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Modifier parameters and quantifications for seismic vulnerability assessment of reinforced concrete buildings

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Abstract. In recent years, some studies have identified and quantified factors that can increase or decrease the seismic vulnerability of buildings. These modifier factors, related to the building characteristics and condition, are taken into account in the vulnerability assessment, by means of a numerical estimation resulting from the quantification of these modifiers through vulnerability indexes. However, views have differed on the definition and the quantification of modifiers. In this study, modifier parameters and scores of the Risk-UE Level 1 method are adjusted based on the Algerian seismic code recommendations and the reviews proposed in the literature. The adjusted modifiers and scores are applied to reinforced concrete (RC) buildings in Boumerdes city, in order to assess probable seismic damage. Comparison between estimated damage and observed damage caused by the 2003 Boumerdes earthquake is done, with the objective to (i) validate the model involving influence of the modifier parameters on the seismic vulnerability, and (ii) to define the relationship between modifiers and damage. This research may help planners in improving seismic regulations and reducing vulnerability of existing buildings.

Keywords: Boumerdes city; LM1 method; modifier parameters; seismic vulnerability

1. Introduction

Varied methodologies and techniques were developed for assessing vulnerability of existing buildings in populated urban areas, with the aim to reduce seismic risk. Some of these methods are empirical, while others evaluate the seismic performance of buildings (Kassem *et al.* 2020a). Empirical methods are based on observing the behaviour of buildings in earthquakes and analyzing their seismic deficiencies (ATC-13 1985, ATC-21 1988, Benedetti *et al.* 1988). In empirical methods, parameters affecting the seismic behaviour of buildings were defined including the structural type and its resistance, the constructive characteristics, materials and condition (Benedetti *et al.* 1988). Over the last few years, many studies focused on factors affecting the seismic vulnerability of buildings (Lantada *et al.* 2010, Hadzima-Nyarko *et al.* 2016, Sonmezer *et al.* 2018, Erdil and Ceylan 2019). In the Risk-UE Project (2003) (Milutinovic and Trendafiloski 2003, Lagomarsino and Giovinazzi 2006, Mouroux and Le Brun 2006), the seismic vulnerability of existing buildings was evaluated, based on the European Macroseismic Scale classification, EMS-98 (Grünthal 1998), as a function of a vulnerability index, resulting from the quantification of a number of modifier parameters. Modifiers were defined based essentially on the structural and constructive characteristics, age and condition of the buildings. Quantifications, or scores, assigned to modifiers were developed based on damage observed in buildings in recent earthquakes.

In more recent studies, views have differed in identifying and quantifying modifier parameters that can increase or decrease the seismic vulnerability of buildings in urban areas (Giovinazzi 2005, Lantada *et al.* 2010, Nanda and Majhi 2014, Tomás *et al.* 2017, Martinez-Cuevas *et al.* 2017, Kassem *et al.* 2020b). Martinez-Cuevas *et al.* (2017) conducted a comparative analysis of different urban modifiers previously proposed for masonry and RC typologies, and selected urban modifiers from the perspective of seismic design; plan and vertical irregularities, high difference, soft story, short column and building position in the block. By analyzing damage to buildings caused by the 2011 Lorca earthquake, the authors established a relationship between urban modifiers and damage. Tomás *et al.* (2017) proposed a modification of modifier parameters of the Level 1 method of Risk-UE Project, to achieve better adjustment and less dispersion between estimated damage and observed damage due to the 2011 Lorca earthquake.

In this study, modifier parameters and scores proposed in the Level 1 method of the Risk-UE Project are adjusted based on the Algerian seismic code recommendations RPA99/03 (CGS 2003) and the reviews proposed in the literature (Giovinazzi 2005, Milutinovic and Trendafiloski 2003, Lantada *et al.* 2010, Tomás *et al.* 2017, Martinez-Cuevas *et al.* 2017). Modifier parameters include; (i) the level of seismic design code, relating to year of construction, and (ii) the constructive and structural characteristics; number of stories, plan and vertical

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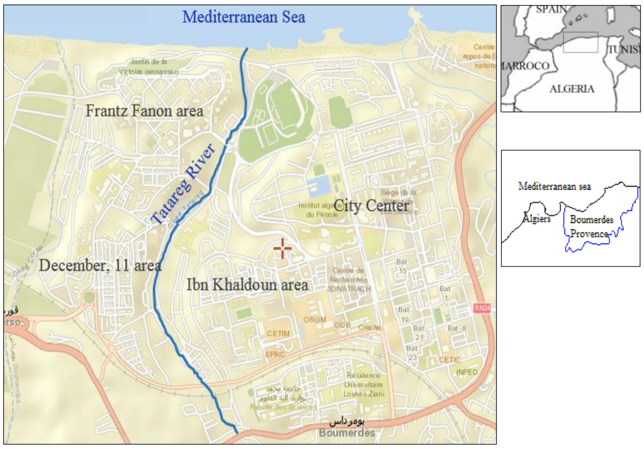


Fig. 1 Plan and location of the city of Boumerdes (captured by satellite.pro)

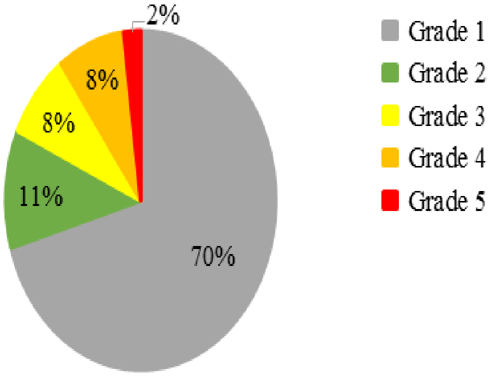


Fig. 2 Distribution of damage grades in Boumerdes city following the 2003 earthquake

irregularities, position of the building in the block, soil morphology, insufficient seismic joint, critical elements (soft story and short columns), and quality of the resisting system and state of preservation. For the study, we have selected 366 RC buildings located in the west side of Boumerdes city, with the objective to evaluate vulnerability, considering the adjusted modifier parameters, to derive relationship between modifiers and seismic damage, and to compare the resulting expected damage to the observed damage due to the 2003 Boumerdes earthquake.

2. Brief overview of Boumerdes city and the 2003 earthquake

Boumerdes city is located in the central part of Algeria on the Mediterranean Sea, at about 45 km east of the capital Algiers (Fig. 1). The city has experienced considerable urban development since it became the capital of the Boumerdes province in 1984. Before this date, the city consisted of few collective housings and administrative buildings. The most commonly used constructive system was the RC frame. In Algeria, RC frame system was adopted from the 1950s, but after the Boumerdes 2003 earthquake, it was completely banned for mid-rise and high-rise buildings in zones with moderate to high seismicity. RC wall system was used since the 1980s, following the strong earthquake of El-Asnam in 1980. The RC dual wall-frame structure type became increasingly frequent since 1999's in the construction of high-rise buildings, particularly, after the 2003 earthquake that shook the Boumerdes region.

The Boumerdes earthquake of May 21, 2003, with a magnitude of 6.8 and an intensity of X according to EMS-98 (Harbi *et al.* 2007b), was the most disastrous earthquake that occurred in northern Algeria, causing more than 1,200 deaths, 3000 injures and damaged over 20,000 buildings (EERI 2003). Post-earthquake data indicates that about 2% of the buildings in the city collapsed and 80% did not suffer a structural damage. According to the available data of the Boumerdes Department of Housing (DLEP) and the Construction Technology Control (CTC), about 70% suffered damage grade 1 and 11% suffered damage grade 2. About 18% of the existing buildings suffered damage grades 3, 4 and 5, with respectively 8%, 8% and 2%. Fig. 2 shows the distribution of damage grades in Boumerdes city following the 2003 earthquake. The most severely damaged buildings were the pre-code and low-code buildings, composed of RC frame structures. Damage grades were defined according to the EMS-98 classification (Grünthal 1998), that considers five categories of damage in structural and non-structural elements of the building. Grade 1 refers to slight non-structural damage. Grade 2 represents slight damage to structural elements and moderate non-structural damage. Grade 3 refers to moderate structural damage and heavy non-structural damage. Grade 4 represents a very heavy damage in both structural and non-structural elements of the building. Finally, grade 5 represents a very heavy damage with partial or total collapse.

3. Vulnerability assessment methodology

3.1 Vulnerability index

Assessing vulnerability of existing buildings refers to evaluate the probability of a structure to experience a certain level of damage when exposed to a seismic event with a given intensity (Lang 2002, Lang and Bachmann 2003, Barbat *et al.* 2010). As mentioned previously, methods to assess vulnerability in urban area can be classified in two main categories; empirical methods and analytical methods (Barbat *et al.* 2008, Vicente *et al.* 2011, Kassem *et al.* 2020a). Analytical methods are based on the response and capacity spectrum of the structures to evaluate their performance level (ATC-40 1996, Fajfar 2000, FEMA 1999). Empirical methods, based on the analysis of observed damage after earthquakes, are founded on the approach that buildings with similar structural characteristics tend to experience similar type of damage in earthquake. Some of the empirical methods include the determination of a vulnerability index V, and then establish a relationship between seismic damage and intensity (Benedetti *et al.* 1988). In the Level 1 method of the Risk-UE Project, named LM1 method (Milutinovic and

Table 1 Building typologies by the EMS-98 scale and index values for masonry and RC typologies (Risk-UE project)

	Building typologies	V^{--}	V^{-}	V_0	V^{+}	V^{++}
Masonry	M1: Ruble stone, fieldstone	0.620	0.810	0.873	0.980	1.020
	M2: Adobe (earth brick)	0.620	0.687	0.840	0.980	1.020
	M3: Simple stone	0.460	0.650	0.616	0.793	0.860
	M4: Massive stone	0.300	0.490	0.616	0.793	0.860
	M5: Unreinforced with manufactured	0.460	0.650	0.740	0.830	1.020
	M6: Stone unreinforced with RC floors	0.300	0.490	0.616	0.790	0.860
	M7: Reinforced or confined	0.140	0.330	0.451	0.633	0.700
Reinforced concrete	RC1: Frame (without ERD)	0.3	0.49	0.644	0.8	1.02
	Frame (moderate ERD)	0.14	0.33	0.484	0.64	0.86
	Frame (high ERD)	-0.02	0.17	0.324	0.48	0.7
	RC2: Shear walls (without ERD)	0.3	0.367	0.544	0.67	0.86
	Shear walls (moderate ERD)	0.14	0.21	0.384	0.51	0.7
	Shear walls (high ERD)	-0.02	0.047	0.224	0.35	0.54

M: Masonry, RC: Reinforced concrete, ERD: Earthquake Resistant Design

Trendafiloski 2003, Lagomarsino and Giovinazzi 2006), empirical procedure is used to assess vulnerability of buildings, through the vulnerability classes (A, B, C, D and E) defined in the EMS-98 scale (Grünthal 1998) and the vulnerability index V obtained according to the Vulnerability Index Method. In the LM1 method, the vulnerability index V was introduced to represent the belonging of a building to a certain vulnerability class and to quantify, in a conventional way, the seismic behaviour of a building, by using the fuzzy set theory (Milutinovic and Trendafiloski 2003). The numerical values of the vulnerability index, indicating that a building pertains to a certain vulnerability class, are ranged between 0 and 1 (1 for the most vulnerable buildings and 0 for buildings with high level of seismic resistant design). These values are defined in an interval between -0.08 and +0.08 with a ±0.02 range. Table 1 shows building typologies according to the EMS-98 scale and the vulnerability index values proposed in the LM1 method. V_0 is the typological (basic) vulnerability index, which depends on the structural type and the level of seismic resistant design. It represents the most probable value of V, V^- / V^+ and V^{--} / V^{++} are, respectively, the probable and less probable vulnerability index ranges.

Since the seismic behaviour of a building does not only depend on its structural system, but also on other modifying parameters, the LM1 proposed to modify the typological vulnerability index V_0 according to scores of penalty or improvement (increase or decrease value). Accordingly, Eq. (1) was suggested to evaluate the vulnerability index V (Milutinovic and Trendafiloski 2003, Lagomarsino and Giovinazzi 2006, Barbat *et al*. 2008):

$$\mathrm{D}V = V_0 + \Delta V_R + \sum \Delta V_m \tag{1}$$

Where V_0 is the typological vulnerability index of the structural typology, to which the building belongs (see Table 1). ΔV_R is a regional modifier depending on characteristics relating to the date of construction and the seismic design codes. ΣV_m are the modifiers that consider the building geometry, and its structural and non-structural characteristics. Modifiers and scores were proposed based on post-earthquake observations, where the influence of these modifying parameters was noted through observed damage. In Table 2, modifiers and scores of RC buildings proposed by the LM1 method are presented (Milutinovic and Trendafiloski 2003).

Table 2 Scores for modifiers of RC buildings depending on the level of seismic code (Risk-UE Project, Milutinovic and Trendafiloski 2003)

Urban modifiers	Score		
	Pre and low-code	Medium-code	High-code
Number of floors			
Low (1 – 3)	-0.04	-0.04	-0.04
Medium (4 – 7)	0	0	0
High (8 or more)	+0.08	+0.06	+0.04
Plan regularity			
Shape	+0.04	+0.02	0
Torsion	+0.02	+0.01	0
Vertical regularity	+0.04	+0.02	0
Short columns	+0.02	+0.01	0
Insufficient joint	+0.04	0	0
Soil morphology			
Slope	+0.02	+0.02	+0.02
Cliff	+0.04	+0.04	+0.04

3.2 Damage assessment

The expected seismic damage is assessed as a function of the vulnerability index V and the macroseismic intensity I, using a vulnerability function according to the LM1 method (Milutinovic and Trendafiloski 2003, Lagomarsino and Giovinazzi 2006) as given in Eq. (2):

$$\mu_D = 2.5[I + tanh\left(\frac{I + 6.25V - 13.1}{Q}\right)] \tag{2}$$

Where μ_D is the mean damage grade and V is the vulnerability index. Q is a ductility coefficient, which is taken equal to 2.3 in this study. In the LM1 method, the value of Q = 2.3 was proposed for most of the building typologies. For RC buildings, the method identifies three levels of Earthquake Resistant Design (ERD) (Table 1)

Table 3 Damage grades according to EMS-98 and corresponding mean damage grade intervals (Lantada *et al.* 2010)

Damage grade	Mean damage grade μ_D
Grade 1: Negligible to slight damage; no structural damage, slight non-structural damage.	0.5–1.5
Grade 2: Moderate damage; slight structural damage, moderate non-structural damage.	1.5–2.5
Grade 3: Substantial to heavy damage; moderate structural damage, heavy non-structural damage.	2.5–3.5
Grade 4: Very heavy damage; heavy structural damage, very heavy non-structural damage.	3.5–4.5
Grade 5: Destruction; very heavy structural damage.	4.5–5.0

without referring to a variation of ductility. The reduction in the vulnerability index corresponds to an increase in the ERD level for the same value of Q. On the other hand, some of the analyzed buildings, designed without or with a low level of seismic design, suffered typically slight to moderate damage in the 2003 earthquake. Consequently, the value of Q = 2.3 as a ductility factor is suitable. In terms of probable damage assessment, the mean damage grade, expressing the mean value of the discrete distribution, can be estimated using Eq. (3), where P_k is the probability of having each damage grade D_k ($k = 0 - 5$). P_k is evaluated according to the probability mass function (PMF) of the binomial distribution (Giovinazzi 2005).

$$\mu_D = \sum_{k=0}^{5} P_k k \quad 0 < \mu_D < 5 \tag{3}$$

To classify seismic damage, the EMS-98 classification of damage grades is used (Grünthal 1998). In Table 3, observed damage to structural and no structural element is given for each damage grade and corresponding intervals of the mean damage grade $0 < \mu_D < 5$, as established by Lantada *et al.* (2010).

4. Proposal for vulnerability modifiers of RC buildings based on the Algerian seismic code

According to the previous proposals for adjusting and calibrating the LM1 modifiers (Milutinovic and Trendafiloski 2003, Lantada *et al.* 2010, Tomás *et al.* 2017, Martinez-Cuevas *et al.* 2017), it is concluded that:

- Modifiers are identified and quantified depending on the damage observed to buildings in recent earthquakes,
- Quantification consists of a range of ±0.02 to ±0.08, accordingly to the membership functions and V values of the six EMS-98 vulnerability classes (A, B, C, D and F) (Milutinovic and Trendafiloski 2003),
- Modifiers are defined based on a knowledge of the seismic features that the buildings present.

However, according to Tomás *et al.* (2017), based on the analysis of damage to buildings caused by the 2011 Lorca earthquake, modifiers can adopt the scores of +0.16 to +0.20, depending on their influence on vulnerability. Based on these previous finding and on the Algerian seismic code recommendations RPA99/2003 (CGS 2003) the proposed modifiers and corresponding quantifications were completed as shown in Table 4. As mentioned previously, and presented below, the modifiers are: (1) level of the design code, (2) number of stories, (3) plan and vertical irregularities, (4) position of the building in the block (separated, intermediate, header or corner), (5) soil morphology, (6) insufficient seismic joint, (7) critical elements (soft story and short columns), and (8) quality of the resisting system and state of preservation.

- Level of the seismic code: four classes A, B, C and D are assigned to buildings relating to the level of seismic code design based on the date of construction. Class A is assigned to buildings constructed prior to the publication of the first official Algerian seismic code RPA81 "Règles Parasismiques Algériennes" in 1981 (CTC 1981). They are treated as buildings without seismic resistant design (pre-code). Prior to 1981, the AS55 and PS62/64/69 French rules, limited to a few anti-seismic recommendations, were applied. Class B is assigned to buildings constructed between 1981 and 1999; they are treated as buildings having a low level of seismic resistant design (low-code). Class C is assigned to buildings constructed between 1999 and 2003; they are treated as buildings having a moderate level of seismic resistant design (medium-code). Class D is assigned to buildings constructed after 2003; they are treated as buildings having a high level of seismic resistant design (high-code). Penalty scores of +0.16, +0.08, +0.04 are considered respectively for classes A, B and C.

In the period of 1981-1999, buildings were designed according to RPA81 and its revised versions made in 1983 and 1988. In RPA99 (CGS 1999), important revisions were made, including the classification of buildings and the PGA for the design of residential buildings. In RPA99 and anterior versions, there were three seismic zones: Zone I, Zone II and Zone III, corresponding respectively to: low seismicity, moderate seismicity and high seismicity. In the last modified version RPA99/03 (CGS 2003) issued after the Boumerdes earthquake in 2003, Zone II was subdivided in Zone IIa and Zone IIb. Boumerdes and Algiers cities, already classified as Zone II, with 0.15 g as the PGA for the design of residential buildings, were reclassified as Zone III, with 0.25 g as the PGA for the design of residential buildings. For zones IIb and III, the minimum column size for RC structures was changed from 25 to 30 cm, and RC dual wall-frame system for mid-rise and high-rise buildings (3 stories or more) became obligatory in zones IIb and III.

- Number of stories: the number of stories modifier has an influence on resulting seismic damage. However, views have differed on the influence of this modifier factor (Tomás *et al.* 2017, Martinez- Cuevas *et al.* 2017, Erdil and Ceylan 2019, Kassem *et al.* 2021). It is clear that its impact is greater on old buildings than on new buildings designed with high seismic design. In case of high-rise buildings, lateral displacement can generate damage in the joint area, as well as in masonry infills. Thus, based on the previous reviews, for mid-rise and high-rise buildings, the scores assigned are respectively +0.04 and +0.08.
- Irregularity in plan and elevation: this parameter relates to the plan shape of the building, and to the mass and

Table 4 Proposal for modifiers and quantification depending on the level of seismic code

Parameters	Classes			
	A Pre-code	B Low-code	C Medium-code	D High-code
1. Level of seismic code	+0.16	+0.08	+0.04	0
2. Number of floors				
Low-rise: 1-2	0	0	0	0
Mid-rise: 3-5	+0.04	+0.04	+0.04	0
High-rise: 6 or more	+0.08	+0.08	+0.08	0
3. Regularity in plan and elevation				
Plan irregularity (shape, asymmetric resistant system, resistant system in one direction)	+0.04	+0.04	+0.04	+0.02
Vertical irregularity (shape, vertical discontinuities of the resisting system)	+0.04	+0.04	+0.04	+0.02
4. Position of the building				
Separated and middle	0	0	0	0
Header	+0.02	+0.02	+0.02	
Corner	+0.04	+0.04	+0.04	
5. Soil morphology :				
Slope < 15° (30° for rocky soil)	+0.02	+0.02	+0.02	+0.02
Slope ≥ 15° (30° for rocky soil)	+0.04	+0.04	+0.04	+0.04
6. Insufficient seismic joint	+0.04	+0.04	+0.04	0
7. Critical elements				
Soft story	+0.16	+0.16	+0.16	+0.16
Short columns	+0.08	+0.08	+0.08	+0.08
8. Quality of the resistance system and conservation				
Bad quality of materials and workmanships, concrete spalling, segregation, cracks, corrosion	0 to +0.08	0 to +0.08	0 to +0.08	0 to +0.08
Strengthened	-0.08	-0.08	-0.08	0

rigidity distribution of resisting elements, which have critical effect on the seismic vulnerability (Ishack, *et al.* 2021). According to RPA99/03 (CGS 2003), plan regularity is evaluated using the ratio l_x / L_X and l_y / L_Y, satisfying the relationships: $l_x / L_X \leq 0.25$, $l_y / L_Y \leq 0.25$ and $0.25 \leq L_X / L_Y \leq 4$. Where l_x, l_y are the smaller sides of the projected or the recessed portion, and L_X, L_Y are the greater sides of the building. Irregularity in elevation considers the vertical configuration of the building. According to the code, the ratio B_i/B_{i-1}, corresponding to the dimensions in plan of the building between two successive levels (i and i-1), does not exceed 20%, and the largest plan dimension does not exceed 1.5 the smallest dimension. Additionally, the variation of the resisting system might be regular to avoid discontinuities of strength and stiffness in structural elements. For both types of irregularities, the penalty attributed is +0.04.

Position of the building in the block: the position of the building within the block; header, middle, corner or isolated position, can increase the vulnerability of buildings having insufficient seismic joint. Corner buildings are more vulnerable than middle or header buildings (Lantada *et al.* 2010, Martinez-Cuevas *et al.* 2017). A score of +0.04 is assigned for corner position and +0.02 for header position, except for high-code buildings having sufficient joint.

- Soil morphology: it consists to examine visually the slope of the terrain and the presence of level differences between foundations. According to previous reviews, in case of building constructed over soil with a slope lower than 15%, or over rock with a slope not exceeding 30%, without differences between foundations, the quantification is +0.02, otherwise +0.04.

- Critical elements: soft story is a flexible story in a structure usually the first story destined to commercial use. This story is weaker than those above against seismic forces (Dilmaç 2020). In Algeria, many buildings and houses possessing open ground floors suffered severe damage in the 2003 Boumerdes earthquake (EERI 2003, Lazzali 2013, Farsi and Lazzali 2003). A penalty score of +0.16 is assigned. As well, in earlier designs, short columns were very common in moment frame structures, which suffered severe damage, because short elements attract larger seismic force due to its stiffness. A penalty score of +0.08 is considered.

- Insufficient seismic joint: most of the existing buildings in urban areas have no, or not, sufficient seismic joint between buildings. Damage in structural elements can be observed in the joint area between buildings (Hermanns *et al.* 2014). According to RPA99/2003, a minimum joint width of 4 cm is required. Except for high-code buildings, a penalty score of +0.04 is considered.

- Quality of the resistant system and conservation: this modifier qualifies the presence of imperfections in the structure (bad quality of materials and workmanships, damage in structural and non-structural elements, concrete spalling or segregation, cracks, corrosion of reinforcement…). A penalty score of 0 to +0.08 is assigned according to the importance of damage. In case of strengthening of structural elements to increase the building seismic performance, a score of -0.08 is assigned.

5. Application for vulnerability index and vulnerability assessment

5.1 Description of the buildings in the study area

For the study, 366 RC buildings located in the western part of Boumerdes city were selected, exactly on the western plateaus along the west side of the Tatarreg River, and south of the eastern side of the Tatarreg River (see Figs. 3-4). Buildings are composed of RC frame, RC wall and dual wall-frame structures. Selected buildings are grouped into five zones. Zone 1 includes a group of pre-code residential buildings, built in 1980 with RC wall structure. Buildings have different heights; mid-rise (5 stories) and high-rise (10 stories). Zone 2 comprises low-code residential buildings, built in the period between 1983 and 1999, with RC wall structure. There are three groups of buildings in zone 2; a group of mid-rise (5 stories) buildings built in 1983, a group of mid-rise (4 stories) buildings built in 1997, and a group of high-rise (7 stories) buildings built in 1997. Most of the buildings suffered slight to moderate structural damage in the 2003 Boumerdes earthquake. Zone 3 contains medium-code and high-code buildings, constructed in the period between 1999 and 2003, and after 2003 with dual wall-frame structure. Buildings are mid-rise (5 stories) and high-rise (6 to 15 stories). Similarly, in this zone, buildings suffered slight to moderate structural damage in the 2003 Boumerdes earthquake. In Zone 4, there were initially mid-rise (4-5 stories) RC frame buildings, built in 1996. Many buildings in Zone 4 suffered very heavy structural damage and collapse in the 2003 earthquake, and were consequently demolished. New mid-rise buildings were constructed with dual wall-frame structure. Finally, in Zone 5, located south of the eastern side of the Tatarreg River, there are high-code residential buildings. Buildings are mid-rise (5 stories), constructed in 2010 with RC wall structure.

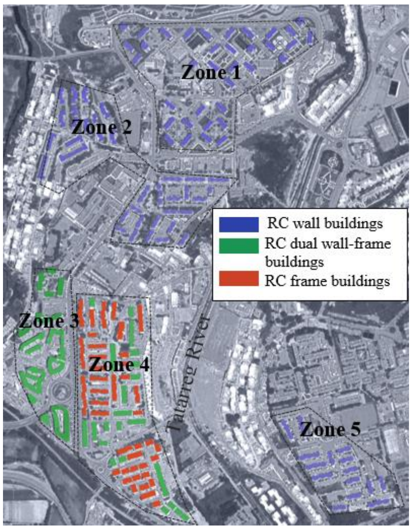


Fig. 3 Zones of selected buildings in the western side of Boumerdes city

5.2 Data collection

Rapid visual screening procedure to collect information is considered to assess vulnerability of building stock (Sonmezer *et al.* 2018, Nanda *et al.* 2014). Therefore, to collect buildings data, a survey Data Form is designed, composed of a number of information sections related to the analyzed building. The exterior of each building is examined as well as the interior if needed, and the results are recorded on the Data Form. The Data Form includes building identification information; address, age, use, drawings, photos, and data related to modifier parameters that can increase or decrease the seismic vulnerability of buildings; type of structure, regularity, soft story, short elements, position of the building in the block and building condition.

(a) RC wall building in Zone 1 (1980) (b) RC wall building in Zone 2 (1983) (c) RC frame building in zone 4 (1996)

(d) dual wall-frame building in Zone 3 (1999) (e) RC wall building in Zone 5 (2010)

Fig. 4 Samples of selected RC buildings in Boumerdes city

Table 5 Distribution of the analyzed buildings in the study area according to the period of construction and the seismic code level

Period of construction	Seismic code	Code level	Number of buildings	Typologies
Before 1981	Recommend-ations of PS69	Pre-code	66	RC2_P
Between 1981-1999	RPA81/83/88	Low-code	99 77	RC2_L RC1_L
Between 1999-2003	RPA99	Medium-code	29	RC3_M
After 2003	RPA99/2003	High-code	36 59	RC2_H RC3_H

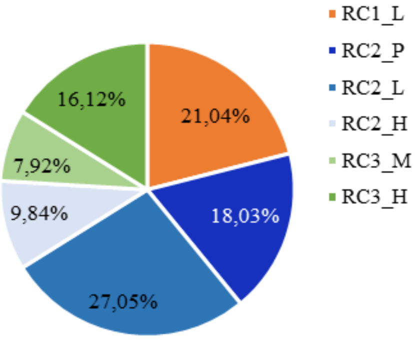


Fig. 5 Percentage of building typologies in the study area

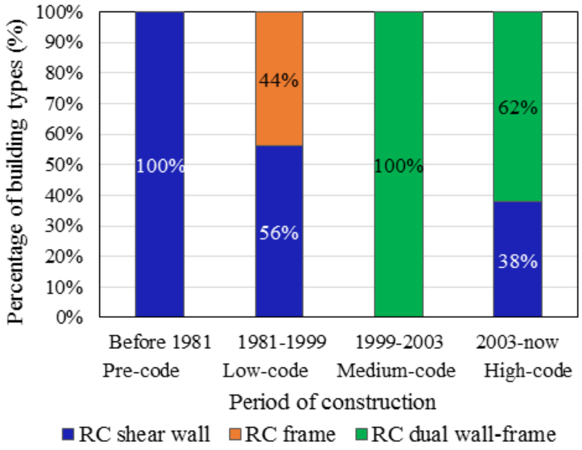


Fig. 6 Distribution of structure types according to the level of the seismic code design

5.3 Statistical analysis

From data processing, analyzed building typologies are defined and distributed according to the level of seismic code design (year of construction), as shown in Table 5 and Figs. 5-6. The predominant typology is RC2; wall structure, with 54.92%, including; 18% are pre-code (RC2_P), constructed before the publication of the first Algerian seismic code RPA81, 27% are low-code (RC2_L), constructed according to RPA83/88 (modified versions of RPA81), and about 10% are high-code (RC2_H), constructed according to the seismic code RPA99/03. The second building typology is RC3; dual wall-frame structure, which represents 24% of the selected buildings, with respectively, 8% are medium-code (RC3_M), designed according to the seismic code RPA99 and 16% are high-code (RC3_H), designed according to RPA99/03. The third building typology is RC1_L; frame structure, which represents 21% of the selected buildings and are classified as low-code buildings.

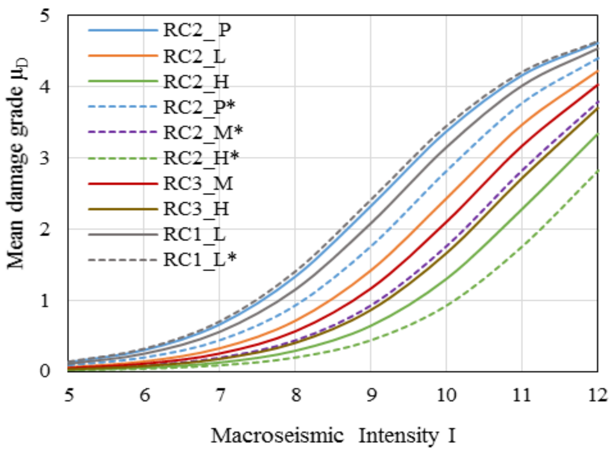


Fig. 7 Vulnerability curves of existing building typologies considering adjusted modifier parameters (continued lines), and vulnerability curves function of the basic vulnerability index V_0 (dashed lines)

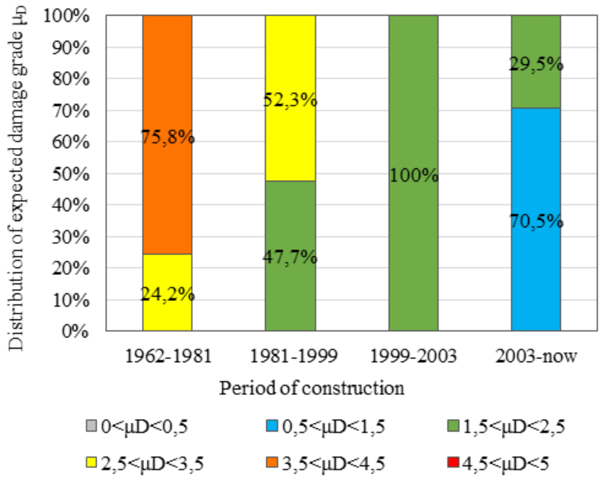


Fig. 8 Distribution of the expected mean damage grade μ_D on RC buildings according to the period of construction

6. Results and discussions

Using collected data and applying modifier quantifications proposed in Table 4 for each selected building, the vulnerability index V is calculated as the sum of the typological index value V_0 (given in Table 1) and the modifiers quantifications according to Eq. (1). ΔV_R, in Eq. (1), is the score assigned to the classes A, B, C and D relating to the seismic design code level (date of construction) and ΣV_m are the modifier scores that consider the building constructive and structural characteristics, as listed in Table 4 from 2 to 8. It is also noted that for the dual wall-frame typology, RC3, not included in the LM1

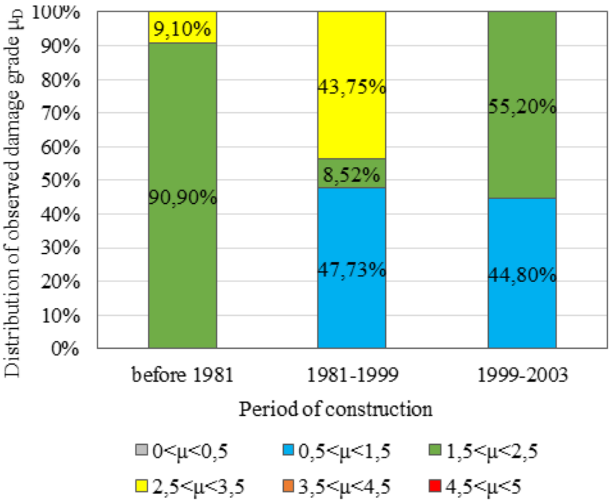


Fig. 9 Distribution of the observed mean damage grade μ_D on RC buildings after the 2003 Boumerdes earthquake, according to the period of construction

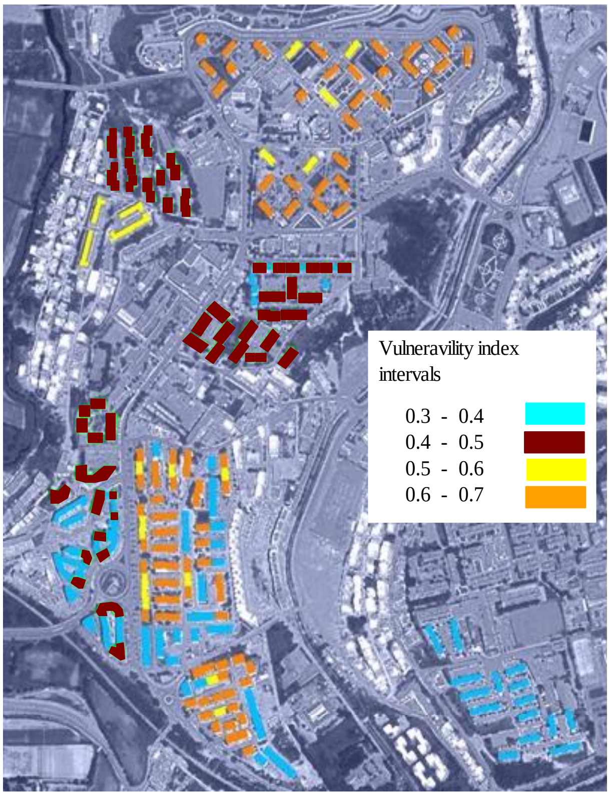


Fig. 10 Distribution of the vulnerability index of the buildings

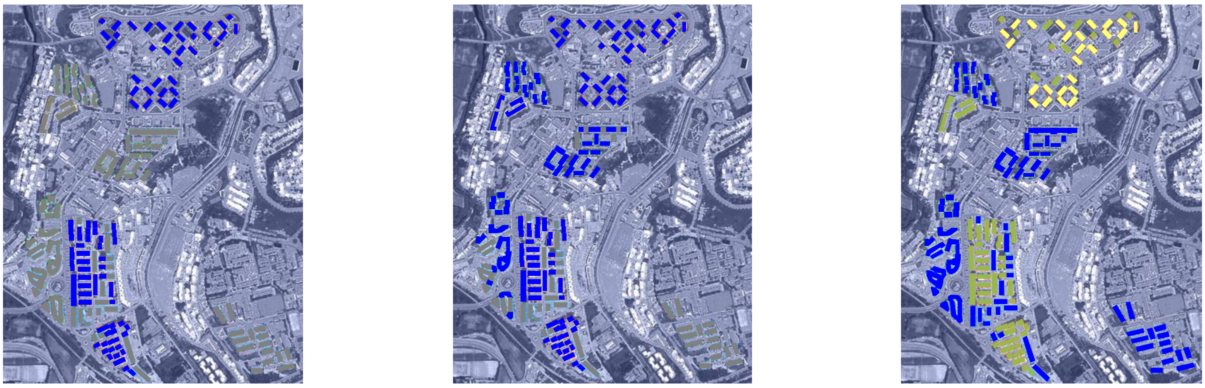
typologies (EMS-98 building typologies) (see Table 1), the typological vulnerability index V_0 is taken as the intermediate value between RC1 and RC2 V_0 values (Lagomarsino and Giovinazzi 2006).

The obtained vulnerability index values for high-code RC2 typology (RC2_H) is V = 0.304. For low-code typology (RC2_L), V is ranged between 0.384 and 0.564 with a mean value V = 0.486. For pre-code RC2 buildings (RC2_P), V is ranged between 0.584 and 0.664, with a mean value V = 0.63. For medium-code RC3 typology (RC3_M), V is ranged between 0.394 and 0.494, with a mean value V = 0.443. For high-code RC3 typology (RC3_H), V is ranged between 0.313 and 0.413, with a mean value V = 0.368. For low-code RC1 typology (RC1_L), V is ranged between 0.584 and 0.604, with a mean value V = 0.594.

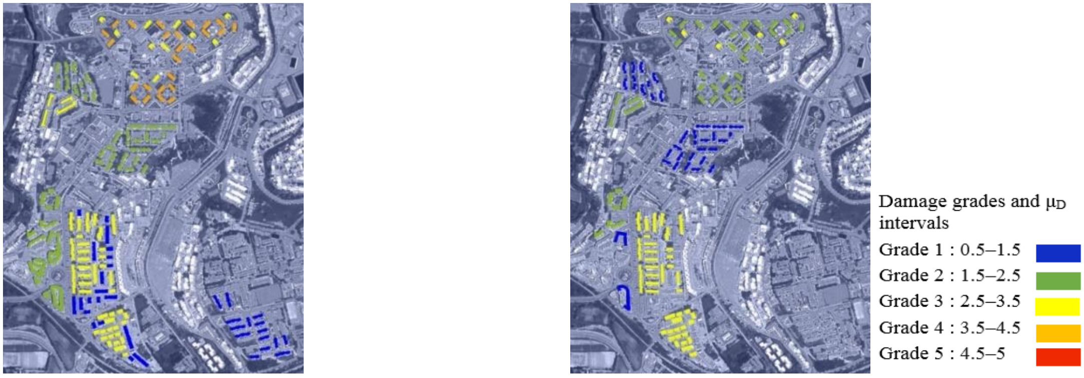
Once the vulnerability index V is obtained, the expected mean damage grade μ_D can be calculated using Eq. (2). Resulting vulnerability curves of the existing buildings RC2_P, RC2_L, RC2_H, RC3_M, RC3_H and RC1_L, expressing the mean damage grade μ_D as a function of the mean vulnerability index V and the macroseimic intensity I, considering modifier parameters, are presented in Fig. 7. The dashed lines indicate the vulnerability curves drawn as a function of the basic vulnerability index values V_0 (without considering modifiers) given in Table 1. We can see that the highest mean damage grade values are obtained for the highest values of the vulnerability index V resulting from the LM1 method considering adjusted modifier parameters.

As a function of the strongest macroseismic intensity, I(EMS) = X, recorded in the 2003 Boumerdes earthquake (Hardi *et al.* 2007b), and the year of construction, the distribution of the expected mean damage grade μ_D is shown in Fig. 8. Accordingly, for pre-code buildings, the expected mean damage grade is ranged between 3.08 and 3.57. 24.24% of the buildings present substantial to heavy damage grade (D3), corresponding to $2.5 < \mu_D < 3.5$, and 75.76% present very heavy damage grade (D4), corresponding to $3.5 < \mu_D < 4.5$ (Lantada *et al.* 2010) (see Table 3). For low-code buildings, the mean damage grade is ranged between 1.76 and 3.21. 47.7% of the buildings present moderate damage grade (D2), corresponding to $1.5 < \mu_D < 2.5$, and 52.3% present substantial to heavy damage grade (D3), corresponding to $2.5 < \mu_D < 3.5$. For medium-code buildings, the mean damage grade is ranged between 1.82 and 2.48. 100% of the buildings present moderate damage grade (D2), corresponding to $1.5 < \mu_D < 2.5$. For high-code buildings, the mean damage grade is ranged between 1.3 and 1.94. 70.5% of the buildings present slight damage grade (D1), corresponding to $0.5 < \mu_D < 1.5$, and 29.5% present moderate damage grade (D2), corresponding to $1.5 < \mu_D < 2.5$.

By consulting the database of damage due to the 2003 Boumerdes earthquake, from the Construction Technology Control agency (CTC) of Boumerdes city, damage to buildings was analyzed. Considering the number of buildings suffered each damage grade Dk (k = 0 – 5), within each zone, the observed damage grade, expressing the mean value of the discrete distribution is obtained applying Eq. (3). Fig. 9 shows the distribution of the mean damage grade observed on building typologies in the 2003 Boumerdes earthquake (I(EMS) = X), according to the period of construction. Therefore, about 91% of pre-code buildings were moderately damaged (D2), with a mean damage value $\mu_D = 2.1$ and 9% were substantially to heavily damaged (D3), with $\mu_D = 3$. For low-code buildings, about 47.7% were slightly damaged (D1), with $\mu_D = 1.33$ to 1.45, 8.52%

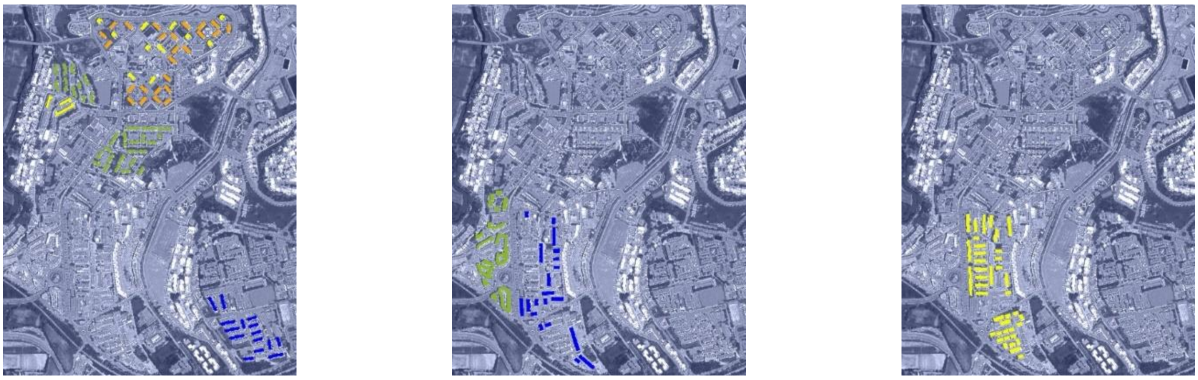


I(EMS) = VII I(EMS) = VIII I(EMS) = IX



I(EMS) = X I(EMS) = X (observed damage)

Fig. 11 Spatial distribution of the expected damage obtained by the LM1 method for different seismic intensities and the observed mean damage from the 2003 Boumerdes earthquake



(a) RC walls (b) RC dual wall-frame (c) RC frames

Fig. 12 Distribution of the expected damage (I(EMS)=X) for each typology separately

were moderately damaged (D2) with $\mu_D = 1.53$, and 43.75% were substantially to heavily damaged (D3), with $\mu_D = 3.13$. For medium-code buildings, about 44.8% were slightly damaged (D1), with a mean damage value $\mu_D = 1.38$, and 55.2% were moderately damaged (D2) with $\mu_D = 1.5$ to 1.85.

Fig.10 shows the spatial distribution of the vulnerability index V, evaluated for each analyzed RC building by the proposed method. In Fig. 11, we can see the distribution of the expected mean damage grade for moderate, high and very high intensity levels (I(EMS) = VII, VIII, IX and X) and the observed mean damage due to the 2003 Boumerdes earthquake, as a function of the most recorded intensity I(EMS) = X. For low seismic intensity (I(EMS) = VI and lower) no structural damage is expected. The probable mean damage, considering each RC typology separately, is shown in Fig. 12. Therefore, the mean damage grade, resulting from the LM1 method considering the adjusted modifiers, is compared with the observed mean damage grade from the 2003 earthquake. As shown in Fig. 13, for each building, the expected (▪) and the observed (×, ▲, ♦) μ_D are plotted with their corresponding vulnerability index V for the macroseismic intensity I(EMS) = X. The plotted points corresponding to the observed damage (×, ▲, ♦) are situated under the line of the expected damage (▪). Dispersion between observed and estimated damage in RC wall structures is observed. However, for RC dual wall-frame and RC frame structures, an appreciable agreement is noted.

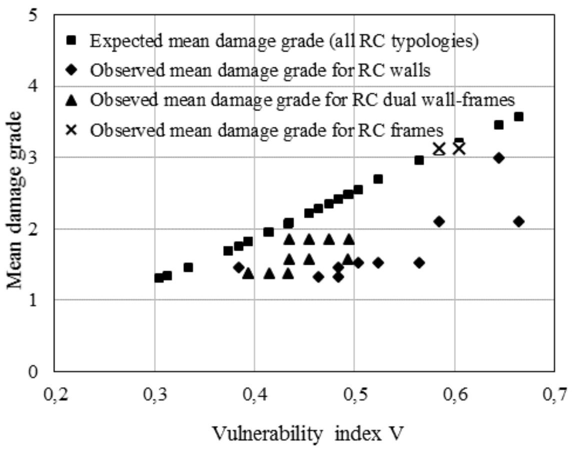
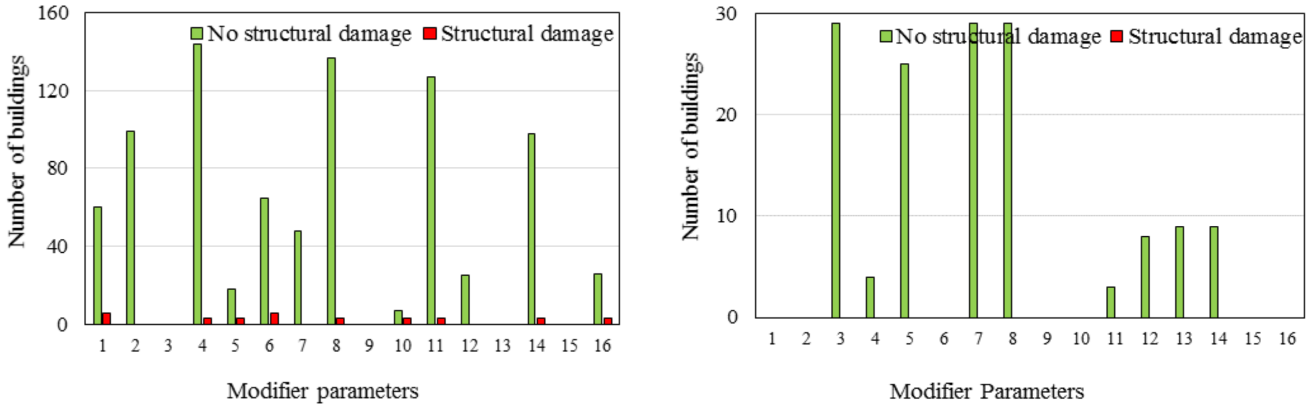


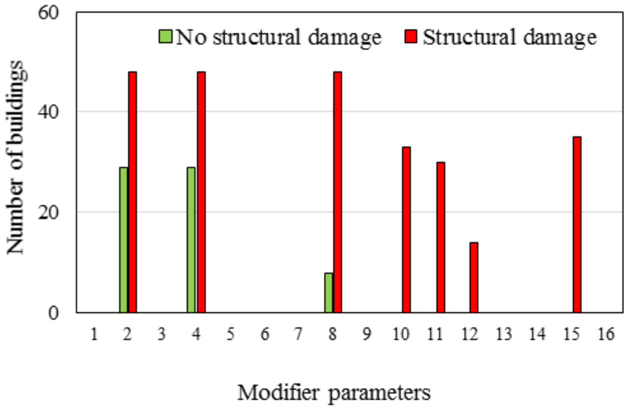
Fig. 13 Comparison between observed damage on RC buildings from the 2003 Boumerdes earthquake and the mean damage grade obtained by the LM1 method considering adjusted modifiers.

In Figs. 14(a)-(c), we can see the percentage of buildings with a given modifier parameter that suffered structural damage and non-structural damage in the 2003 Boumerdes earthquake. Overall, for all analyzed RC typologies, the number of buildings with no structural damage exceeds the number of buildings with structural damage. Within RC2 typology (Fig. 14(a)), structural damage was observed only in pre-code buildings. Cracks at joint areas between two adjacent buildings and on short walls were observed. We can notice that whatever the modifier parameter, few buildings suffered structural damage. Despite the fact that these buildings are pre-code, their resistant system composed of RC walls provided good resistance against seismic action. Similarly, within the RC dual wall-frame typology, RC3, only no structural damage occurred. Vertical and diagonal cracks in infill-masonry panels were observed. As mentioned previously, buildings are medium-code and high-code, designed according to RPA99 and RPA99/03. Therefore, we see through the observed damage the effect of the level of design code on RC dual wall-frame buildings behaviour. Finally, in Fig. 14(c), for RC frame typology, the number of buildings with structural damage exceeds the number of buildings with no structural damage. The poor behaviour of RC frame structures is related to their low lateral resistant due to the design level, to bad quality of materials and workmanships, and to the presence of soft stories (Chaulagain *et al*. 2015, Isik *et al.* 2020, Zeris and Repapis 2018). It seems clear that the effect of modifier factors is more significant in increasing vulnerability of RC frame buildings. In addition to the level of seismic code modifier, parameters relating to the constructive and structural characteristics had an impact on the buildings behaviour.



(a) RC walls

(b) RC wall-frame



(c) RC frames

(1) Pre-code (before 1981), (2) Low-code (1981-1999), (3) Medium-code (1999-2003), (4) Mid-rise, (5) High-rise (6) Plan irregularity, (7) Vertical irregularity, (8) Insufficient joint, (9) Presence of slope, (10) Isolated position, (11) Header position, (12) Middle position, (13) Corner position, (14) Short elements, (15) Bad quality of resistant system, (16) Bad preservation

Fig. 14 Frequency of buildings with no structural and structural damage according to the modifier parameters of the vulnerability

7. Conclusions

In this paper, with the aim to assess buildings vulnerability, modifier parameters and quantifications proposed in the Level 1 method of Risk-UE project, were adjusted with respect to the Algerian seismic code recommendations and the reviews proposed in literature. Resulting expected damage, considering the adjusted modifiers, and observed damage due to the 2003 Boumerdes earthquake, were compared. According to the results, it is noted that the highest probable mean damage grade is obtained for the highest vulnerability index V considering adjusted modifier parameters. In addition, the damage estimated considering modifiers exceeds the observed damage, with an appreciable agreement for RC frame structures and dual wall-frame structures, and a dispersion for RC wall structures. Moreover, the relationship between modifiers and damage reveals that the impact of modifiers is lesser in case of structures with high rigidity such as RC walls, even if they were constructed before the introduction of the seismic code regulation. This indicates once again that the building vulnerability depends fundamentally on the structural type. For buildings designed according to recent codes, the impact of the level of seismic code modifier is more significant.

This work is a part of assessing vulnerability in urban areas. It allowed us to identify more parameters that can influence the seismic behaviour of buildings. Such study can assist professionals for a comparison between modifiers that can increase or decrease the seismic vulnerability without the need to carry out detailed structural analysis. In this way, future works can improve the quantification of modifiers to obtain better agreement between estimated and observed damage in earthquakes.

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