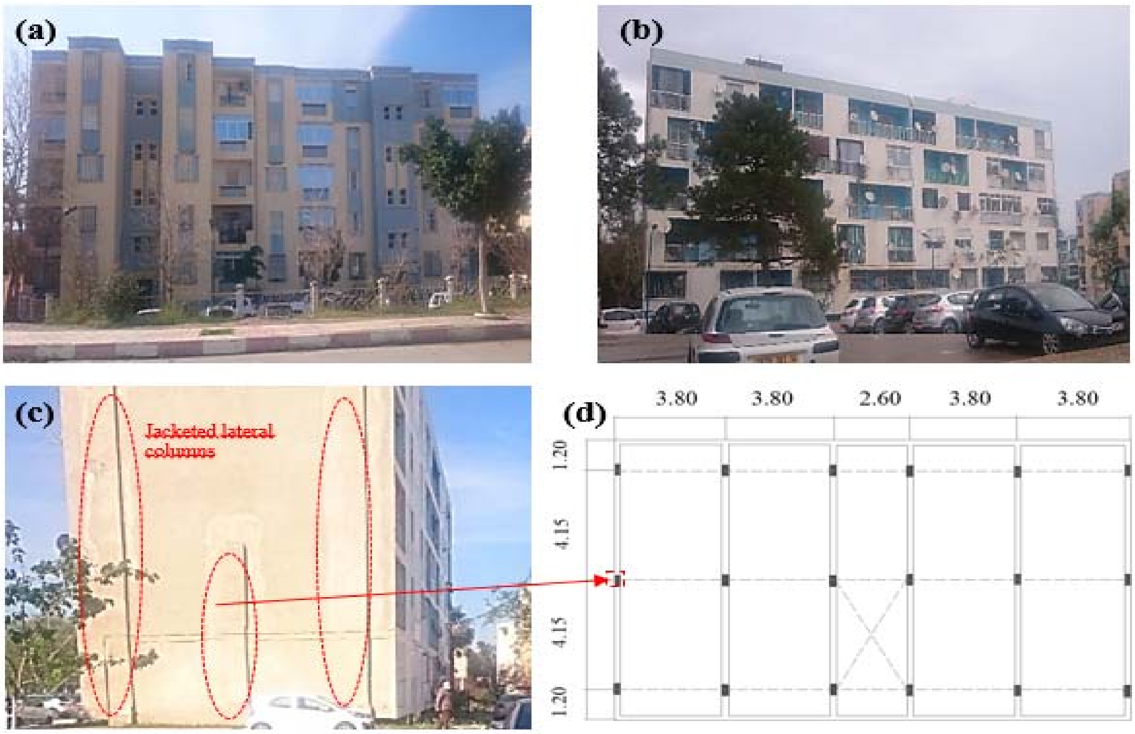

Figure (2): Residential buildings in Ibn Khaldoun area (a) New mid-rise RC shear wall buildings, (b) Strengthened existing RC frame buildings, (c) Strengthened columns on each lateral side and (d) Plan view of the existing RC frame buildings

Analysis Method

The proposed method aims to obtain vulnerability and fragility curves of each building typology in the study area. To achieve this, as mentioned previously, a combination of the vulnerability index GNDT II level method and the macroseismic method is performed by means of correlation between the peak ground acceleration PGA and the macroseismic intensity I (Azizi-Bondarabadi et al., 2016).

The GNDT Level II Method

The GNDT II level method (GNDT 1994) is an empirical method developed using post-earthquake Italian data. The method is based on the identification and, in some cases, the calculation of building parameters to evaluate vulnerability index, with the aim to estimate the probable seismic damage. The vulnerability index V is a score value, which arbitrarily qualifies the seismic behavior of a building. It ranges between 0 and 1; 0 for structures with high earthquake resistance features and 1 for the most vulnerable structures. The method is fundamentally based on visual observation of buildings to identify the structural system and its resistance deficiencies. Building parameters' information is collected using a survey form. The method defines three increasing qualification classes: A, B and C, associated to each parameter (see Table 1). Parameters 1 to 3 evaluate the structural resistant system, where Parameter 1 describes the characteristics of the structural system (RC frame, RC walls,…), Parameter 2 is related to the execution quality and construction materials and Parameter 3 evaluates the ratio between the base-shear action and the resistant base-shear of the structure. Parameters 4 to 11 are also regarded as having an important influence on seismic vulnerability. Parameter 4 evaluates the consistency and the slope of terrain and possible level differences between foundations. Parameter 5 evaluates the rigidity of the slabs and their connections to the vertical structural elements. Plan and vertical irregularities (Parameters 6 and 7) describe the building plan shape and the vertical setbacks. Parameter 8 describes column-beam and column-slab connections, because deficient connection leads to a non-ductile behavior of the structures. Parameter 9 refers to the presence of low-ductility structural elements, such as short columns. Parameter 10 describes non-structural external or internal elements that may collapse depending on their connection quality to the structural elements. Parameter 11 relates to the presence of deficiencies due to lack of maintenance or to poor construction process. Once the eleven parameters are defined and qualification classes are associated to each parameter according to the manual use of the GNDT II level method, a score is assigned to each class and a weighed sum of the eleven parameters is performed. Table 1 shows the GNDT II level parameters, with the respective qualification and weight developed by Yépez et al. (1996). The vulnerability index is obtained as the weighed sum using Equation 1. The normalized vulnerability index V ranges between 0; the lowest vulnerability and 100; the highest vulnerability.

$$I_V = \sum_{i=1}^{11} K_i W_i \quad (1)$$

where; I_V is the vulnerability index, K_i is the quantification associated to each building parameter and W_i is the weight assigned to the parameter.

Table 1. GNTD II level parameters, scores and weights for reinforced concrete buildings, according to Yépez et al. (1996)

Number	Parameter	Quantification K_i			Weight
		A	B	C	
1	Type and organization of earthquake-resistant system	0	1	2	4.0
2	Quality of earthquake-resistant system quality	0	1	2	1.0
3	Conventional strength	-1	0	1	1.0
4	Location and soil condition	0	1	2	1.0
5	Floor diaphragms	0	1	2	1.0
6	Plan configuration	0	1	2	1.0
7	Elevation configuration	0	1	3	2.0
8	Connectivity between elements	0	1	2	1.0
9	Low-ductility elements	0	1	2	1.0
10	Non-structural elements	0	1	2	1.0
11	Building condition	0	1	2	2.0

The Macroseismic Method

The macroseismic approach was developed based on the EMS-98 Macroseismic Scale (Grünthal, 1998). The objective of the method is to assess seismic vulnerability of a single building or a group of buildings, expressing the expected damage as a function of a vulnerability index V and macroseismic intensity I (Multinovic and Trendafiloski, 2003; Giovinazzi and Lagomarsino, 2004; Giovinazzi, 2005). In the EMS-98 scale, there are six vulnerability classes with increasing vulnerability from class A to class F, provided in a table format, assigned to different typologies of engineering and non-engineering buildings. Vulnerability class A is assigned to the most vulnerable or fragile structures, such as adobe or fieldstone, while vulnerability class F is assigned to buildings with high level of ERD. For RC buildings, the probable vulnerability class is C. Five grades of damage D_k (1-5) are introduced by the Scale (D_0: no damage, D_1: slight damage, D_2: moderate damage, D_3: heavy damage, D_4: very heavy damage and D_5: destruction), in a qualitative and quantitative approach, for a given macroseismic intensity degree (I to XII). In fact, the provided Damage Probability Matrix (DPM), which describes, for each of the vulnerability classes considered (A to F), the probability of experiencing certain damage grades at a given macroseismic intensity, is incomplete. In order to complete the distribution model of damage grades, the use of the binomial or the beta distribution was proposed. As employed in ATC-13, the beta distribution was used to complete the distribution model, by means of the beta probability density function (PDF) and the beta cumulative density function (CDF) (Giovinazzi and Lagomarsino, 2004; Lagomarsino and Giovinazzi, 2006). The resulting mean value of the distribution is expressed by the mean damage grade μ_D given in Equation 2, where P_k is the probability of having each damage grade D_k (k = 0–5). The mean damage grade μ_D is a continuous parameter representing the average damage within a set of damaged buildings.

$$\mu_D = \sum_{k=0}^{5} p_k\, k \quad 0 < \mu < 5 \qquad (2)$$

Vulnerability curves are obtained using an analytical function correlating the mean damage grade μ_D with the macroseismic intensity I and the vulnerability index V (Equation 3). This function was obtained by repeating the procedure of damage distribution for each vulnerability class and different intensity degrees, resulting in a curve defining μ_D as a function of I. For the implementation of the methodology, the analytical function (Equation 3) correlating the μ_D curve was defined (Giovinazzi and Lagomarsino, 2004).

$$\mu_D = 2.5\left[1 + tanh\left(\frac{I+6.25V-13.1}{2.3}\right)\right] \qquad (3)$$

In the macroseismic approach, the vulnerability index V assigned to buildings is defined as the sum of the typological vulnerability index vulnerability index V_0 and the vulnerability scores assigned to modifier parameters, such as regularity and state of maintenance (Lagomarsino and Giovinazzi, 2006).

The fragility of a structure is defined as the probability of failure at a given value of intensity or acceleration; peak ground acceleration or spectral acceleration (Taïbi et al., 2020). Fragility curves defining the probability to reach or exceed a certain damage grade are expressed as follows (Barakat et al., 2018; Chieffo and Formizano, 2019a, b):

$$P(D \geq D_k) = 1 - P(k) \qquad (4)$$

The Proposed Method

A combination of the GNDT II level and the macroseismic methods is performed, with the objective to express, through correlation between the peak ground acceleration PGA and the macroseismic intensity I, the seismic fragility of building typologies (Azizi-Bondarabadi et al., 2016). Vulnerability curves express the mean damage grade μ_D as a function of the macroseismic intensity I and the vulnerability index V, while fragility curves express the probability of having a damage grade μ_D as a function of the macroseismic intensity I or the peak ground acceleration and the vulnerability index V. The vulnerability index is an arbitrary value obtained as a sum of scores, which quantify in a conventional way the seismic behavior of a building; it is assessed using the GNDT II level method (Table 1). Having the value of the index V using Equation 1, the mean damage grade μ_D is calculated using Equation 3 and the vulnerability curves are obtained. The resulting fragility curves are obtained by applying Equation 4 of the macroseimic method, where the intensity I is correlated to the PGA.

A number of correlations between the macroseismic intensity I and the peak ground acceleration PGA were formulated, based on post-earthquake observations (Guagenti and Petrini, 1989; Margottini et al., 1992; Murphy and O'Brien, 1977) (see Fig. 3). However, as reported by the EMS-98 scale (Grünthal, 1998), the relationship between them is complex, revealing that correlations between intensity and peak ground acceleration show sometimes scattering. PGA is a parameter related to the local site conditions, while the macroseismic intensity I is used to classify the severity of an earthquake on the basis of observed effects within a limited area. The relationship developed by Guagenti and Petrini (1989) (Equation 5) was employed in this study, where a_{max} is the PGA (g) and I is the EMS intensity.

$$log a_{max} = 0.602I - 7.073 \quad (5)$$

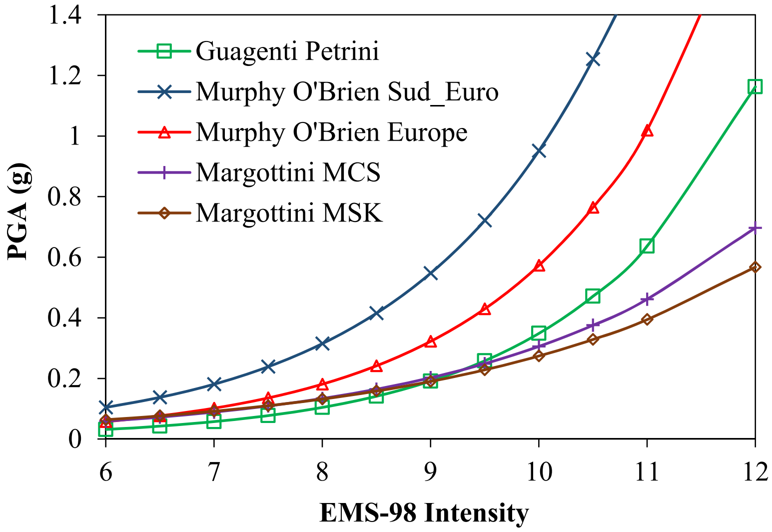

Figure (3): Correlations between macroseismic intensity I and peak ground acceleration PGA

Analysis of Collected Data

The database results from field investigation of buildings in the study area, as well as gathering structural and non-structural characteristics are illustrated in Table 1. According to the database, 58% are primary existing RC building built in 1970 and 42% are new RC buildings built in 2009-2010 (see Fig. 4(a)), with nearly 98% consisting of five stories and 2% consisting of 4 stories. 42% are new buildings with RC shear wall structure and 58% are existing buildings with RC frame structure, from which 56% were strengthened (Fig. 4(b)). Accordingly, three typologies of buildings are defined: (1) RC1: RC frame non-strengthened structure, (2) RC2: RC frame strengthened structure and (3) RC3: RC shear wall structure (see Fig. 4(b)).

According to EMS-98 definitions, the RC1 typology, designed prior to the first Algerian seismic code introduced in 1981, RPA81, is treated as having a low level of ERD, thus its probable vulnerability class is 'C'. Taking into account the low quality of the resistant system, due the presence of continuous frames in one direction only (see plan view in Fig. 2(d)) and the presence of short columns, this typology is finally decreased to vulnerability class B. Consequently, the RC2 typology is treated as having a moderate level of ERD, so its most probable vulnerability class is 'C'. It is assumed that the buildings resistant capacity is moderately increased regarding to the initial structural features and the quality of strengthening (Al-Dwaik and Armouti, 2013; Al-Far and Al-Far, 2016). RC3 typology, with RC shear wall structure system, designed according to the last seismic code RPA99, 2003 version (CGS, 2003), is treated as having high level of ERD; thus, its most probable vulnerability class is 'E'. Distribution of vulnerability classes assigned to buildings within Ibn Khaldoun area is shown in Fig. 5.

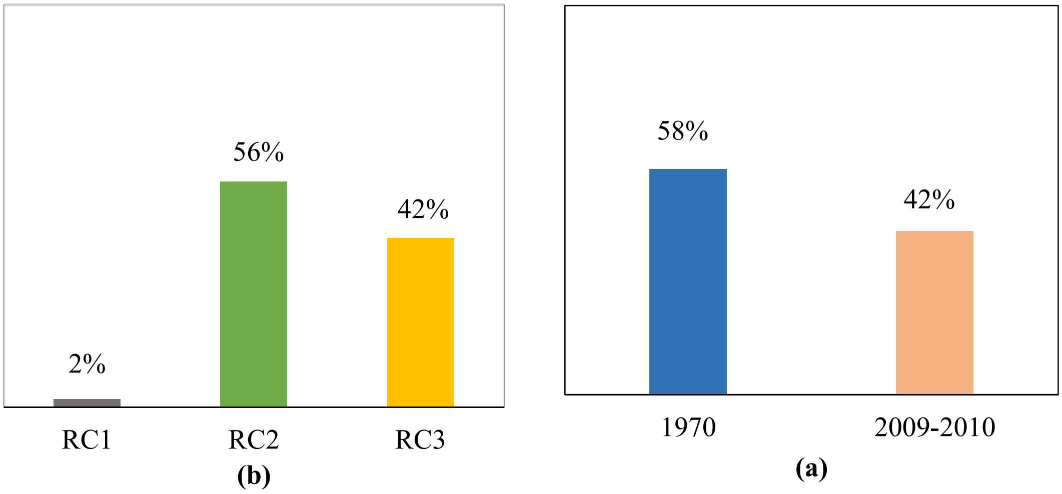

Figure (4): Percentages of residential buildings in Ibn Khaldoun area according to: (a) year of construction, (b) building typologies associated to the structural system (RC1: RC frame system, RC2: RC frame system (strengthened), RC3: RC shear wall system)

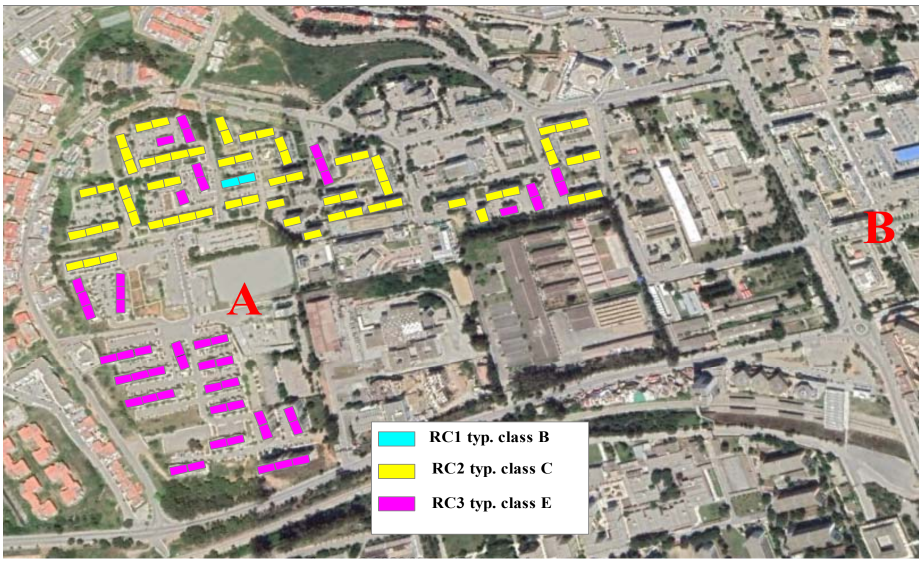

Figure (5): Distribution of vulnerability classes assigned to buildings in Ibn Khaldoun area

Vulnerability and Fragility Curves

As previously noted, the purpose of the proposed method is to construct vulnerability and fragility curves for the three RC building typologies in the study area. Vulnerability curves are obtained according to the macroseismic method using Equation 3, by calculating the mean damage grade μ_D as a function of macroseismic intensity I and the vulnerability index V assessed using Equation 1 of the GNDT II level method (Table 1). Parameters in Table 1 are examined based on field observations and qualifications (A, B, C) are assigned accordingly to GNDT II level definitions, scores and weights, as shown in Table 1. The correlation between PGA and macroseismic intensity I is employed using Equation 5, developed by Guagenti and Petrini (1989). Fig. 6 shows the obtained vulnerability curves of the three RC building typologies (RC1, RC2 and RC3) as a function of the resulting values of the vulnerability index V (V(RC1) = 0.6, V(RC2) = 0.47 and V(RC3) = 0.2) and the macroseismic intensity I. Vulnerability classes were assigned respectively to the three typologies according to the EMS-98 definitions and ranged from B to E. The obtained curves for each type of building indicate a common shape in the central part. The highest mean damage grade values are obtained for the highest values of macroseismic intensity I and vulnerability index V. For the lowest values of I, the expected mean damage grade is very low and approaches zero.

Resulting fragility curves for the three building typologies, defining the probability to reach or exceed a certain damage grade D_k, are obtained using Equation 4 of the macroseismic method. Figs. 7 shows the fragility curves for RC1, RC2 and RC3 building typologies as a function of the intensity I. The curves indicate that the highest probability $P(D \geq D_k)$ to reach or exceed a certain damage level is obtained for the highest values of I and V. For the lowest values of I, there is a high probability to reach non-structural damage (damage grades 1 and 2) and for the highest values of I, there is a high probability to reach structural damage (damage grades 3, 4 and 5). For the less vulnerable type (V=0.2), the probability to reach very heavy structural damage, for the highest value of I, is lowest.

Fig. 8 shows the probability of reaching or exceeding a damage grade as a function of PGA. Similarly, for the highest values of PGA and V, probability of having or exceeding structural damage grades is highest. It is to be noted that earthquake ground motion intensity is usually expressed in terms of PGA. In addition, the Algerian seismic code uses the PGA parameter for the seismic design of structures. From the curves, for intensity I(EMS)=X, PGA=0.348g, corresponding to the most intensity recorded during the 2003 Boumerdes earthquake, the resulting fragility curves show a highest probability of having or exceeding damage grades D_4 and D_5 for RC1 building typology and a lowest (zero probability) for RC3 typology.

Comparison

The objective here is to use the resulting vulnerability curves (Fig. 6) as the damage function for RC building typologies. To verify and validate the curves for past earthquakes in Algeria, detailed post-earthquake data is required. Detailed data relating the recorded damage grades to the structure types as a function of seismic intensity is unavailable, except for the 2003 Boumerdes earthquake. However, this data concerns only the city of Boumerdes, where an intensity of X was estimated according to EMS-98 by the Algerian Research Center of Astronomy, Astrophysics and Geophysics (CRAAG) (Harbi et al., 2007).

It is clear that this data is insufficient to construct a damage probability matrix (DPM) describing the probability of experiencing a certain damage level for each vulnerability class for a given intensity. However, a comparison can be made based on the available limited post-earthquake data and the resulting curves. Table 2 shows the number of RC1, RC2 and RC3 building typologies that suffered different damage grades, during the 2003 earthquake, throughout the city of Boumerdes. The mean damage grade μ_D corresponding to each typology, presented in Table 2, is calculated using Equation 1 and then the resulting μ_D damage points are plotted. Fig. 9 shows the obtained μ_D points and corresponding vulnerability curves with index values of 0.6, 0.47 and 0.2 for the types RC1, RC2 and RC3, respectively.

An accordance is noted between the vulnerability curves of the building typologies resulting by combining the GNDT II level and macroseismic methods and the obtained points for I(EMS) = X, corresponding to damaged buildings in the Boumerdes earthquake.

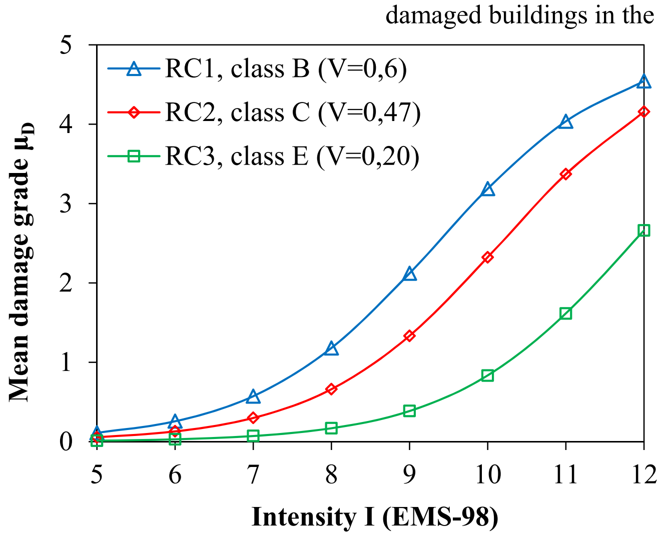

Figure (6): Vulnerability curves as a function of macroseismic intensity I (RC1 (V=0.6), RC2 (V=0.47) and RC3 (V=0.20))

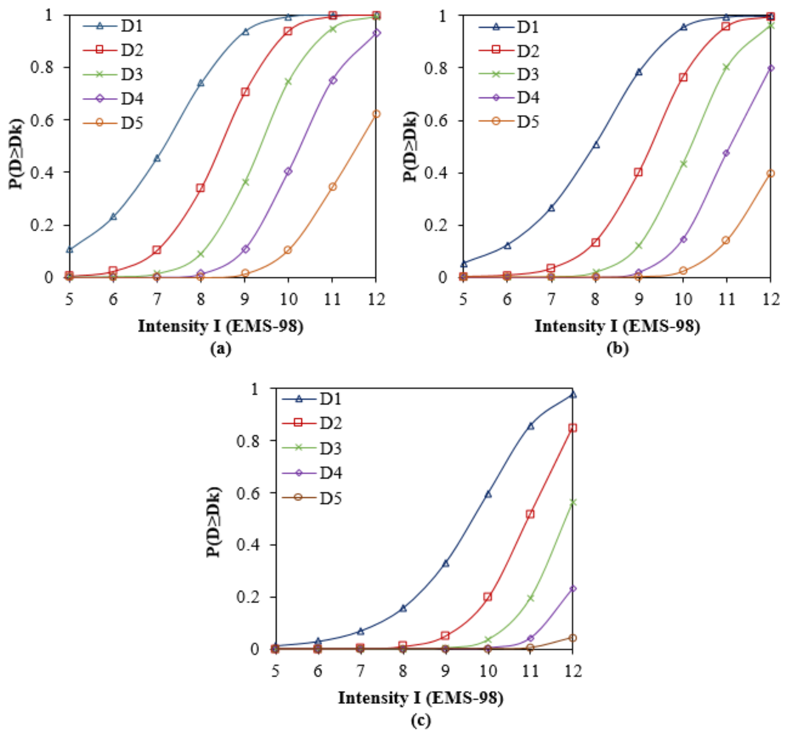

Figure (7): Fragility curves as a function of macroseismic intensity I: (a) RC1 (V=0.6), (b) RC2 (V=0.47) and (c) RC3 (V=0.20)

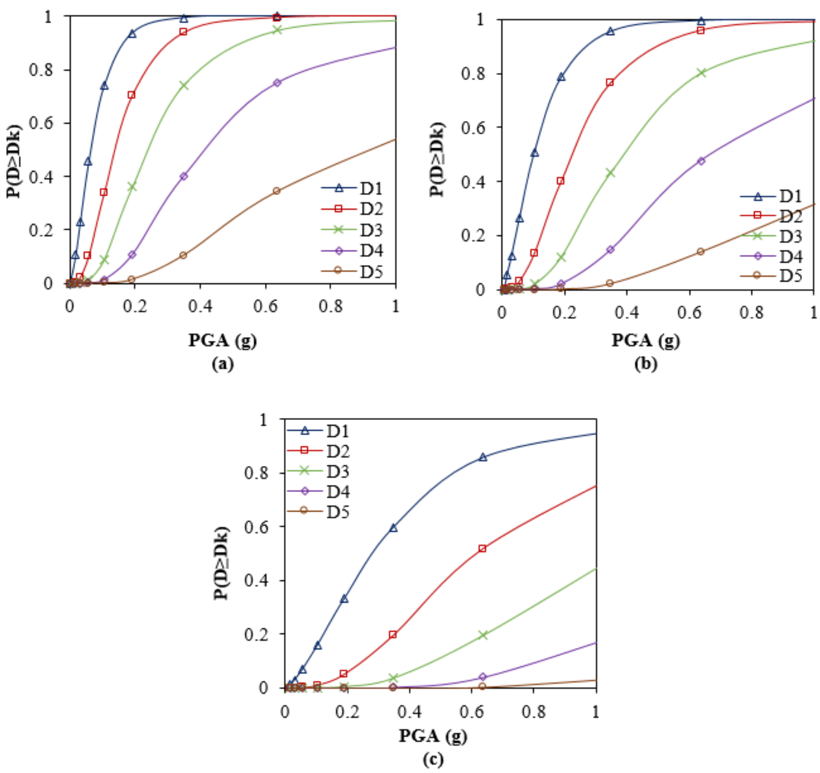

Figure (8): Fragility curves as a function of peak ground acceleration PGA: (a) RC1 (V=0.6), (b) RC2 (V=0.47) and (c) RC3 (V=0.20)

Table 2. Number of damaged RC buildings in Boumerdes city during the 2003 Boumerdes earthquake

	Intensity	D_1	D_2	D_3	D_4	D_5	μ_D
RC1	X	40	132	15	81	15	2.64
RC2	X	62	32	43	18	17	2.39
RC3	X	64	3	1			1.07

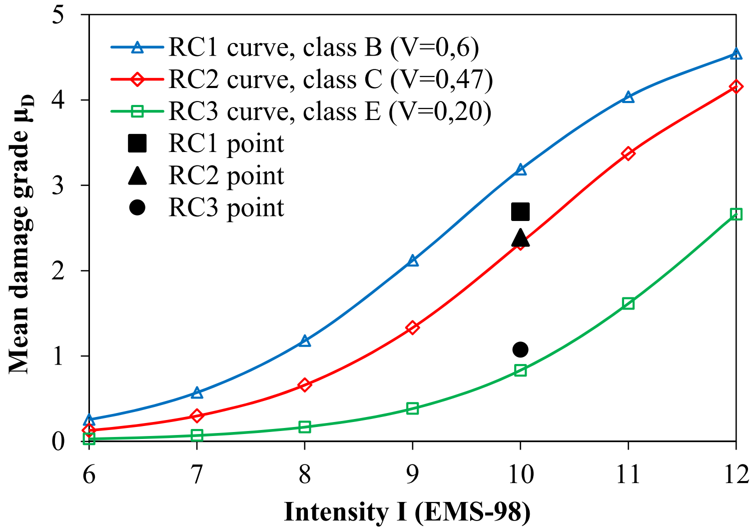

Figure (9): Vulnerability curves for RC1, RC2 and RC3 building typologies and Boumerdes earthquake (I=X) points for corresponding building types

CONCLUSIONS

This paper presents a method to develop vulnerability and fragility curves for three residential building typologies, by combining two seismic vulnerability assessment methods; the macroseismic method and the GNDT II level method, with the aim of obtaining firstly the normalized vulnerability index and then the mean damage grade.

To assess seismic vulnerability, building characteristics were collected based on field survey. Strengthening details were examined, revealing inadequacy in terms of increasing the seismic capacity of the buildings. Using data processing, building typologies were defined and their probable vulnerability classes were assigned. Resulting vulnerability curves are obtained by means of the mean damage grade defined by the macroseismic method, as a function of normalized vulnerability index and macroseismic intensity. Using I-PGA correlation, fragility curves are obtained as a function of peak ground acceleration. Resulting curves show that the highest probability of having very heavy damage grade is obtained for the highest values of I for the most vulnerable typology.

Comparison of post-earthquake data of the 2003 earthquake with the resulting curves show good accordance; hence, the method can be used for buildings with similar structural characteristics. However, regarding insufficient data, it is concluded that the use of the resulting vulnerability curves as the damage function for RC building typologies cannot be generalized.

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