SEISMIC VULNERABILITY OF A STRATEGIC BUILDING DESIGNED BY ALGERIAN SEISMIC CODE RPA 99, USING THE CAPACITY SPECTRUM METHOD

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ABSTRACT :

This paper aims to present a methodology to evaluate the seismic vulnerability of Reinforced Concrete (R/C) existing buildings, based on Capacity Spectrum Method (CSM). The seismic capacity of a strategic R/C frame building, designed by the Algerian seismic code RPA99, before Boumerdes Earthquake 2003, is evaluated according to the new revised seismic code RPA99/Version 2003. The CSM procedure results are used to get a safety criterion for the R/C frame structure, to evaluate its seismic vulnerability and take decision on the potential strengthening of the building. The capacity approach in terms of force and deformation will be the way for checking the resistance of the structure such as limitation in deformation. Pushover analysis method is adopted in order to obtain the performance curve of the existing building using a three dimensional nonlinear program CANNY. A Nonlinear Time History Analysis is also performed using real accelerograms of Boumerdes, 2003 (Algeria) and El–Centro, 1940 (USA) to check the building's performance. It's shown that this methodology is practical and provides accurate results on the vulnerability of middle and low rise R/C frame structures.

KEYWORDS: R/C moment resisting frame building, Seismic Vulnerability, Static Nonlinear Analysis, Capacity Spectrum Method, Nonlinear Time History Analysis.

1. INTRODUCTION

The severe Earthquake of El Asnam October 10, 1980 with a magnitude 7.3, was the start point of regulations in Algeria. First was Algerian Seismic Regulation 81 (RPA81) then 83, 88 and 99, further comes Zemmouri Earthquake (Algeria) May 21, 2003, with a magnitude 6.8, and shake again some chapters in the code and revised it to a newer version RPA99/Version 2003 (CGS, 2003).

The main target of this paper is to evaluate the seismic vulnerability of existing buildings (moment resisting frame structure) designed by Algerian code RPA99 using Capacity Spectrum Method (CSM). For this purpose, we choose an existing RC Frame structure designed in 2002 using old version of seismic regulation RPA99. The height of the three stories building is greater than 8 m (H = 9.52 m) and it is located in Algiers City which is classified in Zone III (high sismicity) by RPA99/Version2003, therefore, the structure does not conform to the article (3.4-A-1.b) in the new regulation. In this case the building must be stronger and the solution suggests is strengthening by adding reinforced concrete shear walls. Therefore, the vulnerability study of this existing building (moment resistant frame structure without adding reinforced concrete shear walls) is discussed in order to criticize the chapter (3.4-A-1.b) about the height restriction.

Pushover analysis method is adopted in order to obtain the performance curve of the existing building using a three dimensional nonlinear program CANNY (Li, 2002). A Nonlinear Time History Analysis is also performed using real accelerograms of Boumerdes 2003 (Algeria) and El–Centro 1940 (USA) to check the building's safety.

2. CHARACTERISTICS AND MODELING OF THE STRUCTURE

2.1. The Layout of the structure

The data of the building used for the analysis are shown in Fig. 1.

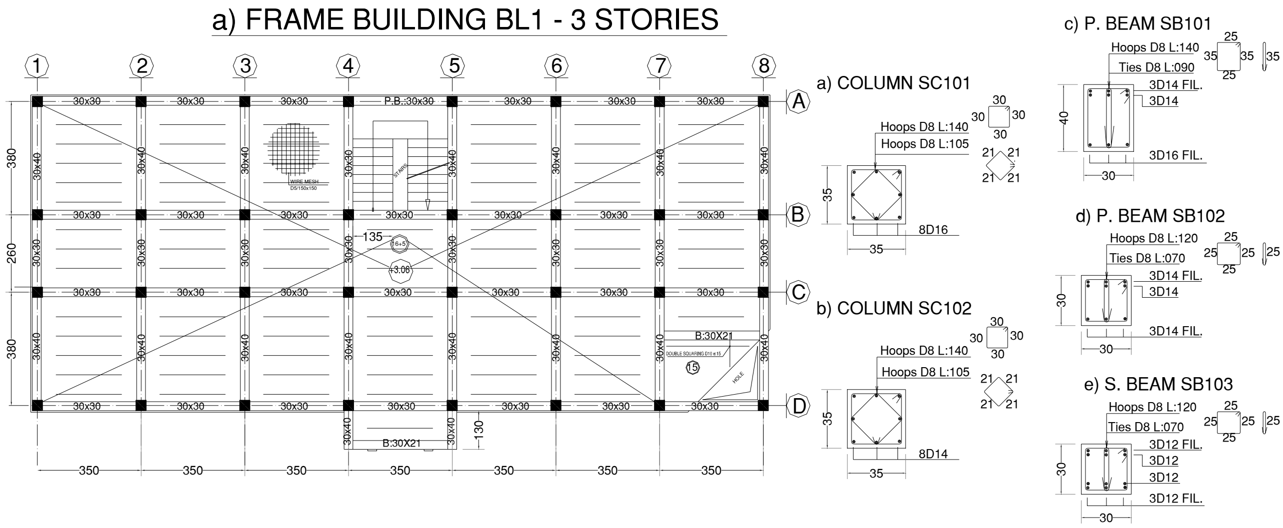


Figure 1. The plan view and details of the three stories building.

The characteristics of the materials used in Algeria are summarized as follows:

- Concrete: f_{C28} : 25 MPa (compressive strength), f_{t28}: 2.1 MPa (tensile strength).
- Steel: High adherence rebar FeE40 f_e: 400 MPa (General using)

2.2. Modeling of structural members

Nonlinear dynamic analysis of a reinforced concrete structure requires two types of mathematical modeling: a) modeling of stiffness distribution along a member; and b) modeling of the force-deformation relationship under stress reversals. The former models are called "member models", and the latter "hysteresis models". The member models used to represent the stiffness behavior of columns and beams are presented in the following part.

Column Model:
The axial force is taking into account; by the use of Multi-axial Spring Model “MS Model”, which take in account the interaction between bending and axial forces and also by adding a nonlinear shear spring at the middle.

Beam Model:
Beam member is idealized by perfectly elastic massless line element with two nonlinear rotational springs at the ends. The model has two rigid zones outside the rotational springs. We add at the middle nonlinear shear spring with Uniaxial Hysteresis Damping with trilinear model and degradation unloading stiffness.

3. CONCEPT OF CAPACITY SPECTRUM METHOD

The general idea of the structural characteristic is represented by the capacity curve which is the relationship of shear coefficient vs. displacement for an equivalent SDOF system. The capacity curve is determined by statically loading the structure with realistic gravity loads combined with a set of lateral forces to calculate the displacement and base shear coefficient (Freeman, 1998).

The capacity spectrum is usually expressed as the responses of an equivalent single degree of freedom system (SDOF) corresponding to the first mode of the building (Fig. 2).

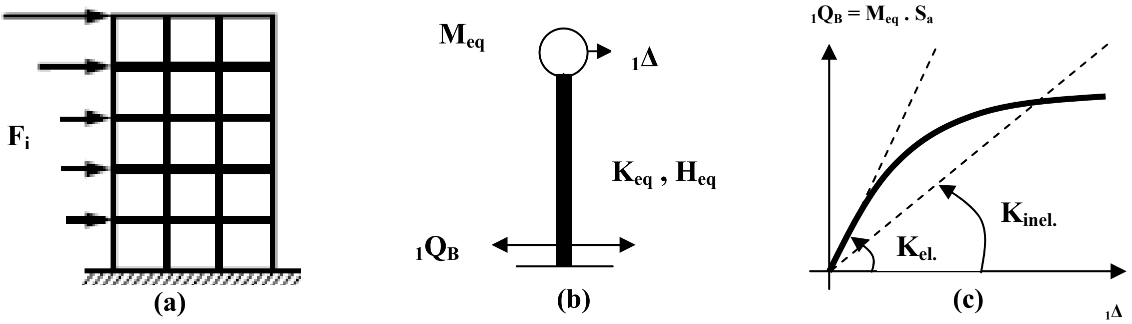


Figure 2. Conversion method MDOF to SDOF system
a) MDOF system, b) Equivalent SDOF system corresponding for the first mode, c) Capacity curve

3.1. Procedure of conversion MDOF to SDOF system

The horizontal displacement of the i^{th} story in MDOF system, 1δi, is expressed as:

$$ {}_1\delta_i = {}_1\beta \cdot {}_1u_i \cdot {}_1\Delta = {}_1\beta \cdot {}_1u_i \cdot {}_1S_d \tag{3.1}$$

where, ${}_1\delta_i$: displacement at i^{th} story;
${}_1\beta$: modal participation factor for 1^{st} mode;
${}_1u_i$: amplitude (mode shape) at i^{th} story for 1^{st} mode;
${}_1\Delta$: displacement response of SDOF system;
${}_1S_d$ and ${}_1S_a$: spectral displacement and acceleration in the equivalent SDOF system respectively.

MDOF system can be converted to an equivalent SDOF system with equivalent lumped mass, stiffness and height (Shibata, 1993). Equivalent mass M_{eq} and equivalent height H_{eq}, are respectively given by:

$$ M_{eq} = \frac{\left(\sum_{i=1}^{N} m_i \delta_i\right)^2}{\sum_{i=1}^{N} m_i \delta_i^{\,2}} \quad ; \quad H_{eq} = \frac{\sum_{i=1}^{N} m_i . H_i \cdot {}_1\delta_i}{\sum_{i=1}^{N} m_i \cdot {}_1\delta_i} \tag{3.2}$$

with, m_i : mass of i^{th} story and H_i: height of i^{th} story.

Base shear force is given by:

$$ Q_B = {}_1Q_B = \sum_{i=1}^{N} P_i = M_{eq} \cdot {}_1S_a \tag{3.3}$$

where P_i : external Force at i^{th} story.

Therefore, the yield natural circular frequency of the first mode is given by:

$$ {}_1\omega^2 = \frac{\sum_{i=1}^{N} {}_1P_i \cdot {}_1\delta_i}{\sum_{i=1}^{N} m_i \cdot {}_1\delta_i^{\,2}} \tag{3.4} $$

From Eqn. (3.3) and relation between spectral displacement and spectral acceleration we obtain:

$$ {}_1S_a = {}_1Q_B / M_{eq} \quad \text{and} \quad {}_1S_d = {}_1S_a / {}_1\omega^2 \tag{3.5} $$

Using Eqn. 3.5 and information on the displacements of each story and the base shear in each loading step obtained from nonlinear pushover analysis with the external force distribution proportioned to the first mode, a S_a-S_d curve (Capacity spectrum) can be drawn as shown in Fig. 3. Next, we compare the structural capacity (in the form of a pushover curve) with the structural demands (in the form of response spectrum) (Bakhti *et al*, 2006). When both the capacity spectrum and the demand response spectrum are defined with the same set of coordinates, they can be plotted together (Fig. 3). The graphical intersection of the two curves approximates the response of the structure (performance point).

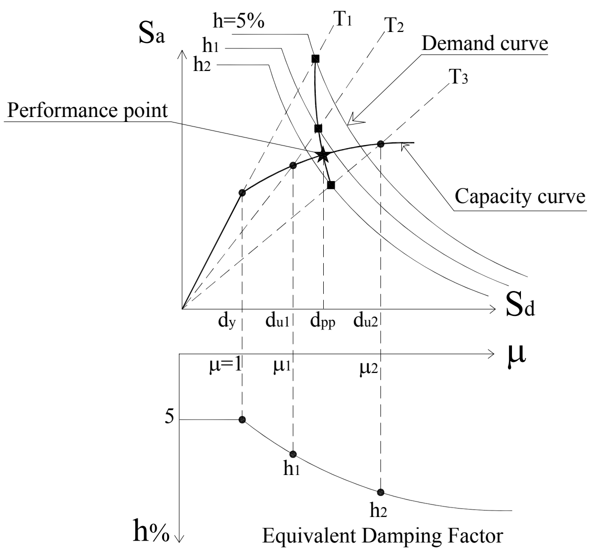


Figure 3. The general vision of Seismic Performance evaluation and application.

In order to account for nonlinear behavior of the structural system, effective damping values are used in the elastic-linear response spectrum to imitate an inelastic response spectrum. Equivalent damping factor h is related to the ductility factor μ by the following relation (BSL 2004):

$$ h = 0.25(1 - 1/\sqrt{\mu}) + 0.05 \tag{3.6} $$

4. PUSHOVER ANALYSIS

Pushover analysis was performed under the following assumption:

- Lateral shear force distribution at each story is Ai according to BSL2004;
- Bending, and shear deformations are considered in beams;
- Bending, shear, and axial deformations are considered in columns;
- The hysteresis characteristics are modeled as tri-linear, with degradation of unloading stiffness as show in Fig. 4.

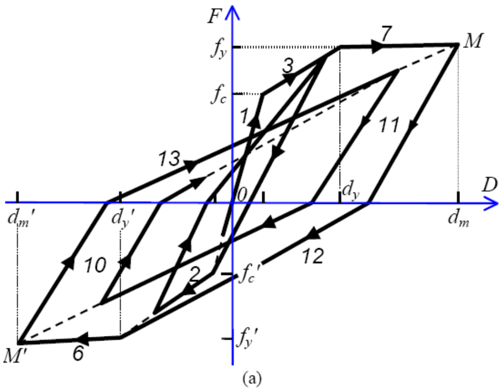
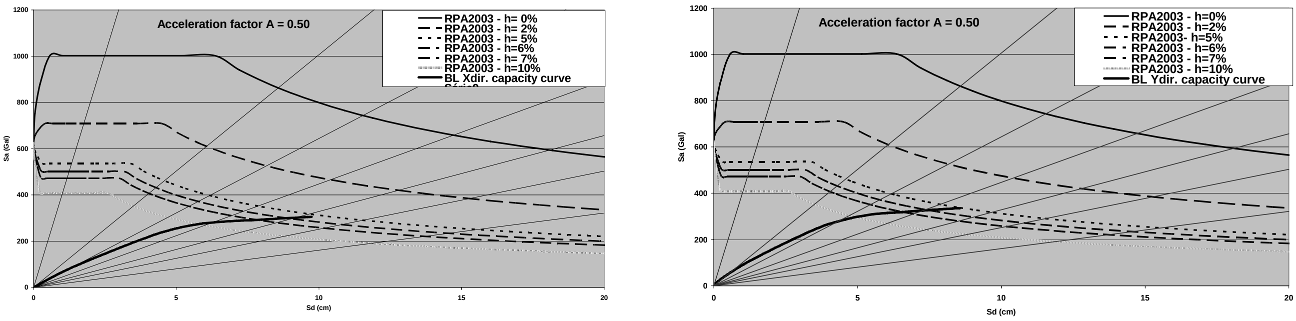


Figure 4. Cross Peak tri-linear/bilinear model CP3

4.1. Demand Spectra and Capacity of Building

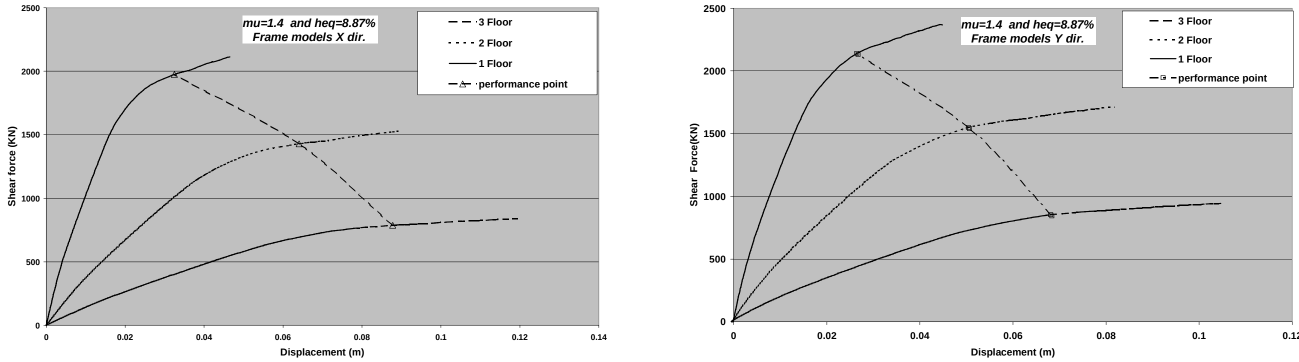
The demand spectra and the capacity of the buildings are described in ADRS format (S_a–S_d diagram) as shown in Fig. 5. The demand spectra for each damping with acceleration factor A=0.5, is summarized in elastic response spectrum given by RPA99/Version 2003.



a) Building Results in X direction

b) Building Results in Y direction

Figure 5. Structural Capacity and Demand curve in ADRS Format.



a) Response of the Building in X direction

b) Response of the Building in Y direction

Figure 6. Responses of MDOF system corresponding to the performance point.

Using Fig. 6, we can obtain the performance point (Seismic design), with the inverse conversion SDOF system to MDOF system for the performance point, you can find easily the limit design for each floor (shear force vs. displacement) in the Building as shown in Fig. 6.

5. NONLINEAR TIME HISTORY RESPONSE ANALYSIS

To evaluate the maximum responses of shear force and displacement for each story, we use a more precise elasto-plastic multi-mass time-history analysis using a three dimensional nonlinear program CANNY (Li, 2002) and real earthquake records shown in Table 1.

Table 1. Input Earthquake waves

Input Earthquake waves	PGA (Gal)	Time Duration (s)
Zemmouri 2003 NS	331.55	35
Zemmouri 2003 EW	260.14	35
El Centro 1940 NS	341.7	30
El Centro 1940 EW	210.1	30

5.1. Safety checking in story shear force

In order to evaluate the safety factor in story shear force of the building, you should assess the ratio of the ultimate capacity Q_u on the request demand Q_{req} as follows :

$$F_s = \frac{Q_u}{Q_{req}} \tag{5.1}$$

The value of safety factor should be $F_s \geq 1.15$.

Comparing the coefficient results to the allowable safety factor according to the methodology for each story as shown in Table 2 and Table 3, we conclude in the case of Zemouri Earthquake almost all stories is in accordance with the criteria, but for Elcentro earthquake the condition of safety in story shear force is not verified.

Table 2. Maximum story shear force (KN) and safe factor Fs in X direction

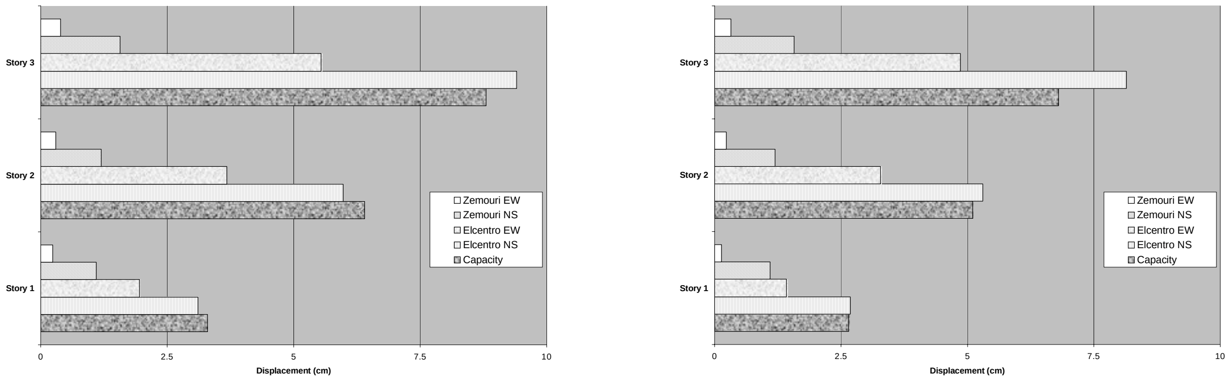
Story	Capacity	Elcentro NS	F_s	Elcentro EW	F_s	Zemmouri NS	F_s	Zemmouri EW	F_s
3	786.70	1347.0	0.47	1091.10	0.72	1244.90	0.63	451.40	1.74
2	1428.4	1672.4	0.85	1401.00	1.02	994.20	1.43	689.60	2.07
1	1974.	2117.1	0.93	1862.70	1.06	1630.00	1.21	720.90	2.734

Table 3. Maximum story shear force (KN) and safe factor Fs in Y direction

Story	Capacity	Elcentro NS	F_s	Elcentro EW	F_s	Zemmouri NS	F_s	Zemmouri EW	Fs
3	853.50	1419.90	0.60	1031.70	0.827	647.80	1.31	191.60	4.455
2	1548.70	1945.10	0.79	1453.90	1.065	822.50	1.88	257.60	6.012
1	2140.90	2180.00	0.98	1520.60	1.408	1122.80	1.90	347.00	6.170

5.2. Safety checking of story displacement according to RPA99/Version2003

The displacement results, obtain by Non-linear dynamic analysis as shown in Fig. 7, those results are compared with the allowable displacement recommended by Algerian Code in Table 4.



a) Story Displacement in X direction   b) Story Displacement in Y direction

Figure 7. Maximum response Demand of the Building

In Y direction the Displacement criteria is verified, however in the direction X the condition is slightly checked, note that for allowable story drift 1.1%H (H: Story height) is totally verified in two direction.

Table 4. Maximum relative story displacement in two directions

Story	Earthquake	Demand in X-dir.	Capacity Disp. in X-dir	Demand in Y-dir.	Capacity Disp. in Y-dir.	Allowable disp H/100
1	Elcentro NS	3.11	3.33	2.68	2.65	3.06 cm
	Elcentro EW	1.95		1.42		
	Zemouri NS	1.10		0.56		
	Zemouri EW	0.24		0.14		
2	Elcentro NS	2.87	3.07	2.62	2.45	3.06 cm
	Elcentro EW	1.73		1.86		
	Zemouri NS	0.10		0.27		
	Zemouri EW	0.06		0.09		
3	Elcentro NS	3.43	2.40	2.84	1.70	3.40 cm
	Elcentro EW	1.86		1.58		
	Zemouri NS	0.37		0.36		
	Zemouri EW	0.09		0.095		

6. CONLUSIONS

Conclusions are summarized as follows:

- Performance based seismic design can be attained through CSM under appropriate assumptions.
- Results obtained through CSM method are consistent in order to get all the characteristics (Strength and ultimate displacement) of the structural capacity by using Pushover Analysis.
- The methodology for seismic vulnerability assessment of the RC structure is practical to get accurate results and make a judgment for each story facing the strength.
- The chapter (3.4-A-1.b) is too much penalty about the restriction building height, this Article should be revised i.e. increase the height limitation.
- Because only the first mode of vibration is considered, the Capacity Spectrum Method used here, is valid for low and middle rise building; for high-rise building the upper modes must be included.

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