Seismic vulnerability of an existing strategic RC building using non linear static and dynamic analyses

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Algeria is the most seismically active country in the northern part of Africa, and it has so far suffered a number of catastrophic earthquakes. The 2003 Boumerdes earthquake, magnitude 6.8, was the most devastating earthquake that occurred near the capital Algiers, killing and injuring thousands of people. Many existing strategic RC buildings were severely damaged and hence made unfit for use after the earthquake. Seismic vulnerability of an old RC concrete strategic building designed without consideration for any seismic loading is assessed in the paper.

Key words:
Seismic vulnerability, RC building, nonlinear dynamic and static analysis, storey drift displacements

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Ocjena seizmičke oštetljivosti postojeće strateški značajne AB zgrade pomoću nelinearno statičkih i dinamičkih analiza

Alžir je država s najvišom razinom seizmičke aktivnosti u sjevernoj Africi, a do sada je pretrpio više katastrofalnih potresa. Potres magnitude 6,8 koji je 2003. godine pogodio Boumerdes smatra se najrazornijim potresom koji je do sada pogodio područje u blizini glavnog grada Alžira. U njemu je poginulo ili ozlijeđeno više tisuća osoba. U potresu su mnoge strateški značajne AB zgrade pretrpjele velika oštećenja što je onemogućilo njihovu uporabljivost. U radu se ocjenjuje seizmička oštetljivost stare strateški značajne AB zgrade projektirane bez prethodne analize seizmičkog opterećenja.

Ključne riječi:
seizmička oštetljivost, AB zgrada, nelinearna dinamička i statička analiza, međukatni pomaci

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Abschätzung des seismischen Schadens an einem strategisch bedeutenden Stahlbetongebäude mithilfe nicht linearer statischer und dynamischer Analysen

Algier ist das Land mit der höchsten seismischen Aktivität in Nordafrika, und hat bisher mehrere katastrophale Erdbeben erlebt. Ein Erdbeben der Stärke 6,8, das 2003 Boumerdes heimgesucht hat, betrachtet man als das verheerendste Erdbeben, das sich bis dahin in der Nähe der Hauptstadt Algiers ereignet hat. Dabei wurden mehrere Tausend Menschen getötet oder verletzt. Nach diesem Erdbeben haben viele strategisch wichtige Stahlbetongebäude großen Schaden genommen, was ihre Nutzbarkeit unmöglich machte. In dieser Abhandlung wird der seismische Schaden an alten strategisch wichtigen Stahlbetongebäuden eingeschätzt, die ohne vorherige Analyse der seismischen Belastbarkeit geplant wurden.

Schlüsselwörter:
seismischer Schaden, Stahlbetongebäude, nicht lineare dynamische und statische Analyse, Verschiebung der Zwischengeschosse

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1. Introduction

Earthquakes of large magnitude are often considered to be the most important natural risk. Thousands of people are usually killed or injured in such earthquakes, with many more becoming homeless. The 6.8 magnitude Boumerdes earthquake that occurred in May 2003, caused significant damage to buildings in Zemmouri, Boumerdes, and Algiers prefectures, with a death toll of 2278, with 6782 injured, and with 130000 homeless and also with thousands of collapsed buildings [1-5]. Almost all old buildings, built prior to implementation of the new Algerian seismic design code RPA 99/version 2003 [6], suffered some kind of heavy damage. Among these buildings, many are located in the area of Algiers and are considered to be of strategic significance. They must have high seismic performance in case of major earthquakes, with no damage to structural elements and slight damage to non structural elements. The aimed seismic performance level of such buildings is Immediate Occupancy (IO) and they must remain fully operational after a major earthquake. Unfortunately, many existing strategic buildings were designed for vertical loads only. This paper analyses seismic vulnerability of an existing strategic reinforced-concrete building based on non linear static and dynamic analyses. The comparison between non linear dynamic response and non linear static analyses of the strategic building was conducted for our case study in terms of shear forces and inter-storey drift displacements. The deterministic approach for seismic performance was derived using the nonlinear static analysis, which was used in seismic design and evaluation of structures to determine structural yield and potential failure mechanisms. Furthermore, the nonlinear dynamic analysis is the most adequate and comprehensive analysis procedure for evaluating nonlinear response of structures. The capacity and demand were calculated based on nonlinear considerations using static and dynamic analyses. The performance of the building was examined at the yield and ultimate states under two levels of design earthquakes. The results show that the building is highly vulnerable and is likely to collapse even in case of a moderate earthquakes.

2. Analytical techniques for evaluation of seismic performance

The evaluation of seismic performance of any structure requires assessment of its dynamic characteristics and the prediction of its response to a probable earthquake motion that could take place in the future during service life of the building. The deterministic approach to seismic performance is derived by using the nonlinear static analysis which determines the lateral load resisting capacity of a structure, and the maximum level of damage in the structure at the ultimate load in terms of a capacity curve [7-11].

2.1. Non linear static analysis

Nonlinear static analyses are commonly used in the seismic design and evaluation of structures as indicators of structural yield and potential failure mechanisms. These types of analyses incorporate directly the nonlinear force-deformation characteristics of individual components due to inelastic material response. The advantage of these procedures with respect to linear procedures is that they directly take into account the effects of nonlinear material response and, hence, the calculated internal forces and deformations will be more realistic and closer to the values expected during an earthquake. Several methods exist: ATC 40, FEMA 273, FEMA 440, and EC8 [12-14]. They all consider that the nonlinear force-deformation characteristics of a building can be represented by a pushover curve which shows a building's resistance in terms of storey shear force versus top displacement.

2.2. Static pushover analysis

The non linear static analysis was conducted using the push-over method incorporated in the SAP 2000 computer software. The analysis was conducted in two orthogonal directions, and structural response values were obtained. These values were expressed as the total shear force at the base and the maximum horizontal displacement of the top.

The static pushover analysis is basically made by subjecting a building model to constant gravity loads and by monotonically increasing lateral forces assumed over the height of the structure from zero to the ultimate level in accordance with the first mode of vibration, until the collapse of the building [15-17]. The system of equations to be solved is given by:

$$[K_T]\{\Delta U\} = \{\Delta F\} \tag{1}$$

where:
$[K_T]$ - the stiffness matrix,
$\{\Delta U\}$ - the vector of incremental displacement,
$\{\Delta F\}$ - the vector of incremental forces.

The pushover analysis is very useful for estimating the following characteristics:
- Capacity of the structure in terms of shear base versus roof displacement for global damage.
- Maximum rotation and ductility of critical structural members for local damage.
- Distribution of plastic hinges at ultimate state to assess the mechanism phenomenon.
- Distribution of damage in the structure expressed in terms of local damage indices at ultimate state.

Since the study will compare the nonlinear dynamic and nonlinear static results in terms of inter-storey displacements, we will consider only these parameters for the two procedures.

2.3. Construction of capacity curve

The capacity curve, see Figure 1, is generally constructed to represent the first mode response of the building based on the assumption that the structure responds to a seismic input predominantly in its fundamental mode of vibration. The distribution of horizontal forces over the height of the building should comply with the first mode shape. Assuming the floors are rigid diaphragms, the lateral storey forces are proportional to the product of the mass and the fundamental mode shape [18]:

$$F_i = \frac{m_i \varphi_i}{\sum m_i \varphi_i} V_b \qquad (2)$$

where:
F_i - concentrated mass at the i-th floor level
m_i - concentrated mass at the i-th floor level
φ_i - first mode displacement at the i-th floor level
V_b - base shear force corresponding to the sum of lateral storey forces.

The main results of the capacity curve can be summarized as follows. In the longitudinal direction, the first yielding displacement and the corresponding yielding shear force amount to δ_y = 0.013 m and V_y = 1103.953 m, respectively. As for the ultimate displacement and the corresponding ultimate shear force, they amount to δ_u = 0.227 m and V_u = 5488.754 kN, respectively. In the transverse direction, the first yielding displacement and the corresponding yielding shear force amount to δ_y = 0.028 m and V_y = 1847.336, respectively. The ultimate displacement and the corresponding ultimate shear force amount to δ_u = 0.462 m and V_u = 3370.884 kN, respectively.
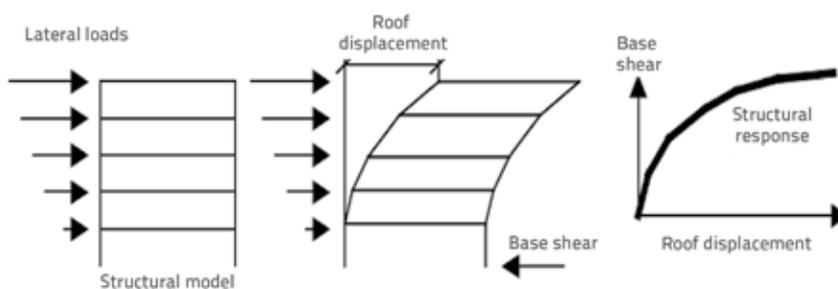

Figure 1. Capacity curve in terms of base shear versus roof displacement

2.4. Non linear dynamic analysis

The nonlinear dynamic analysis is the most adequate and comprehensive analytic procedure for evaluating the nonlinear response of structures. It is today the state-of-the-art methodology for predicting building response to an earthquake ground motion. In nonlinear dynamic analysis,

nonlinear properties of the structure are considered as a part of a time domain analysis. The seismic input is considered using the time history analysis, which involves step by step time evaluation of the building response. This approach is the most rigorous analytic procedure for predicting forces and displacements during an earthquake. However, the calculated response can be very sensitive to characteristics of ground motion records. Therefore, several time history analyses are required using different ground motion records at various levels of intensity to represent various earthquake scenarios. The loading time history is divided into a number of small equal time increments. During any time increment, the behaviour of the structure is assumed to be linear elastic. As nonlinear behaviour occurs, the incremental stiffness changes for the next time or load increment. Hence, the response of the nonlinear system is approximated by response of a sequential series of linear systems having varying stiffness values [19-21]. The non linear dynamic analysis was performed using the methodology developed at IZIIS, Skopje [22, 23]. Definition of dynamic response of the structure involves solving dynamic equation of motion of the system, and computation of system parameters (displacement, velocity, and acceleration) during an earthquake effect. The solution is given in incremental form using the following equation:

$$[M]\{\Delta\ddot{U}\} + [C]\{\dot{U}\} + [K_T]\{\Delta U\} = \{\Delta F_{eff}\} \qquad (3)$$

where:
$[M]$ - the mass matrix of the structure
$[C]$ - the damping matrix
$[K_T]$ - the tangent stiffness matrix
$\{\Delta F_{eff}\}$ - the vector of incremental effective dynamic forces
$\{\Delta U\}, \{\Delta\dot{U}\} \{\Delta\ddot{U}\}$ - incremental vectors of structure displacement, velocity, and acceleration, respectively

The bilinear hysteretic model was used for structural members.

2.4.1. Selection of earthquake ground motion

When performing nonlinear dynamic analyses, proper attention must be paid to the selection of recorded ground motions in keeping with seismic hazard of the region of interest, geotechnical specifications, soil conditions, and compatibility with the design spectrum of the region. An appropriate range of accelerograms must be provided so that possible variations in structural response are not underestimated [24, 25]. The seismic hazard analysis of the region has been done based on the synthesis of the seismic hazard study of Algeria [26]. In the scope of preparation of this study, seismic zoning by code, and seismic hazard and attenuation laws, are used for

Table 1. Characteristics of recorded ground motions

Earthquake	Country	Direction	Year	Duration [s]	A_{max} [m/s²]
Ulcinj, Albatros	Montenegro	N – S	1979	40	1.68
El Centro	USA	N – S	1940	40	3.42
Cherchell	Algeria	N – S	1989	24	2.26

the definition of the maximum expected acceleration level at bedrock as a function of a 100 and 500 year return period [27]. Table 1 and Figure 2 show characteristics of accelerograms used in this analysis, as based on the geotectonic structure and the existing strong motion data.

2.5. Limit states

According to observations during past earthquakes and previous research, the effect of interstorey drift on structures has been well correlated with the level of structural damage. As a result, this study will place emphasis on the inter storey drift, as the key parameter in the development of vulnerability assessment. Two limit states are considered in this study. The first limit state is for the Immediate Occupancy, IO. This damage limit state is attained when the allowable first yield storey drift is reached in any member of the building. The structure would undergo minimal damage and occupants would have access to the building following the earthquake event. At this state, the pre-earthquake design strength and stiffness are retained. The
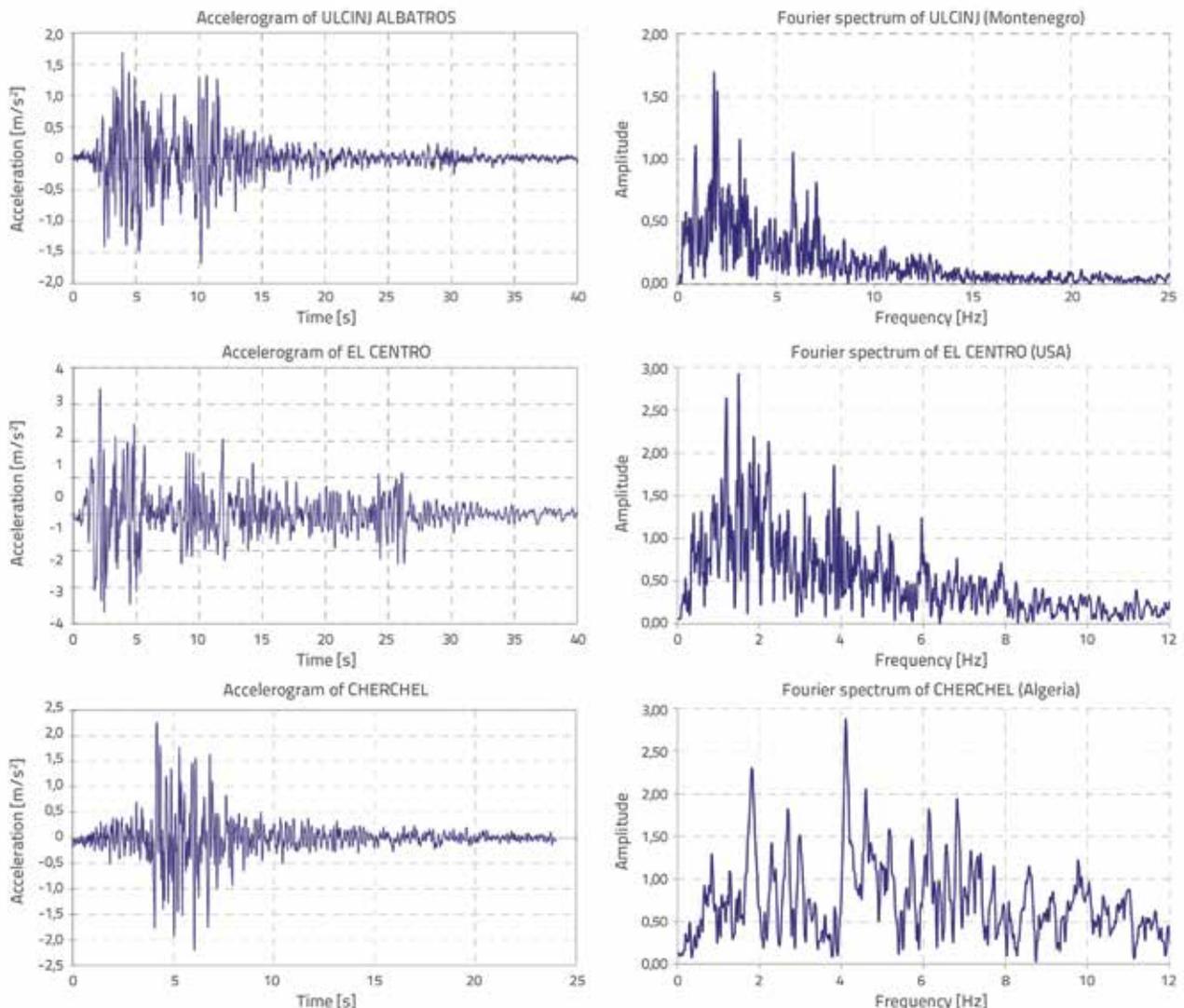

Figure 2. Selected accelerograms and their Fourier spectra

second limit state is for Life safety, LS. The damage limit state is attained when the allowable first ultimate storey drift in the building, given by Equation 4, is reached. At this state, building's occupants are protected from loss of life with a significant margin against the onset of partial or total structural collapse [28-32].

$$\Delta = \min \left\{ \Delta_{capU} \; ; \frac{H}{125 \div 150} \; ; 1\%H \right\} \tag{4}$$

3. Case study

In order to achieve the aforementioned objectives, an existing strategic seven-storey RC building located in the capital city of Algiers, and accommodating the Ministry of Telecommunication, was selected. The building is a part of the country's major national telecommunication infrastructure that is expected to be operational during and after a major earthquake. It was built in the 1970s according to the then applicable French recommendations, PS 69 [21]. The study revealed many deficiencies with regard to the behaviour of the structure.

3.1. Data collection and preliminary investigations

The existence of some architectural drawings provides a good starting point for determining column locations, floor to floor heights, and for approximation of the loads for which the structure is designed. Dates of original drawings can give a clue as to which building code was probably used when the building was designed. Unfortunately, the unavailability of any architectural or structural drawings made the analysis quite difficult. A site visit and a measured drawing showed some modifications within the building, noticeable steel corrosion, and poor maintenance.

The seven storey building was constructed in 1970. The structural system consists of the reinforced concrete moment resisting frames with infill walls made of hollow clay bricks. It rises 37.31 m above ground and, in plan, it measures 30 m in longitudinal direction and 24 m in transverse direction. The floor system consists of joists and hollow concrete blocks 20 cm in thickness, supported by reinforced concrete beams in both directions.

Since the building underwent several moderate earthquakes, in this case infill walls are considered as disconnected from the structure and are not in adherence with the frame elements, i.e. they only act as an additional mass applied to the structure, and have no significant effects on the global lateral stiffness.

Based on geological, geotechnical and geophysical data, the building was founded on soil of medium quality. Therefore, the soil-structure interaction was not taken into account in dynamic analysis. A general view of the building considered in this case study is shown in Figure 3. Basic properties of the reference building are shown in Table 2.

Figure 3. General view of the building

Table 2 Basic properties of reference building

Properties	Description
Total height [m]	37.31
Number of storeys	7
Storey height [m]	Storey 1: 4.91
	Storeys 2 to 7: 5.40
Floor structure	hollow concrete floors 20 cm in thickness
RC beams [cm x cm]	30 x 60 cm in longitudinal direction
	40 x 120 cm in transverse direction
RC columns [cmxcm]	Storeys 1 to 3: 80 x 80
	Storeys 4 to 6: 70 x 70
	Storey 7: 45 x 45
Modulus of elasticity of concrete [MPa]	29859

3.2. Data collection and preliminary investigations

Based on field investigations using a range of in-situ and laboratory testing and inspection techniques (ultrasonic tests), the necessary information to assess the capacity of the existing structure were obtained. The following material characteristics were selected:

Concrete:
- Compressive strength: f_c = 20 MPa
- Tensile strength: σ_t = 1.8 MPa
- Strain at peak compression strength: ε_y = 0.002
- Compression ultimate strain: ε_u = 0.0035

Steel:
- Yield strength of longitudinal reinforcement: f_{yl} = 400 MPa
- Yield strength of shear reinforcement: f_{yt} = 235 MPa
- Yield strain of longitudinal reinforcement: ε_{yl} = 0.002
- Yield strain of shear reinforcement: ε_{yt} = 0.0018
- Ultimate strain of longitudinal reinforcement: ε_{ul} = 0.010

3.3. Occupancy of structure and definition of design code

The building is currently used for telecommunication purposes and, as a strategic building, it must satisfy safety criteria of the current Algerian seismic regulations, RPA99/version 2003.

3.4. Model description and analysis method

Considerable advances in computer technology and availability of greater computational resources has enabled a more detailed approach to the modelling of reinforced concrete structures using the finite elements method. According to the seismic requirements specified in RPA99/version 2003, a primary linear analysis was carried out to investigate the global response of the entire structure. This phase involves calculation of vertical distribution of lateral forces by the equivalent static method, calculation of the eccentricity relative to the additional torsional moment, distribution of shear force among frames, evaluation of storey drift, etc. The program SAP 2000 [22] was used to model the structure in three dimensions, determine a detailed mass and stiffness distribution of the building, and the effect of plan and vertical irregularities.

Response spectrum analysis was conducted to estimate seismic response and determine overall design forces acting on the lateral load resisting elements. The 3D structural model of the building is illustrated in Figure 4.

The linear elastic analysis was conducted using the computer software SAP 2000 [26]. The periods of the structure are for longitudinal direction, and for transverse direction.
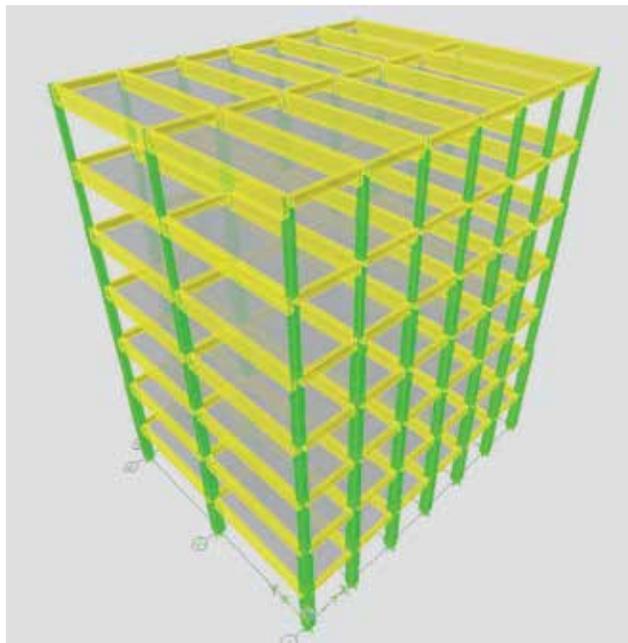

Figure 4. 3D structural model

4. Results of analysis and seismic risk indicators

Taking into account that the building is a strategic one, no significant structural or non structural damage are allowed, and its seismic performance must satisfy the Immediate Occupancy (IO) criteria. The design base shear is distributed across the height of the building frames, using the procedure suggested by RPA99/version 2003 to obtain the floor level forces. The seismic forces and the shear forces at different storeys in each main direction, as well as safety coefficients, are shown in Tables 3

Table 3. Seismic and shear forces for both main directions (XX and YY)

Storey	F_{ix} [kN]	V_{ixd} [kN]	F_{iy} [kN]	V_{iyd} [kN]
7	2736.13	2736.13	2494.94	2494.94
6	2084.66	4820.79	2566.89	5061.83
5	2094.66	6915.45	2199.39	7261.22
4	1648.73	8564.18	1731.16	8992.38
3	1350.07	9914.25	1417.58	10409.96
2	1039.76	10954.01	1091.75	11501.71
1	400.72	11354.73	420.76	11922.47

where:
F_{ix} & F_{iy} – are seismic forces at level "i" for longitudinal and transversal directions
V_{ixd} & V_{iyd} – are shear force demand values at level "i" for longitudinal and transversal directions

Table 4. Safety coefficients for both main directions (XX and YY)

Storey	V_{ixc} [kN]	V_{ixd} [kN]	S_{ix} (V_{ixc}/V_{ixd})	V_{iyc} [kN]	V_{iyd} [kN]	S_{iy} (V_{iyc}/V_{iyd})
7	1014.29	2736.13	0.381	986.62	2494.94	0.395
6	1871.60	4820.79	0.388	2074.20	5061.83	0.409
5	2172.14	6915.45	0.314	2440.57	7261.22	0.336
4	3127.87	8564.18	0.365	3452.11	8992.38	0.383
3	3136.80	9914.25	0.316	3408.73	10409.96	0.327
2	4363.25	10954.01	0.398	4606.64	11501.71	0.400
1	5487.46	11354.73	0.483	5409.30	11922.47	0.453

where:
V_{ixc} & V_{iyc} – are shear force capacity values at level "i" for longitudinal and transversal directions
V_{ixd} & V_{iyd} – are shear forces demand values at level "i" for longitudinal and transversal directions
S_{ix} & S_{iy} – are safety coefficients for longitudinal and transversal directions

and 4, respectively. To be considered safe, in our methodology, the ratio shear force capacity to shear force demand must be greater than 1.15 [34].

4.1, Non linear modelling of the building

The DRABS (Dynamic Response Analysis of Building Structure) software and the selected ground motion records were used to conduct the nonlinear dynamic response analysis of the structure. The mathematical model used for elastic analysis was extended to include the strength of structural elements and their post-elastic behaviour [35, 36]. The stress-strain relationships for concrete and reinforcement, compliant with recommendations given in CBA 93 [37], were adopted in order to present, as realistically as possible, the real behaviour of the structure during nonlinear analysis.

The UARCS (Ultimate Analysis of Rectangular Cross Section) software for frame/wall systems was used in order to determine the bearing capacity (capacity curve) of the structure in terms of strength and deformability. The input data included vertical loads, geometrics characteristics of cross sections, uniformly distributed steel, stirrup steel, and material characteristics.
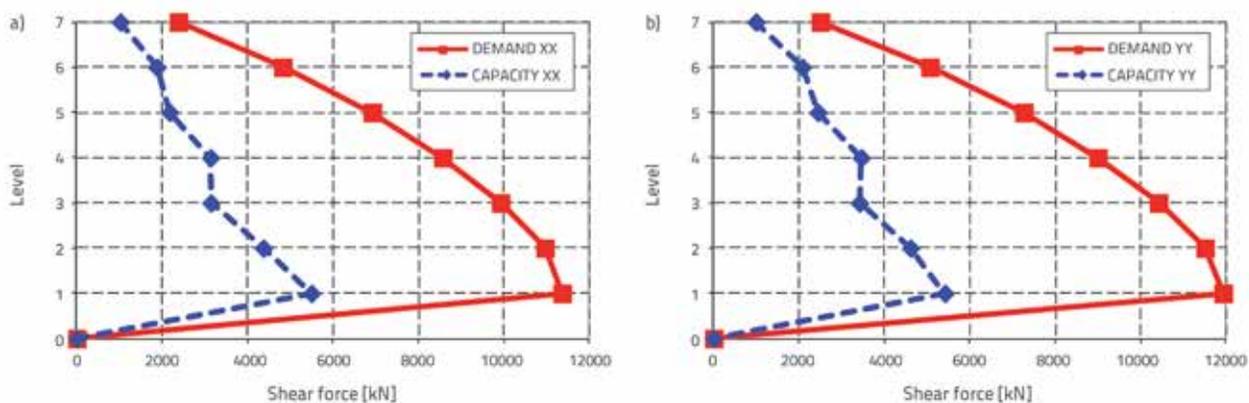

Figure 5. Comparison of capacity and demand in term of shear forces: a) Longitudinal direction; b) Transverse direction
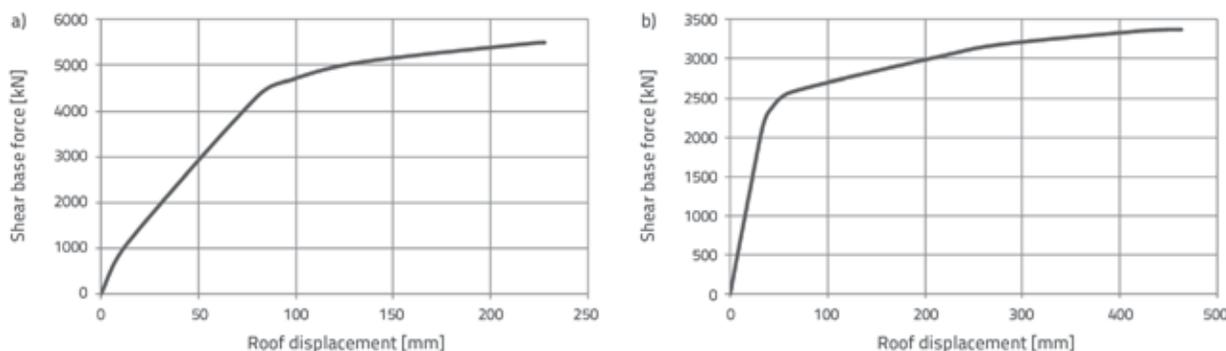

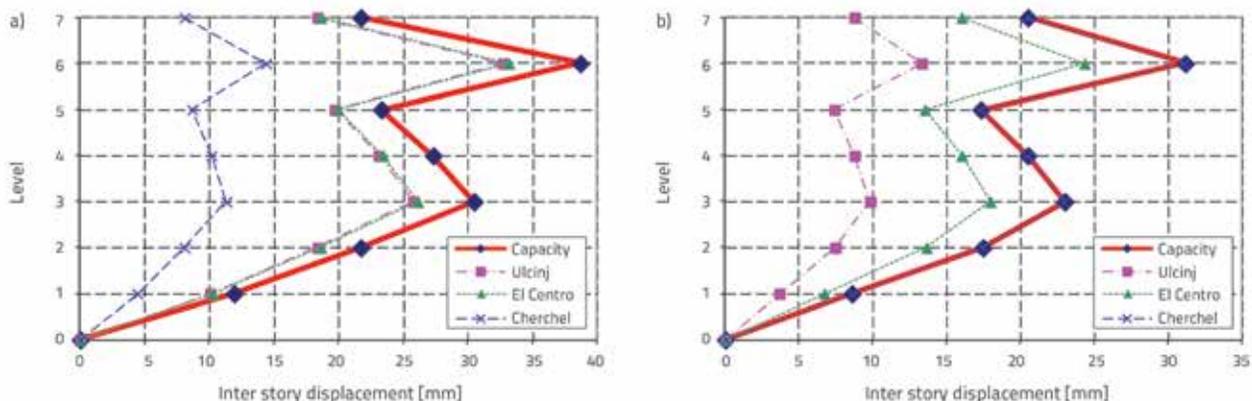**Figure 6. Capacity curves: a) Longitudinal direction; b) Transverse direction**

Figure 7. Interstorey displacement obtained by non linear static analysis for both main directions: a) Longitudinal direction; b) Transverse direction
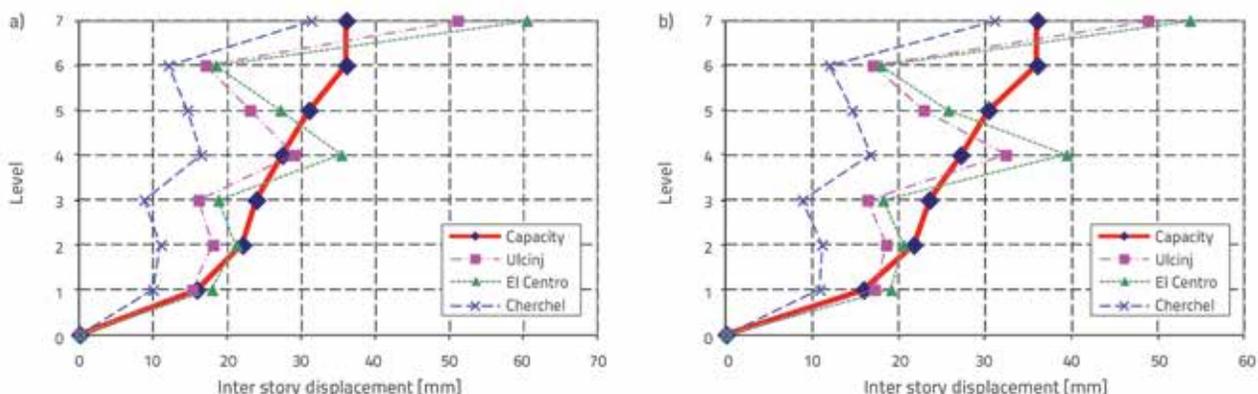

Figure 8. Inter storey displacement by non linear dynamic analysis for both main directions: a) Longitudinal direction; b) Transverse direction

According to results shown in Table 4, the safety factors S_{ix} and S_{iy} are greater than 1.15 at each level, and so the building is considered stable and resistant to seismic forces.

Figure 5 shows the demand calculated with the Algerian regulation code, RPA 99/version 2003, and the capacity in term of shear forces in the longitudinal (XX) and transverse (YY) directions, respectively.

Pushover curves of nonlinear static behaviour of the structure in the longitudinal (XX) and the transverse (YY) directions, representing the variation of base shear with the roof displacement, are shown in Figure 6.

Figure 7 shows capacity and demand results in terms of drift displacement, based on non linear static analysis (Pushover analysis) in longitudinal and transverse directions.

For the non linear dynamic analysis, the capacity of the structure is determined using the computer program for Ultimate Analysis of Rectangular reinforced-concrete Cross Sections of frames and walls systems (U.A.R.C.S), and the computer program called the Dynamic Response Analysis of Building Structures (D.R.A.B.S) [22, 23] for each structural element and at each level of the structure. Figure 8 shows the capacity and demand results in terms of drift displacement for a major earthquake (Amax=0.40 g, according to RPA99/version 2003 for important buildings), in longitudinal and transverse directions.

5. Analysis results

The following results were obtained during the analysis:
- In terms of storey shear forces, the structure is totally unsafe for both directions. The safety-factor values are very low compared to the limit (1.15), as illustrated in Table 2.
- Considering the nonlinear static analysis results, see Figure 7, it can be observed that the drift displacements capacities exceed the demand.
- However, the results of the nonlinear dynamic analysis showed that the structure is unable to withstand a major earthquake. Drift displacement capacities are lower than the demand, as shown in Figure 8. The building deforms beyond its ultimate capacity, which may lead to a severe damage followed by total collapse of the building during major earthquakes.

It is recommended that nonlinear dynamic analysis procedure be used for seismic evaluation of such existing buildings.

6. Conclusions

The seismic performance evaluation of an existing strategic reinforced-concrete building was conducted in accordance with the current Algerian seismic regulations (RPA99/version 2003). Nonlinear static and dynamic analyses were carried out to compute the demand and capacity of the structure in terms of drift displacement.

According to analysis results and the current Algerian seismic code RPA99/version 2003, the building does not meet the target confidence level and must be retrofitted.

Since the building is located in a high seismicity area (Zone III), and according to the prescriptions of the Algerian seismic design code for buildings (RPA99/version 2003), a dual structure (RC frames and shear walls) must be considered when the total height of the building is over eight (08) meters. The reinforced concrete structural walls extending over the entire height constitute the most suitable bracing system against seismic actions for skeleton structures. To improve seismic performance of the building, a pair of reinforced concrete shear walls should be added in each major direction and positioned symmetrically with respect to the centre of mass and, preferably, close to the edges of the building to stabilize dynamic response and minimize damage to diaphragms. By doing so, the top absolute displacement will be reduced considerably, and the structure should remain fully operational after a major earthquake. It has to achieve a high seismic performance in case of major earthquake, with no damage to structural elements, and slight damage to non structural elements. The Immediate Occupancy (IO) is the aimed seismic performance level for such kind of strategic buildings.

Acknowledgements

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