Seismic vulnerability assessment of strategic buildings in Algeria: methodology and case study

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SUMMARY:
On May 21, 2003, the city of Boumerdes was severely damaged by a 7.0 magnitude earthquake causing more than 2300 people death. In order to reduce this risk in the main cities, the government has enforced measures to make strategic existing buildings more resistant to earthquakes. They decided to invest into seismic upgrade, strengthening and retrofitting of these buildings. Seismic vulnerability study of this category of buildings has been considered. Structural analysis is performed based on the site investigation, and existing drawings. The aim of these seismic vulnerability studies is to develop guidelines and a methodology for retrofitting of existing buildings. This paper presents the methodology followed in our study and summarizes the vulnerability assessment and strengthening of the medical center of KHROUB hospital in Constantine. The building was assessed according to the new Algerian seismic code. Results of equivalent static method and nonlinear dynamic analysis are presented in this paper.

Keywords: RC buildings, Vulnerability assessment, Capacity design, nonlinear dynamic analysis, Strengthening

1. INTRODUCTION

The northern part of Algeria has a high seismic activity, where a major part of its population, buildings and facilities are concentrated. Recently, many strong earthquakes occurred in this region, causing enormous losses in human lives, houses and infrastructure (Ousalem and Bechtoula, 2003). In order to reduce this risk, the Algerian government decided as a first step to protect the strategic existing buildings from the adverse effects of future expected earthquakes. Hence, seismic vulnerability study of this category of buildings has been considered. A building is considered strategic by its function and by the equipments that it contains. The vulnerability assessment and strengthening of the medical centre of KHROUB hospital in Constantine, one of the most important strategic existing buildings, is presented in this paper.

2. METHODOLOGY USED TO ANALYZE REINFORCED CONCRETE BUILDING STRUCTURES

The seismic vulnerability methodology for existing buildings used in this context was developed at the National Earthquake Engineering Centre, CGS, with the cooperation of the University of Skopje, Republic of Macedonia, IZIIS, (I.Z.I.I.S/C.G.S 1993). The methodology takes into account the following steps:

1 - Data collection.
2 - Definition of the seismic hazard.
3 - Choice of the soil accelerations at the bedrock.
4 - Seismic safety criterion.
5 - Structural building safety and damageability analysis.

2.1. Definition of seismic risk and safety criterion

The seismic hazard analysis in Constantine region has been done on the basis of synthesis of the seismic hazard study of Algeria (Geomatrix, 1998; Bouhadad and Laouami, 2002). In this study, the definition of seismic hazard and attenuation laws are used to define the expected maximum acceleration at bedrock for a return period of 100 and 500 years are as follows:
A_{max} = 0.15g, for 100 years return period.
A_{max} = 0.25g, for 500 years return period.
The following sets of selected ground motion records are used in our methodology:
- El Centro (California, USA) N-S May, 1940.
- Ulcinj (Albatros, Montenegro) N-S, 1979.
- Cherchel (Algeria) N-S, 1989.

In general, the safety criterion should be set up for two levels of the expected seismic action which are:
First level: corresponding to moderate earthquakes that are expected to happen many times during the life of the building, with a return period of 100 years. The behavior of the structures should remain in the elastic range, without any damage and the building can be used immediately.

The maximum allowable story drift displacement and ductility are defined by Eqn. 2.1 and Eqn. 2.2.
Reinforced Concrete Frame Structure:

$$\Delta = \min \left\{ \Delta_{capel} \;;\; \frac{H}{300 \div 400} \right\} \quad \text{and} \;\; \mu = 1 \text{ to } 1.25 \qquad (2.1)$$

RC Shear Wall plus Frames:

$$\Delta = \min \left\{ \Delta_{capel} \;;\; \frac{H}{350 \div 450} \right\} \quad \text{and} \;\; \mu = 1 \text{ to } 1.25 \qquad (2.2)$$

Where: H is story height, Δ_{capel} is the yield displacement capacity and μ is the maximum ductility demand.

Second level: corresponding to major earthquakes that are expected once during the life of the building, with a return period of 500 years. The structure may behave in the non linear range, with a controlled level of damage. No heavy damage or collapse is allowable, and the building must be reused after inspection and slight repairs.

The maximum allowable story drift displacement and ductility are given by the following equations:
Reinforced Concrete Frame Structure:

$$\Delta = \min \left\{ \Delta_{capU} \;;\; \frac{H}{125 \div 150} \right\} \qquad (2.3)$$

RC Shear Wall plus Frames:

$$\Delta = \min \left\{ \Delta_{capeU} \;;\; \frac{H}{150 \div 175} \right\} \qquad (2.4)$$

Maximum ductility demand:

$$\begin{cases} \mu \le \mu_{cap} \\ \mu \le 2.5 \text{ to } 3.0 \end{cases} \qquad (2.5)$$

Δ_{capU}: Ultimate displacement capacity.
μ_{cap}: Capacity ductility.

To estimate the safety of the building, static and dynamic analysis for the expected moderate and major seismic ground motions should be carried out and compared to the capacity of the structure.

2.3. Static and dynamic analysis

For the defined vertical and horizontal loads, linear static and dynamic analysis is performed with SAP2000 (Wilson and Habibullah, 2006) to obtain the periods, the mode shapes, the story stiffness and relative displacements. Demands in terms of bending moments M, shear forces Q, and axial forces N, are checked for each element constituting the structure.

2.4. Seismic analysis according to the new seismic building code "RPA 99/Version 2003"

Structural elements of the building have been checked according to the new Algerian Seismic Design Code RPA 99/version 2003 (RPA99, 2003) requirements which is the latest seismic code applied in Algeria, based on the observed damage caused to structures by the 2003 Boumerdes earthquake. With the expected applied horizontal seismic forces, demands in terms of bending moments, M, Shear forces, Q, and axial forces, N, are computed and compared to the original design data if they are available.

2.5. Deformability and capacity Analysis

The capacity approach considers the real bearing and deformability characteristics of the structures in the elastic and plastic state. This approach uses the theory of the Ultimate Limit State of reinforced concrete structures. The capacity of the structure is determined using the Ultimate Analysis of Rectangular reinforced Concrete cross Sections of frames and walls systems, U.A.R.C.S. (Bozinovski and Gavrilovic, 1993).

The output results of the capacity analysis, is first given for each element and then the envelope curves are determined for each storey. The envelope curves can be expressed by the following equations respectively for the yield and the ultimate state.

$$Q_y = Q_{y\,min} + \delta_{y\,min}\left[\sum_{i=1}^{i=N-1}\frac{Q_{yi}}{\delta_{yi}}\right] \tag{2.6a}$$

$$Q_u = Q_{u\,min} + \sum_{\delta_{u\,min} > \delta_{yi}}\left[Q_{yi} + K_{2i}\left(\delta_{u\,min} - \delta_{yi}\right)\right] + \sum_{\delta_{u\,min} \le \delta_{yi}} K_{1i}\delta_{u\,min} \tag{2.6b}$$

$$\text{where: } K_{2i} = (Q_{ui} - Q_{yi})/(\delta_{ui} - \delta_{yi}) \quad \text{and} \quad K_{1i} = Q_{yi}/\delta_{yi}$$

2.6. Dynamic response analysis

To determine the non-linear response of the structure, the Dynamic Response Analysis of Building Structures, D.R.A.B.S, program (Bozinovski and Gavrilovic 1993) is used to assess the force-displacement relationship curve at each story of the structure.

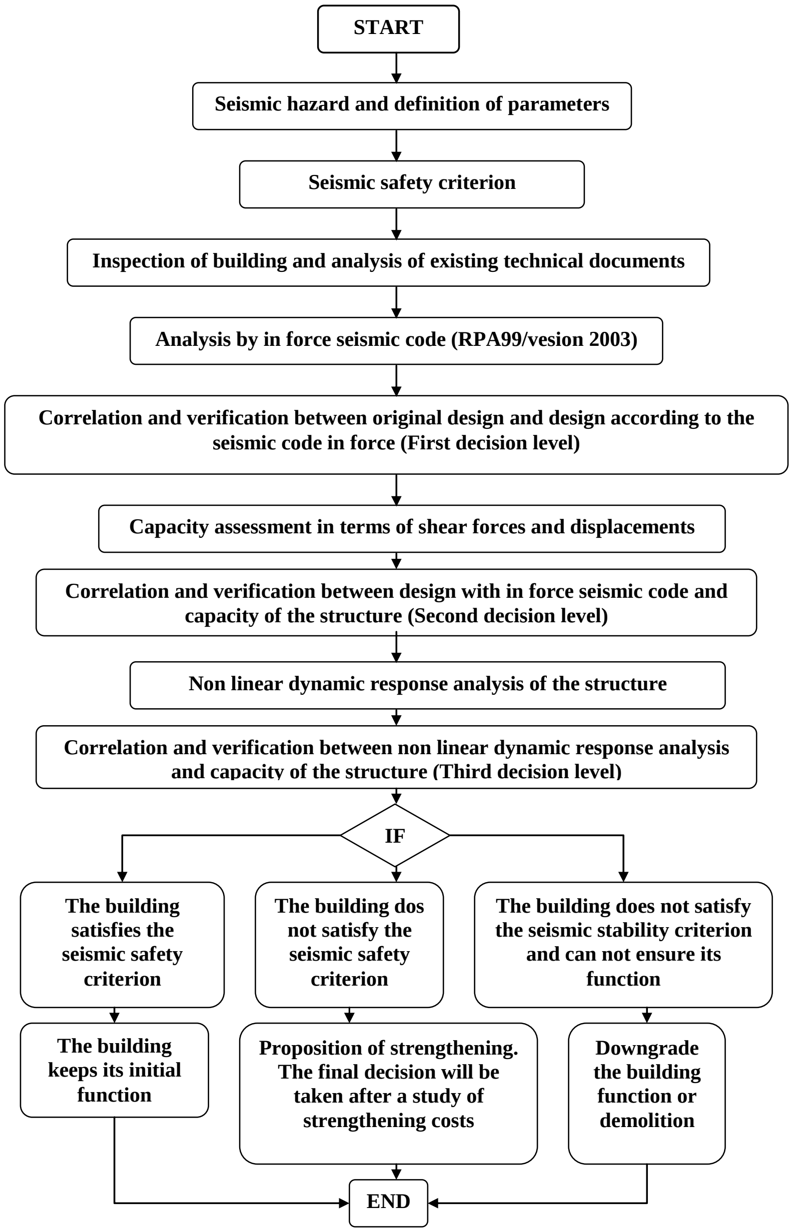

Figure 2.1: Methodology flow chart

2.7. Vulnerability assessment

Based on the analysis performed in accordance with the previously discussed procedure, a final decision and proposal should be submitted to the owner of the building according to the following:

1- If the structure satisfies the stability criteria in accordance with its function, the building can be used in its existing state.
2- If the structure does not satisfy the stability criteria, strengthening or modification of its function should be recommended.
3- If the structure does not satisfy the elementary criteria, a decision has to be made either to strengthen demolish the building.

The final decision should also take into account the results of the feasibility and the cost analysis of the proposed solution. Figure 2.1, summarizes the flow chart of the adopted methodology.

3. CASE STUDY

3.1. Description of the building

The building is for medical purpose and serves a surgery for children. It was built in the last century, according to the recommendations of that era before the apparition of any seismic code. The building is composed of three stories. The structural system is a moment resisting RC frames with reinforced concrete shear walls at the first level.

3.4. Structural analysis

The structural elements of the building were modeled in a 3D space, using the non linear SAP 2000. Figure 3.1 shows the analytical model of the existing structure.

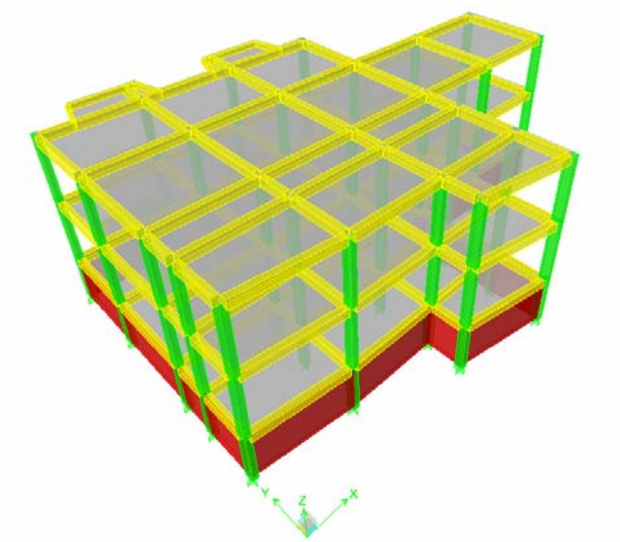

Figure 3.1: Three-dimensional view of the initial structure.

3.5. Seismic assessment by the Algerian seismic code RPA 99/version 2003

The total design seismic base shear force is estimated using the static equivalent force procedure (Dimova, 2005). For our case study, distribution of the lateral seismic loads is shown in Table 3.1, for both longitudinal and transversal directions.

Table 3.1: Distribution of the longitudinal (X-X) and transversal (Y-Y) seismic forces

Level	W (t)	Longitudinal (KN)	Transversal (KN)
3	313.8	842.71	949.71
2	401.1	1466.13	1634.87
1	480.0	1962.91	2067.45

3.6. Deformability and strength capacity

As mentioned previously in the methodology, the capacity of the structure in terms of strength and deformability, was evaluated using U.A.R.C.S. The structure is considered stable when the safety factor, Fs, given in Eqn. 3.1, is greater than 1.15 at each level.

$$Fs = \frac{Q_k^u}{V_k} \geq 1.15 \tag{3.1}$$

Where:

Q_K^U : Shear force capacity at level k.

V_K: Shear force demand at level k.

Tables 3.2 and 3.3 summarize the results of shear capacity, shear demand and safety factors, for both longitudinal and transversal directions.

Table 3.2: Shear capacity; shear demand and safety factors of the structure in the longitudinal direction

Longitudinal direction (X-X)						
Level	W (t)	K (KN/cm)	Qy (KN)	Qu (KN)	V (KN)	Fs
3	313.8	504.4	1118.25	1578.03	842.71	1.87
2	401.1	602.3	1471.42	1647.05	1466.13	**1.12**
1	480.0	253149.7	10125.99	10125.99	1962.91	5.16

Table 3.3: Shear capacity; shear demand and safety factors of the structure in the transversal direction

Transversal direction (Y-Y)						
Level	W (t)	K (KN/cm)	Qy (KN)	Qu (KN)	V (KN)	Fs
3	313.8	1239	1768.05	2474.81	949.71	2.61
2	401.1	1489.5	2369.79	2606.91	1634.87	1.59
1	480.0	109701.7	4388.07	4388.07	2067.45	2.12

It is shown from Table 3.2, that the safety factor, Fs, is not satisfied for the second level in the longitudinal direction.

Table 3.4 summarizes the characteristics of the selected accelerograms used in the analysis. The indicated duration in the table represents the total duration of the motion and not the duration of the strong motion only. The time history and the frequency content of these accelerograms are shown in Fig. 3.2.

Table 3.4: Characteristics of the selected earthquakes

Earthquake	Country	Direction	Year	Duration (s)	Amax (m/s²)
Ulcinj Albatros	Serbia	N-S	1979	40	1.68
El Centro	U.S.A	N-S	1940	40	3.42
Cherchel	Algeria	N-S	1989	24	2.26

Figure 3.3 through Fig. 3.6 show the obtained results of the capacity and the demand in terms of drift displacements for a moderate (Amax=0.15g) and major (Amax=0.25g) earthquakes, in the transversal and longitudinal directions, respectively.

Ductility demand was also evaluated for the major earthquake at each story and compared to the capacity for both directions. However, these results are not presented in this paper due to the limitation of the number of pages.

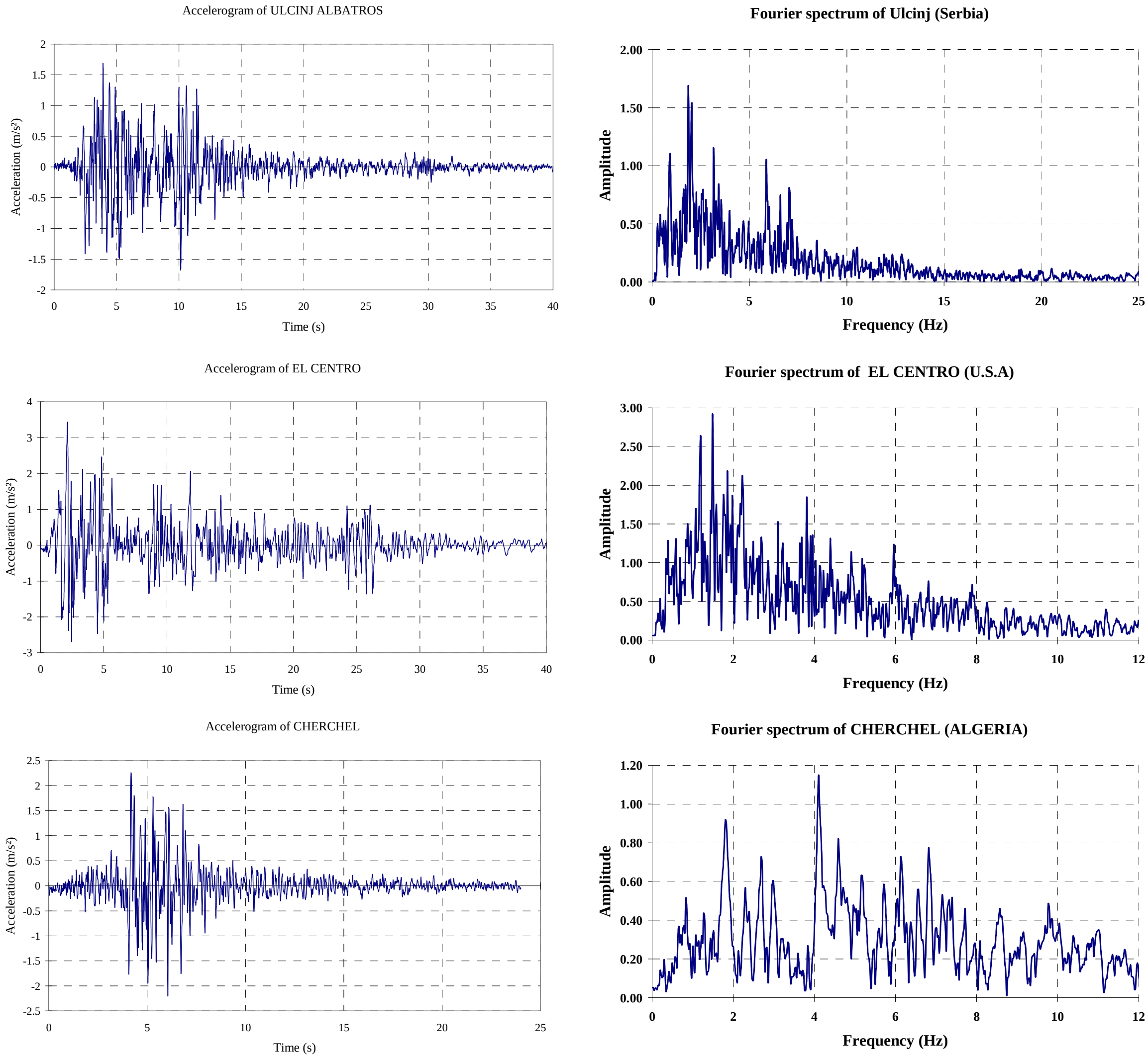

Figure 3.2: Selected earthquake accelerograms with their respective frequency contents.

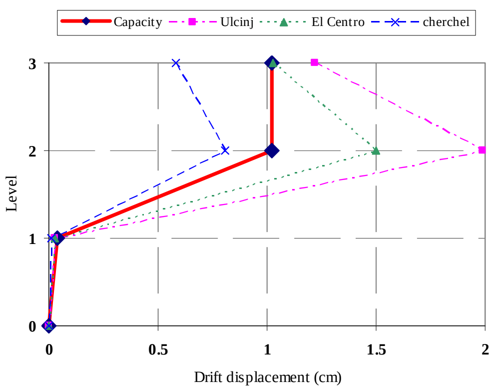

Figure 3.3: Displacement Capacity-Demand, transversal direction Amax=0.15g.

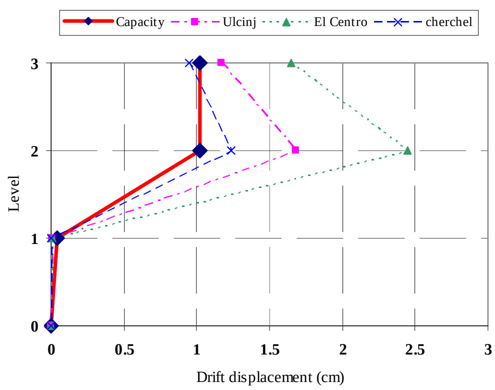

Figure 3.4: Displacement Capacity-Demand, longitudinal direction Amax=0.15g.

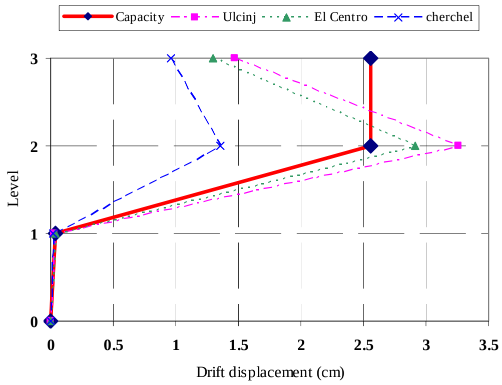

Figure 3.5: Displacement Capacity-Demand, transversal direction Amax=0.25g.

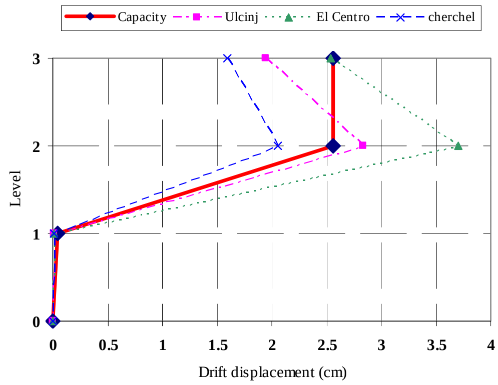

Figure 3.6: Displacement Capacity-Demand, longitudinal direction Amax=0.25g.

From the obtained results, it can be observed that, drift displacements under lateral forces exceeded considerably the allowed capacity values. All computations led to the conclusion that the structure needs strengthening in order to increase the strength and to limit the drift displacements under a major earthquake. Many simulations have been tried in order to get the most economic and convenient solution.

3.7. Suggestion of strengthening

In order to get a dual system with a behavior factor R=5, four new RC shear walls with 15 cm thickness were added in both directions along the height of the structure (Rocha, 2004), two in the transversal direction and two in the longitudinal direction. Figure 3.7 shows the suggested strengthening of the structure with the new RC shear walls. The selected strengthening method was based on the Authors experience in the field and using the catalogue for repair and strengthening of buildings edited by the National Earthquake Engineering Research Center (CGS, 1994; Varum, 2003).

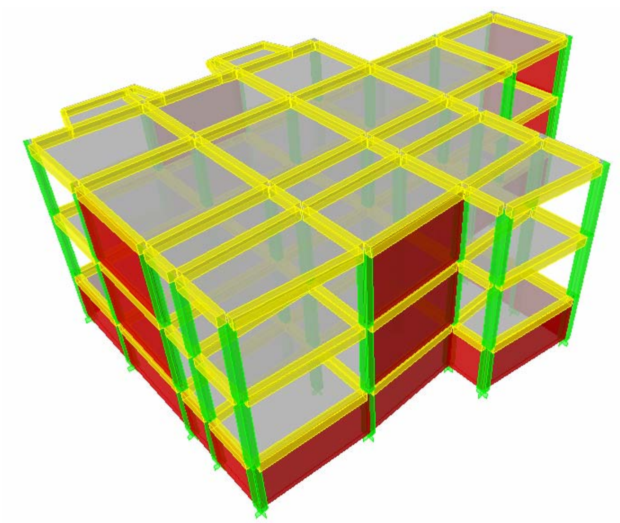

Figure 3.7: Three-dimensional view of the strengthened structure.

The strengthened structure was reanalyzed using the same procedure.. Figure 3.8 through Figure 3.13 show the new capacity and the demand in terms of shear forces, displacements and ductility for the proposed method of strengthening. It can be observed that the proposed method increased the performance of the structure in both directions either for strength, displacement and ductility capacity.

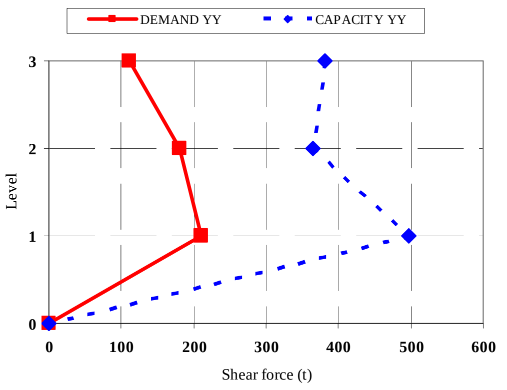

Figure 3.8: Capacity and demand in transversal direction for the strengthened structure.

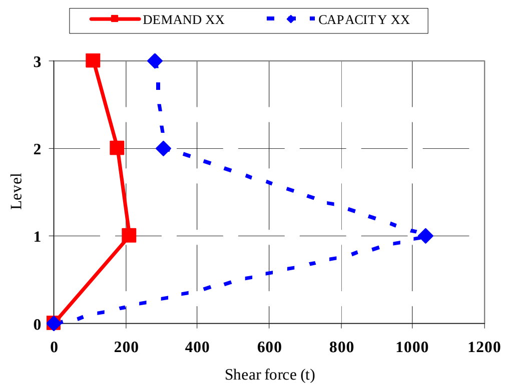

Figure 3.9: Capacity and demand in longitudinal direction for the strengthened structure.

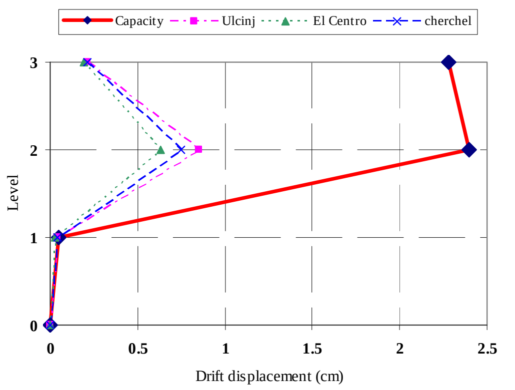

Figure 3.10: Displacement Capacity-Demand for the strengthened structure, transversal direction Amax=0.25g.

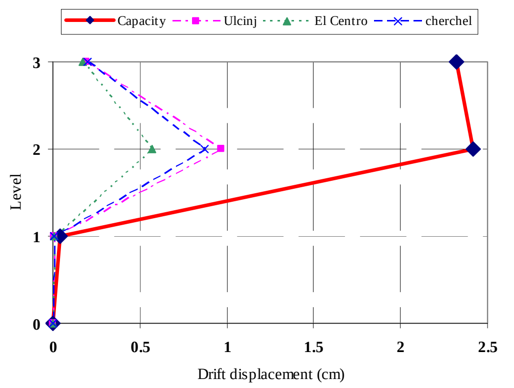

Figure 3.11: Displacement Capacity-Demand for the strengthened structure, longitudinal direction Amax=0.25g.

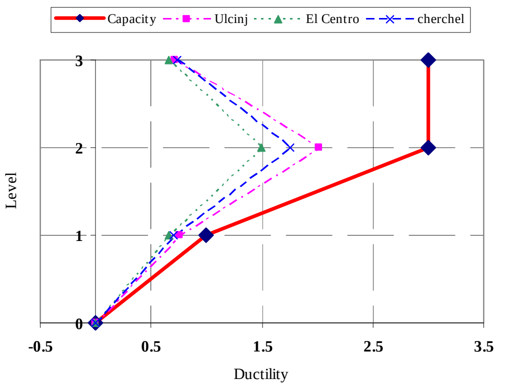

Figure 3.12: Ductility Capacity-Demand for the strengthened structure, transversal direction Amax=0.25g.

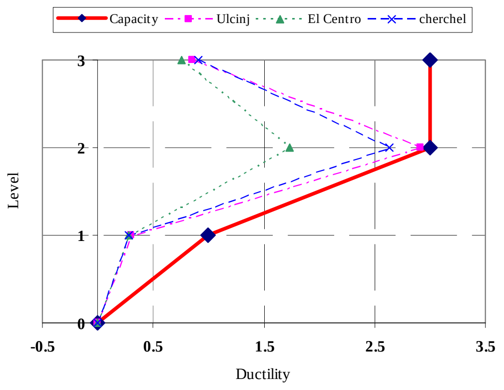

Figure 3.13: Ductility Capacity-Demand for the strengthened structure, longitudinal direction Amax=0.25g.

4. GENERAL CONCLUSION

A methodology of the vulnerability study of the strategic buildings in Algeria was introduced. A case study of one of these buildings located at Constantine province, Algeria, was presented. The original structural system showed an important deficiency in capacity criteria in terms of shear strength, displacements and ductility at each level of the structure. One of the most difficult problems of strengthening of an existing building is how to find the most adequate solution that satisfies both economical and technical aspects. In our case, many solutions were carried out to get the best and feasible solution. Four additional RC shear walls placed at the external frames were inserted to the existing system. This retrofitting method showed a great improvement in the capacity of the building, and satisfied the criteria of the methodology.
It is important to mention that the vulnerability and functionality of a strategic building must include the whole neighboring buildings even if they are not strategic, since they may block the access and the functionality of this building, during an major earthquake event.

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