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Seismic vulnerability of Algerian reinforced concrete houses

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Abstract. Many of the current buildings in Algeria were built in the past without any consideration to the requirements of the seismic code. Among these buildings, there are a large number of individual houses built in the 1980's by their owners. They are Reinforced Concrete (RC) frame structures with unreinforced hollow masonry infill walls. This buildings type experienced major damage in the 2003 (Algeria) earthquake, generated by deficiencies in the structural system. In the present study, special attention is placed upon examining the vulnerability of RC frame houses. Their situation and their general features are investigated. Observing their seismic behavior, structural deficiencies are identified. The seismic vulnerability of this type of buildings depends on several factors, such as; structural system, plan and vertical configuration, materials and workmanship. The results of the vulnerability assessment of a group of RC frame houses are presented. Using a method based on the European Macroseismic Scale EMS-98 definitions, presented in previous studies, distribution of damage is obtained.

Keywords: damage; individual houses; reinforced concrete; seismic vulnerability

1. Introduction

During the last few decades, the northern part of Algeria has been struck by a series of moderate to strong earthquakes, resulting in many deaths and considerable economic losses. It was during that period, that the northern cities were experiencing a high growth rate, and a large number of residential buildings, infrastructures and facilities were constructed. The latest earthquake that affected Algiers region is the Zemmouri earthquake (in Boumerdes province), on May 21st, 2003 (Io =X, Ms=6.8). It was located along the northern margin of the Tellian Atlas, along the offshore part of the eastern continuation of the Mitidja basin (Bouhadad *et al*. 2004). This event caused widespread damage to buildings and infrastructures, particularly to masonry and RC frame structures. RC houses were seen to suffer damage ranging between extensive damage and collapse.

In Algeria, the construction of RC frame buildings with unreinforced infill walls became more common after the 1960's. Prior to 1960 and during the first half of the 20th century masonry was the predominant type of construction. According to their resisting elements type, RC buildings can be classified into two groups: (1) RC frame buildings with unreinforced masonry hollow brick infill walls, and (2) RC shear wall buildings. The first category includes a large number of private houses built after 1980 without any consideration to the requirements of the seismic code in force

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or using any quality control measures. In fact, before the 2003 earthquake, the existing seismic codes in Algeria were only required to be applied to public buildings, and not to private houses for which only architectural plans were required to obtain a construction permit. The houses were built by their owners, including usually structural irregularities and soft first stories for commercial purposes.

Before 1981, there was no official seismic design code for buildings in Algeria. The French guidelines and recommendations for the design of buildings had been introduced and enforced, for example: AS55, PS62 and PS69 (AS55: Règles Anti-Sismiques in 1955, PS62: Règles Para-Sismique in 1962, and PS69 in 1969). In 1981, following El Asnam earthquake of 1980, the first official Algerian seismic design code RPA81 was published (CTC 1981). Revisions with minor modifications were made to the code in 1983 and 1988. The seismic code was revised again in 1999, RPA99 (CGS 1999), where major modifications were made such as the introduction of soil classification. It was the last version to be published before the 2003 earthquake, and all versions concerned only public buildings.

Most of the recorded damages to RC houses in the 2003 earthquake were due to particular conditions, including: undersized sections, insufficient longitudinal reinforcement, weak concrete strength, building irregularity, bad quality of construction materials and workmanship, and soft stories (Belazougui 2008). In fact, a high percentage of heavily damaged RC houses have soft stories at the first-floor level. Observed damage after strong earthquakes indicates a poor performance of this type of structures.

In the present work, the seismic vulnerability of RC frame houses is assessed. The seismic vulnerability study is conducted considering a group of individual houses: “El Djorf” group, situated in Algiers area. The macroseismic method, which was originally developed by the authors (Giovinazzi and Lagomarsino 2001, 2004) from the definitions provided by the European Macroseismic scale EMS-98 (Grunthal 1998), is used to assess the seismic vulnerability. The seismic vulnerability is obtained in terms of distribution of damage for given intensities. Considering a representative prototype house, structural analysis according to the Algerian seismic code is performed to obtain the inter-storey drifts. Damage presentation is expressed in terms of vulnerability and fragility curves, expressing the probability of reaching or exceeding a performance level for a given earthquake intensity measure.

2. Situation of RC frame houses

In the 1980’s, Algeria was in a rapid growth population and difficult living conditions period. To solve the housing crisis, the Algerian government encouraged its citizens to build their own homes. The housing developments were established surrounding large cities and in some cases separately. They are very close neighboring RC buildings, where the distances between them are just a few centimeters (about 5 cm). The buildings are 1 to 3 stories height (in some cases more), used for housing purposes, while the first level is frequently used for commercial purpose (Fig. 1). Generally a family unit, composed by parents and more than four children, occupies a single floor. When one of the boys establishes his own new family, they move to an upper new floor, built over the one of their parents. The houses are built usually in phases, starting from the first storey and progressively growing up to 3 stories or more. The used materials consist of reinforced concrete for the frames and hollow bricks bonded with mortar for the walls. The plan configuration of the buildings is mostly rectangular. The façades are in the shortest side of the plan

Fig. 1 General view of a group of RC houses

with the openings for doors and windows, which are built in different materials such as wood and steel. The structural system is a two-direction RC frame, with a square or rectangular section of beams and columns (25×25 cm², 25×30 cm², in max. 30×30 cm²). The infill walls are built with hollow brick masonry, bonded together with a low-quality of mortar. The floors and roofs consist of concrete beams of 12 cm wide, parallel to the shortest side and spaced 65 cm apart, hollow blocks (65cm×20cm×16cm) between them, and a RC topping of around 4 cm. The total slab height is 20 cm. The stairs connecting the levels are generally inside the building, built in reinforced concrete. The foundations are composed of isolated RC footings supporting the columns, and connected at most with 20×20 cm² reinforced concrete tie beams. The first phase of construction starts with the isolated footings, from which come out the longitudinal reinforcements of the columns. The next step is to cast the columns with leaving longitudinal reinforcement bars at the top of the columns (about 30 to 40 cm). The beam-column connections have a poor detailing with absence of stirrups. The beams and the floor are casted at the same time. After, the exterior and interior brick masonry walls of the first storey are erected.

The construction quality of many elements in the structure is not adequate. This type of buildings was addressed by the codes and standards of the country; all the versions of the seismic code and the reinforced concrete code “CBA93” (CGS 1993). However, the seismic code was not enforced in private buildings construction, and most of the buildings have been built without any seismic resistant design or strengthening provisions and have been severely affected in Algerian earthquakes. In addition, the self-constructed and phased features did not allow quality control for the materials and the workmanship. After the 2003 earthquake, all newly built private houses were, for the first time, required to comply with the requirements of the code in the goal to protect human lives and safety in case of strong earthquake.

3. Damage observed in RC frame houses

RC frame buildings with hollow brick infill walls experienced great amounts of damage in

Table 1 Categories of building damage

Category	Damage state
Green	Very little damage. Can be reoccupied immediately.
Orange	Needs further study before it can be either occupied or condemned.
Red	Condemned and should be demolished

Table 2 Categories of building damage and damage degrees according to the EMS-98 scale

Category	Damage	Description
Green	Degree 1	Negligible to slight damage (no structural and slight non-structural damage)
	Degree 2	Moderate damage (slight structural and moderate non-structural damage)
Orange	Degree 3	Substantial to heavy damage (moderate structural and heavy non-structural damage)
	Degree 4	Very heavy damage (heavy structural and very heavy non-structural damage)
Red	Degree 5	Destruction (very heavy structural damage)

(a) Excessive shear and axial failure

(b) Soft storey collapse

Fig. 2 Damage to RC houses during the 2003 Algeria earthquake

several earthquakes. The damage observation for recent earthquakes in Algeria, express in general, how RC frame structures suffer severe damage from a strong earthquake, and identifies the deficiencies of the structural and non-structural system. The earthquake of 2003 affected the entire Boumerdes province (Wilaya) and a part of Algiers province, where the effects accounted for approximately 2287 dead and more than 11000 injured (EERI 2003). A total of 181658 buildings were investigated using an evaluation form for the quick inspection. The first task of this field investigation was to classify all buildings into one of the damage categories shown in Table 1. These categories of damage employed (Green, Orange and Red), corresponded very closely to the five degrees of damage classification reported in the EMS-98 scale (Grunthal 1998) as shown in Table 2. In Boumerdes only, 7400 RC buildings were collapsed and 7000 buildings were heavily damaged.

In general, failure mechanisms are related to the lack of adequate sizing and reinforcing of

(a) Shear failure in columns (b) Damage to beam-column joint (c) Damage to short columns

Fig. 3 Structural failure mechanisms

columns, beams and beam-column joints, and to the performance of the infill masonry walls (Fig. 2(a)). Also, a greatest part of partially collapsed structures that could not be repaired were the structures with the soft first storey (Fig. 2(b)). The observed damage in the infill walls are diagonal cracks, out-of-plane failure with partial or total collapse of walls. This damage was due to the fragility of the walls and to the poor connection between the masonry units and the RC frames.

The typical damages in columns were; shear failure, compressive failure with buckling of longitudinal reinforcement and loss of concrete confinement, and in some cases rotations at the ends of the columns with cracking and loss of concrete (Fig. 3(a)). This damage was generated by deficiencies in RC frames; non-ductile detailing such excessive stirrup spacing and insufficient anchorage of longitudinal reinforcing bars, inadequate shear strength of beam-column joints and inadequate confinement (absence of transverse reinforcement in beam-column connection) (Fig. 3(b)). Columns were also small-sized with inadequate and poor reinforcing; longitudinal reinforcement amount was usually 4 rebars of 12 mm, with excessive distance between consecutive transverse reinforcement bars.

4. Vulnerability assessment

The seismic vulnerability of a structure can be described as its susceptibility to suffer a certain level of damage when subjected to a seismic event of a given intensity (Lang and Bachmann 2003). In other words, the aim of a vulnerability assessment is to obtain the probability of damage to a given building type in relation to a seismic event. The classification of the methods of seismic vulnerability assessment is based on the criteria used in the evaluation study and the scale of application (building, aggregate, urban area). It is important to understand the difference between the detailed approaches used for individual buildings and the techniques used for analysis of groups of buildings. Vicente *et al*. (2011) divided the different techniques of seismic vulnerability assessment in four groups; direct, indirect, conventional and hybrid techniques. (a) Direct techniques assess in a simple way the damage caused in a structure by a given earthquake. (b)

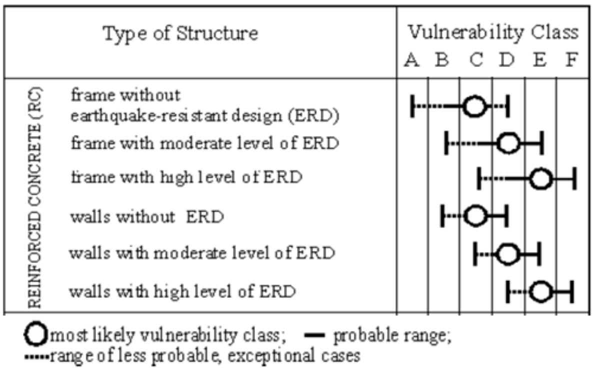

Fig. 4 EMS-98 Vulnerability Table for reinforced concrete building typologies

Indirect techniques determine first a vulnerability index of the structure and then assess the relationship between damage and seismic intensity. (c) Conventional techniques are essentially heuristic, introducing a vulnerability index independently of the damage prediction. (d) Hybrid method combine features of the methods described previously, such as vulnerability functions based on observed vulnerability and expert judgment. Calvi *et al*. (2006) divided the various existing methods of vulnerability assessment into two main categories; empirical and analytical methods, both of which can be used in hybrid methods. Empirical methods for the seismic vulnerability assessment of buildings are essentially based on the damage observed after earthquakes. The selection of one of these methods depends on the objectives of the study, on the available information and the type of the results required.

The concept of the damage probability matrices (DPM) was introduced expressing in a discrete form the conditional probability of obtaining a damage level, due to a ground motion of a given intensity (Whitman *et al.* 1973). A macroseismic method has recently been proposed (Giovinazzi and Lagomarsino 2001, 2004), expressing the damage probability functions based on the definitions provided by the EMS-98 macroseismic scale. The EMS-98 scale defines qualitative descriptions of “Few”, “Many” and “Most” for five damage grades for the levels of intensity ranging from V to XII for six different classes of decreasing vulnerability (from A to F). Damage matrices, containing a qualitative description of the proportion of buildings that belong to each damage grade for various levels of intensity, were obtained for all vulnerability classes.

In the EMS-98 scale, the RC buildings are represented by six typologies; RC frame and RC shear walls with increasing level of earthquake resistant design (ERD) as shown in Fig. 4. Their most likely vulnerability classes are: C, D and E, representing respectively: structures without ERD, with moderate level of ERD and with high level of ERD. According to the scale, buildings with high level of ERD are those designed to earthquake with high intensities and will sustain structural damage without loss of structural integrity and stability. For these buildings damage is permitted but should not exceed grade 3. Structures with moderate level of ERD are buildings designed to earthquakes of medium intensity and should sustain such events with only slight non-structural damage, but without loss of serviceability. For each building type in Fig. 4 there is a line showing the probable and the less probable ranges. These ranges exist because vulnerability also depends on modification factors such as; quality of workmanship, state of preservation, regularity, ductility, position, strengthening, and earthquake resistant design level.

A conventional vulnerability index V representing the belonging of a building to a vulnerability

Table 3 Vulnerability index values for RC building typologies

RC typologies	Building type	V^{--}	V^{-}	V_0	V^{+}	V^{++}
RC1	RC frame without ERD	0.3	0.49	0.644	0.8	1.02
RC2	RC frame with moderate ERD	0.14	0.33	0.484	0.64	0.86
RC3	RC frame with high ERD	-0.02	0.17	0.324	0.48	0.7
RC4	Shear walls without ERD	0.3	0.367	0.544	0.67	0.86
RC5	Shear walls with moderate ERD	0.14	0.21	0.384	0.51	0.7
RC6	Shear walls with high ERD	-0.02	0.047	0.224	0.35	0.54

class was introduced (Lagomarsino and Giovinazzi 2006). The values of this index are arbitrary because they are scores to qualify the building behavior. The index value is ranging between 0 and 1, 1 for the most vulnerable buildings and 0 for structures with high level of ERD. Table 3 shows the most probable value V_0 for each vulnerability class, the probable V^-/V^+ and the less probable vulnerability index ranges V^{--}/V^{++}. The correlation between the expected damage, in terms of mean damage μ_D, and the seismic input as a function of the assessed vulnerability, is expressed in terms of vulnerability curves described by a closed analytical function (Lagomarsino and Giovinazzi 2006)

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

Where; I is the macroseimic intensity, V and Q are, respectively, the vulnerability and the ductility index. In particular, for the ductility index, the value Q = 2.3 resulting from the macroseismic approach has been maintained representing buildings not especially designed to have ductile behavior. μ_D represents the mean damage value of the discrete damage distribution (Eq. (2)); it ranges from 0 to 5. P_k is the probability of having a damage grade D_k (k = 0/5).

$$\mu_D = \sum_{k=0}^{5} P_k k \tag{2}$$

The methodology applied in this study for the evaluation of the vulnerability of the entire group of houses can be considered as a hybrid technique in respect to criteria presented previously. The vulnerability index formulation proposed here, is based fundamentally on the GNDT II level approach (GNDT 1994), for the vulnerability assessment of RC buildings. This Italian methodology was based on post-seismic damage observation and survey data covering a vast area, considering the most important parameters affecting building damage. This procedure has been used in Italy and has been adopted for use in other European countries as Spain and Portugal, by the introduction of new parameters and redefinition of the criteria of some of the most important parameters. Here, a simplified form to assess the vulnerability of RC houses is proposed, containing 13 parameters (see Table 4), describing the deficiencies of the structural system based on visual observations.

A qualification is established from the less vulnerable “Low” to the most vulnerable “High”. A score ‘K_i’ is assigned to each vulnerability class of each parameter; from 0 (Low vulnerability) to 2 (High vulnerability). A weight W_i is assigned to each parameter, ranging from 1 for the less

Table 4 Vulnerability index parameters for RC buildings

Number	Parameters	Vulnerability Level ‘K_i’			Weight ‘W_i’
		Low	Medium	High	
1	Age of construction	0	1	2	1
2	Number of floors	0	1	2	1
3	Structural system type	0	1	2	3
4	Resisting system quality	0	1	2	1
5	Diaphragms	0	1	2	1
6	Soft storey	0	1	2	2
7	Short columns	0	1	2	1
8	Plan configuration	0	1	2	1
9	Vertical configuration	0	1	2	2
10	Seismic joints	0	1	2	1
11	Non-structural elements	0	1	2	1
12	Foundation and soil conditions	0	1	2	1
13	Preservation state	0	1	2	2

important parameters (in terms of structural vulnerability) to 3 for the most important ones (for example parameter 3 represents the structural system type). However, the definition of each parameter weight is a major source of uncertainty (Vicente *et al*. 2011).

The building vulnerability index V is calculated as the weighted sum of the vulnerability scores of the various parameters using Eq. (3). The weighted sum are finally modified to obtain a normalized range of variation $0<V<100$.

$$V = \sum_{i=1}^{i=13} K_i W_i \tag{3}$$

Some parameters were selected from the GNDT II level form, while the rest were proposed and defined according to the Algerian seismic code (CGS 2003). These parameters are described briefly as follows: (1) Three building age intervals were considered according to the code eras; before 1981, between 1981 and 1998 and after 1999. (2) The assumed building height classification is 1-2, 3-5 and more than 5 floors. (3) Buildings designed after 1981 were built according the seismic codes, with a certain level of ERD. Three categories of resisting system with increasing vulnerability classes were considered; “frame with no infill walls”, “frame with infill walls” and “shear walls”. The resisting system type describes the characteristics of the structural components able to absorb the major part of the seismic action. (4) The quality of the resisting system is evaluated with criteria related to construction materials and workmanship, such as; consistency of concrete, presence of irregular or porous areas, quality of execution of masonry walls and mortar quality. (5) Diaphragms parameter evaluates the rigidity of the slabs and their connections to the vertical resisting elements. (6) Soft storey parameter is introduced as an important parameter for which a weight 2 is assigned, because a majority of Algerian RC houses have soft first stories, and a greatest part of collapsed RC houses in the 2003 earthquake were the structures with soft first stories. (7) Short columns were also one of the main causes of damage to

Fig. 5 General view of the study area: “El Djorf” group of houses

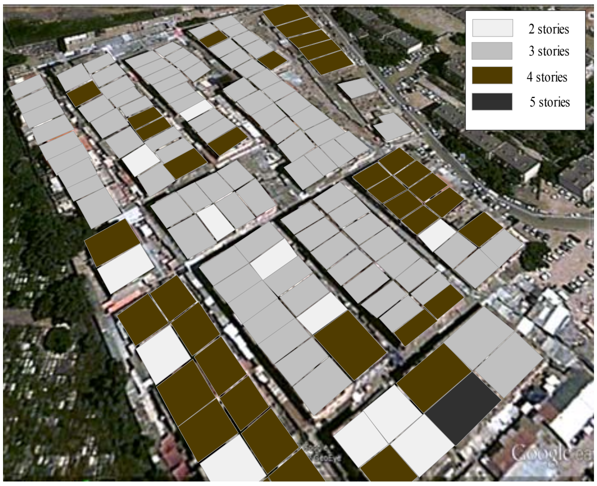

Fig. 6 Distribution of buildings according the number of stories

reinforced concrete structures. (8) Plan configuration depends of the plan shape of the building, as well as the mass and rigidity distribution of the resisting elements. (9) The vertical configuration parameter considers the vertical irregularity of the building by describing the vertical setbacks and quantifying mass variations. (10) The seismic joint width between two adjacent blocks should not be less than 40 mm according to the seismic code requirements. (11) The quality of the internal and external non-structural elements (partition walls, chimneys, balconies, etc.) depends on their connection quality to the resisting structural elements. (12) Through visual observation, the consistency and the slope of site are evaluated, as well as the level differences between foundations. (13) The preservation state is a subjective parameter, qualified through visual inspection and penalizing the presence of structural fragilities and imperfection such as fissures or poor construction process.

5. Case study

Fig. 5 shows the study area; “El Djorf” group of houses. This group of individual RC houses is located 15 km East from Algiers the capital. The houses are privately owned, built after 1980 in the same style as in the previous descriptions. Some houses have been under construction from that time until now. The first stories are used as commercial areas. The houses structural system consists of reinforced concrete frames, with 1 to 5 stories height. Masonry infill walls are made out of hollow brick usually provided in the residential part of the building in the upper floors. The total number of surveyed houses is 145 (out of 150). This size allows visual observation and analysis of the entire houses.

5.1 Building typologies and vulnerability assessment

The inventory technique of assessing building information was derived with the European Macroseismic Scale EMS-98. General information like building age and number of floors can be easily assessed. While, the structural information assessment needs providing some detail levels. At the first stage, considering groups of buildings with similar characteristics in terms of seismic performance (masonry, reinforced concrete, steel or wood). In this case study, there is one group; reinforced concrete buildings. Secondly, a corresponding sub-type can be defined, e.g. RC frame or shear wall, with or without earthquake resistant design. Then, additional parameters can be considering such as; configuration and preservation state. With this technique, an inventory of buildings through the study area is carried out. 145 houses were inventoried considering the following characteristics; age of building, number of floors, structural system, plan and vertical configuration, soft storey, short columns, seismic joints, non-structural elements, soil conditions and state of preservation.

The site investigation shows that 63.4% of the houses are three stories height (Fig. 6). The plan configuration is mostly rectangular, while, about 35% of the houses present vertical irregularities and 20% contain soft first stories. The assignment of vulnerability classes to the inventoried buildings according the EMS-98 scale provides the following percentages; 64% of the buildings are vulnerability class B and 36% are class C.

The global vulnerability index of each building is evaluated using the proposed method based on the GNDT II level form (Table 4). The values obtained were normalized from 0 to 100, where 0 represents the least vulnerable buildings and 100 the most vulnerable. The range of the index variation is between 65 and 82, with the mean value V=72. Fig. 7 shows the spatial distribution of vulnerability classes depending on the type of structure according to EMS-98, and Figs. 8-9 show the spatial damage distribution in terms of mean damage grade for intensities I(EMS)=VIII and I(EMS)=IX. Such seismic vulnerability maps allow the identification of vulnerable buildings, which can be useful for the planning of urban management and protection plans. The vulnerable buildings correlate well with the observed building construction features; the configuration irregularity, the soft storey and the small-sized structural elements of the buildings.

5.2 Representative prototype house

Vulnerability of existing buildings can be assessed based on an estimation of their displacement under seismic forces (Calvi 1999, Priestley 1997). So, in order to compare the inter-storey drifts due to the lateral seismic forces to the allowed displacement required by the Algerian seismic code,

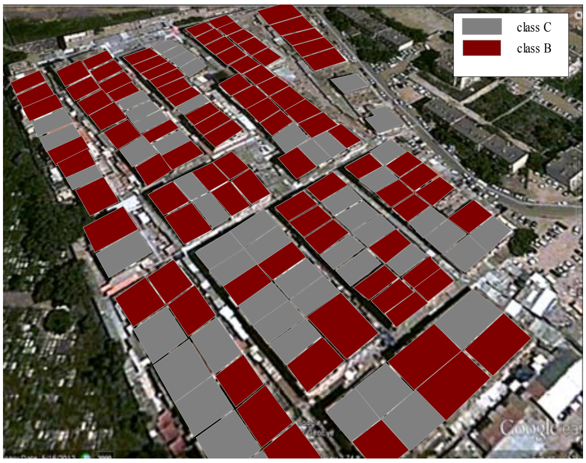

Fig. 7 Spatial distribution of vulnerability classes according to EMS-98

Fig. 8 Spatial damage distribution in terms of mean damage grade for *I*(EMS)=VIII

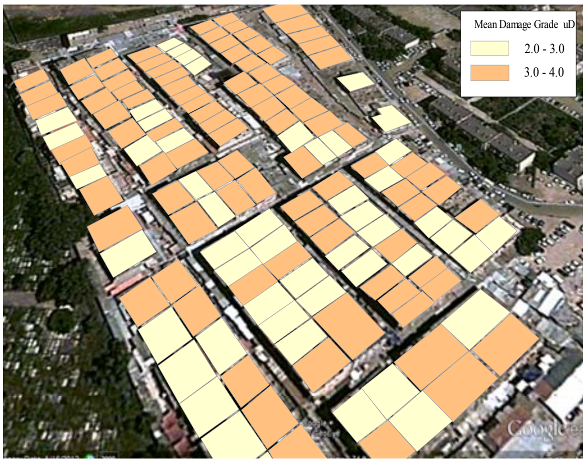

Fig. 9 Spatial damage distribution in terms of mean damage grade for *I*(EMS) =IX

a structural analysis of this type of buildings by the code is performed. Since each RC house cannot be analyzed separately, a representative prototype structure is considered. In the study area, the three-storey house with two-direction RC frame structural system is the most common. So, this representative building with average features is assumed to be built in the same style as in the previous descriptions. The RC prototype house is considered with the following characteristics:

- Regular configuration
- Ground storey height is 4.00 m
- Upper stories height are 3.06 m
- Building is erected on S_2 site category
- Compressive strength of the concrete at 28 days f_{c28} = 20 MPa
- Tensile strength σ_t = 1.8 MPa
- Columns section is 30×30 cm²
- Beams section is 25×30 cm²

These characteristics were selected based on the site investigation, including the following: exterior inspection of the buildings, interior ground floors inspection, and from the available data on material characteristics. A scheme of the prototype house is shown in Fig. 10.

5.3. Analysis by the Algerian seismic code "RPA 99 Version 2003"

After the 2003 earthquake, the Algerian seismic code was revised and published under the title "RPA99 version 2003" (CGS 2003). In this last version, the seismic zoning map was revised including new increased values of the seismic zoning factor A (acceleration coefficient). Algiers and Boumerdes, that had always been classified as Zone II, with A=0.15 (0.15 g as the PGA for the design of apartment buildings), were upgraded to Zone III, including new value of the seismic zoning factor A=0.25. In this version the earthquake-resistant provisions were improved. For example; (i) severe limitation of the height of RC frame buildings (2 stories in Zone III and 5 stories in Zone I); (2) the width of a short column must be less than the value of 1/4 of the column height to avoid short column failure; (3) the stirrup must be arranged with less than 10 cm interval at both ends of a column, and less than the interval of the minimum between the half of column width and the length of 10 times of rebar size. As mentioned previously, in this version, application of the seismic code became obligatory for private house owners.

In this section, the static lateral force procedure for seismic load calculation is presented briefly. The seismic code "RPA99 version 2003" defines a static lateral force procedure (simplified method) for determining the seismic actions on buildings. These actions do not apply to nuclear power stations, bridges, dams, tunnels and other important structures. The design base shear V is given by the following formula:

$$V = \frac{A\ D\ Q}{R} W \tag{4}$$

Where; A is the seismic zoning factor, D is the dynamic amplification factor, Q is the quality factor (penalty factor) and R is the behavior factor. The weight W of the building is calculated by assuming that the masses are concentrated at the floors. The value of A is given by the code, varying from 0.1 to 0.35 and depending of the seismic zone and the category of building. The value of D is computed by Eq. (5), where, T is the fundamental period, η is the correction factor of damping, given by the code according to the system resisting type (η=0.882). T_2 is the period

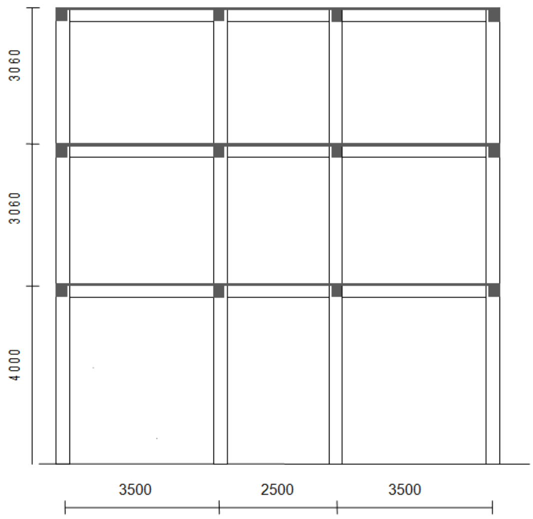

Fig. 10 Elevation of the representative prototype house

associated to site category (S_1: rocky, T_2= 0.3s; S_2: firm, T_2= 0.4s; S_3: soft, T_2= 0.5s and S_4: very soft, T_2= 0.7s) (Fig. 11). Q is depending of the resisting system organization, varying from 1 to 1.35. R is depending of the resisting system quality, varying from 2 to 5 for RC buildings. According to the seismic code, the weight W includes the dead loads and 20% of the live loads.

$$D = \begin{cases} 2.5\eta & 0 \le T \le T_2 \\ 2.5\eta (T_2 / T)^{\frac{2}{3}} & T_2 \le T \le 3.0s \\ 2.5\eta (T_2 / 3.0)^{\frac{2}{3}} (3.0 / T)^{\frac{5}{3}} & T \ge 3.0s \end{cases} \tag{5}$$

To conduct the structural analysis according to the code, the basic structural system is considered with gravity and permanent loads. The selected characteristics of structural materials are considered. This simplified analysis is performed in order to obtain the base shear force V and the inter-storey drifts under lateral forces. The fundamental period T of the building is computed from empirical expressions given by the seismic code (Eq. (6)). Where; C_t = 0.05 for RC frames with infill masonry walls and h_N is the height of the building.

$$T = C_t h_N^{\frac{3}{4}} \tag{6}$$

The total seismic force is distributed over the height of the structure as follows

$$F_i = \frac{(V - F_t)\, W_i\, h_i}{\sum_{j=1}^{n} W_j h_j} \tag{7}$$

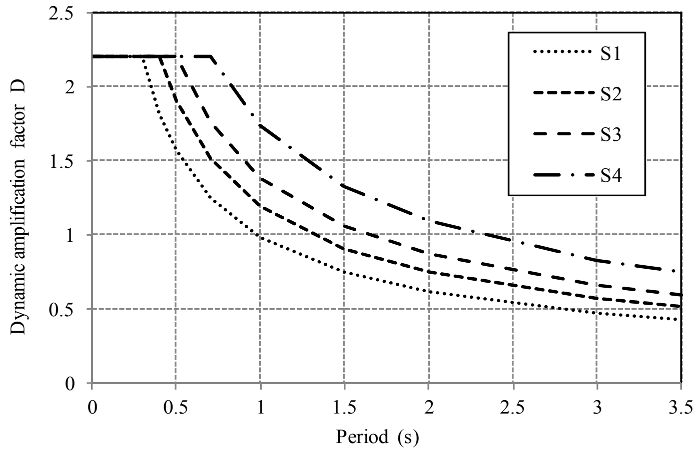

Fig. 11 Dynamic amplification factor D for different site categories

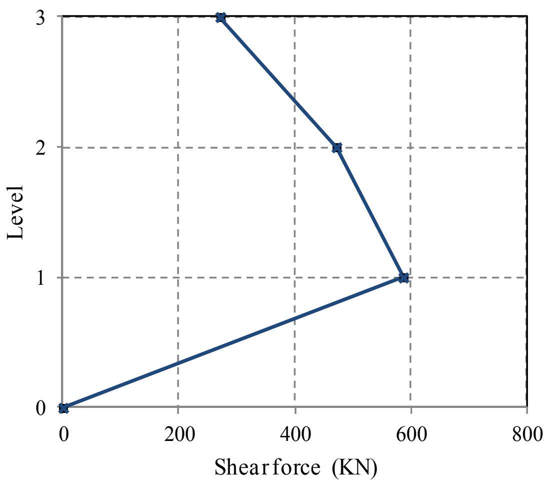

Fig. 12 Shear forces at different levels

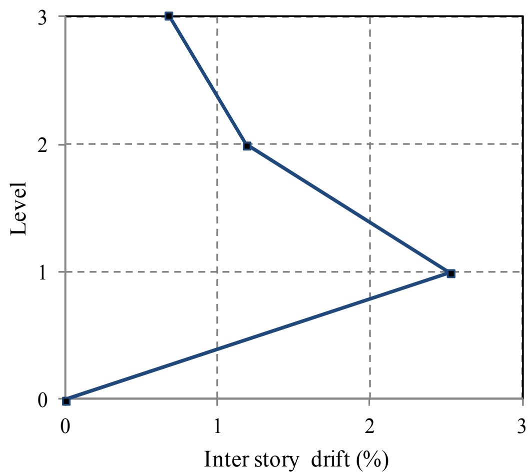

Fig. 13 Inter-storey drift ratios

F_i is the seismic horizontal force at the i^{th} level. F_t, is a concentrated force at the top of the structure, and equal to 0.07 TV, with the condition that $F_t \leq 0.25\ V$ and $F_t = 0$ when the period does not exceed 0.7 s. W_j is the weight at the j^{th} level and h_j the height from the base to the j^{th} level. h_i is the floor level where the force is applied (height from the base). Table 5 shows the distribution of the lateral seismic loads for both directions, and Fig. 12 shows the shear forces at different levels.

According to the requirements of the seismic code, the relative horizontal displacement between two adjacent floors should not exceed 1% of the storey height. The horizontal displacement δ_k, considered as a design displacement, at each level k of the structure is calculated by Eq. (8), where; δ_{ek} is the calculated horizontal displacement due to the seismic forces F_i, and R is the behavior factor. Displacement Δ_k at k level relative to k-1 level is given by Eq. (9). From the results shown in Fig. 13, it can be observed that the maximum inter-storey drifts under lateral forces exceeded the allowed values required by the seismic code.

Table 5 Distribution of the transversal and longitudinal seismic forces

Level	W_i (KN)	h_i (m)	$F_{i,x}$ (KN)	$V_{i,x}$ (KN)	$F_{i,y}$ (KN)	$V_{i,y}$ (KN)
3	990.15	10.12	271.08	271.08	271.08	271.08
2	1050.22	7.06	200.58	471.67	200.58	471.67
1	1065.66	4.00	115.32	586.98	115.32	586.98

Table 6 Structural performance levels, damage and inter-storey drift limit states (FEMA 356)

Performance Level	Collapse Prevention Level	Life Safety Level	Immediate Occupancy Level
Overall damage	Severe	Moderate	Light
Drift	4%	2%	1%

The maximum inter-storey drift ratio is adopted as a parameter to define the structural performance level as described in FEMA 356 (FEMA 2000). Three discrete qualitative structural performance levels are described in FEMA 356: immediate occupancy (IO), life safety (LS), and collapse prevention (CP). The inter-storey drift limit states for different structural performance levels are given in Table 6. The results show that the inter-storey drift ratio exceed the limit state of life safety (LS) level. The structural performance can be also quantified in terms of economic losses and collapse safety (Goulet *et al.* 2007).

$$\delta_k = R\ \delta_{ek} \tag{8}$$

$$\Delta_k = \delta_k - \delta_{k-1} \tag{9}$$

5.4. Vulnerability curves

The prototype house is RC1 typology according to the EMS-98 Vulnerability Table, as shown in Fig. 4 and Table 3. Its most likely vulnerability class is C, and its vulnerability index is ranging between 0.3 and 1 with the most probable value V_0=0.644 (Lagomarsino and Giovinazzi 2006). The mean vulnerability index value obtained for all RC houses in the first detailed evaluation V=0.72 (using Table 4) is considered as a typological vulnerability index that can be affected by modifiers of the mean vulnerability index for each RC house (Vicente *et al*. 2011). The calculated vulnerability index can then be used to estimate the expected building damage for a specified seismic intensity as shown previously, because in the methodology applied in this study, the vulnerability index is used as an intermediate step to estimate damage suffered by a building. Therefore, the average value V = 0.72 is used as the vulnerability index of the prototype house (probable value). Using Eq. (1), the vulnerability curve of this typology describing the mean damage grade for various intensities is obtained as shown in Fig. 14.

For each vulnerability class, the damage described by the scale for each degree of intensity may be reported in terms of a damage probability matrix (DPM). It is a matrix which expresses the statistical distribution of the degrees of damage (from damage grade 1 or slight damage, to damage grade 5 or destruction) for a given macroseismic intensity. These DPM are built for each of the vulnerability classes and intensities, expressing the probability that the damage grades are reached

Table 7 Probability P_k of occurrence of a damage grade for different intensities

EMS-98 Intensity	D_1	D_2	D_3	D_4	D_5
VI	0.3175	0.0662	0.0069	0.0004	0.0000
VII	0.4096	0.2038	0.0507	0.0063	0.0003
VIII	0.2889	0.3428	0.2034	0.0604	0.0072
IX	0.0860	0.2436	0.3449	0.2442	0.0692
X	0.0105	0.0709	0.2396	0.4048	0.2735
XI	0.0007	0.0106	0.0858	0.3457	0.5572
XII	0.0000	0.0011	0.0210	0.2017	0.7762

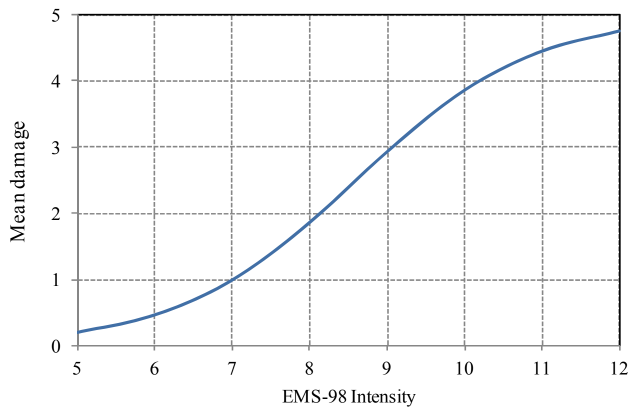

Fig. 14 Vulnerability curve of the prototype house

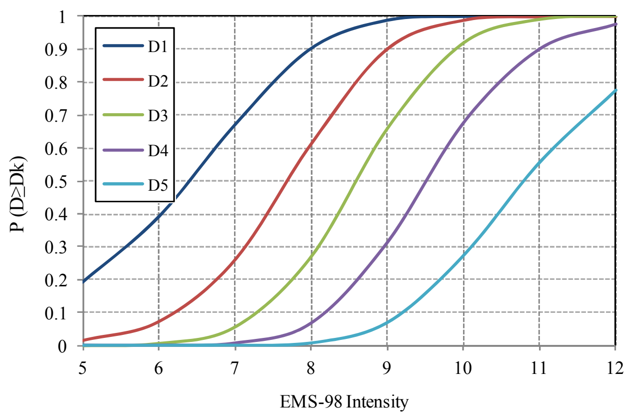

Fig. 15 Fragility curves of the representative prototype house

by the buildings. The DPM can be built using the binomial distribution to express building damage (Braga *et al*. 1982). The probability P_k of having each damage grade D_k (k = 0/5), for a certain mean damage μ_D, is evaluated according to the probability mass function (PMF) of the binomial distribution given by Eq. (10). For each mean damage, probability of having a damage grade is obtained considering intensities from I = VI to I = XII as shown in Table 7.

$$P_k = \frac{5!}{k!(5-k)!}\left(\frac{\mu_D}{5}\right)^k\left(1-\frac{\mu_D}{5}\right)^{5-k} \tag{10}$$

This DPM shows the evolution of the damage states as the intensity degree is incremented. For intensity I = VI, the probabilities of occurrence for slight-damage (D_1), moderate damage (D_2), substantial to heavy damage (D_3) and very heavy (D_4) are respectively 0.3175, 0.0662, 0.0069 and 0.0004. For intensity I = X, the probabilities of occurrence for heavy (D_3), very heavy (D_4) and destruction (D_5) damage grades are respectively 0.2396, 0.4048 and 0.2735.

The damage representation may be directly obtained in terms of fragility curves for each of the macroseismic intensities, where the curves represent the probability that the expected damage of the building will reach or exceed a fixed damage grade during the seismic event. The expression to obtain such curves is

$$P(D \geq D_k) = \sum_{j=k}^{5} P_j \tag{11}$$

Where; $P(D \geq D_k)$ is the probability of reaching or exceeding certain damage grade D_k, and P_j is the discrete beta density probability associated with damage grade j (for j = 0, 1, 2, 3, 4, 5). The obtained fragility curves of the RC prototype house are shown in Fig. 15.

6. Conclusions

Seismic vulnerability assessment of a group of RC frame houses was conducted. “El Djorf” group, situated in Algiers area, was selected to perform this study. In the first stage, buildings inventory for vulnerability and damage evaluation was assembled. Analysis of the inventoried houses based on visual observation, showed that the entire houses are vulnerability classes B and C, with respectively 64% and 36%. Distribution of damage for intensities *I*(EMS)=VIII et *I*(EMS)=IX was evaluated and mapped.

Structural analysis was then performed according to the Algerian seismic code “RPA 99 version 2003” considering a prototype house, for which a typological vulnerability index was determined. From the results obtained, it can be observed that the inter-storey drifts under lateral seismic forces exceed the allowed value required by the seismic code. The expected damage was expressed in terms of vulnerability and fragility curves, where the probability of reaching or exceeding certain damage grade was obtained considering various intensities. These fragility curves can be used in determining the potential losses resulting from earthquakes, and consequently retrofitting priorities. The study shows also that the use of simplified method based on statistical approaches and damage observation to treat a population of buildings in urban area becomes capable of providing important indicators of seismic vulnerability.

The existing RC frame houses in Algeria are vulnerable for moderate to severe earthquake. To reduce human and economic losses due to structural failure of this type of structures, it is desired to improve their seismic performance (Goulet *et al*. 2007). Unfortunately, besides the retrofitting of damaged buildings that were initiated after the 2003 earthquake, no actions of seismic upgrading of existing structures in high seismic zones were made. The need to take preventive measures of structural strengthening that would reduce vulnerability and avoid human losses must be seen as a priority by the urban planners. As well, it seems necessary to provide private owners with motivation to strengthen their buildings.

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