Seismic Vulnerability of Buildings through Robust Database of Earthquakes and Buildings

Tharwat A. Sakr[1], Atef Eraky[2], Osman Shallan[2] and Sajad Kareem[3]

[1] Ass. Professor, [2] Professor, Faculty of Engineering, Structural Engineering, Zagazig University
[3] Msc Student, Faculty of Engineering, Structural Engineering, Zagazig University
eng_sajad23@yahoo.com

Abstract: Earthquake Engineering aims to reduce seismic risks resulting from earthquakes and facilitate the process of designing earthquake-resistant buildings. Evaluation of seismic vulnerability of structures is of most importance due to the increase number of seismic events that causes significant losses and damages. The capacity spectrum method (CSM) is a nonlinear static analysis method suggested by several regulations such as the ATC and FEMA, which compares the global force-displacement capacity curve of a structure with an earthquake response spectrum in graphical bases. In this paper, the capacity spectrum method is investigated and applied to buildings through the development of robust database including large stock of historical earthquakes. The developed database is customized in the vulnerability assessment of different example buildings with emphasize on the characteristics leading to the alteration of seismic vulnerability class. The results are presented in formValuable to practical design guides.
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1. Introduction

A severe earthquake is one of the most frightening phenomena of nature. Earthquakes are the result of sudden movements of the Earth, caused by the release of strain energy that has accumulated over a long time. If the earthquake occurs in a populated area, it may cause deaths, injuries and extensive property damage.In the last century the death toll due to earthquakes was between 1.6 million - 2.2 million people and injured toll from 2 - 10 times the dead. Seismic risk is related to the consequences caused by the occurrence of damaging earthquakes such as the loss of life, direct physical damage, or business interruption losses [1], The term “seismic risk” combines two parts: seismic hazard and structure vulnerability as

Risk = Hazard× Vulnerability.

Seismic hazard deals with earthquakes, where and when they occur, how big they are and why they happen,it includes also the evaluation of the frequency and severity of earthquakes for a given place and provides information in order to take measures to reduce the possible damages[2]. Structure vulnerability is related to how the structure is affected by earthquakes.The evaluation of seismic vulnerability of structures is thus of most importance due to the increase number of events and losses[3],too many techniques have been developed during the last decades for seismic vulnerability assessment to avoid such losses. These methods differs in the degree of complexity and area of application as follows.

Rapid visual screening (RVS): This is very quick way of assessing the building vulnerability based on visual screening. Evaluation in this first level does not require any analysis. The RVS methodology is referred to as a “sidewalk survey”in which an experienced screener visually examines a building to identify features that affect the seismic performance of the building, such as the building type, seismicity, soil conditions and irregularities[4].

Probability of failure: The method makes use of discrete probability distributions in risk and reliability calculations–application to seismic risk assessment. The estimation of the fraction of structures in the class not expected to survive the period of observation may be formulated assuming that the class is the entity the failure probability has to be computed for, as seismic reliability methods compute the probability of failure (Pf) for specific structures. To this aim the probabilistic characterization of the class-capacity and of the class-demand, which are functions associating to any building belonging to the class of its seismic performances, is needed.[5, 6].

Where:

$[P_f = P[Z(X) \leq 0] = P[C(X) \leq D(X)]]$ eq. (1)

Pf: failure probability, since for any x, the C(x) and D(x) functions return the seismic capacity and demand respectively of the structure defined by x, the risk assessment is possible only if statistics for the components of the X vector are available.

Fragility curves are considered useful tools for predicting the extent of probable damage. They describe the probability of a structure being damaged beyond a specific damage state for different levels of ground shaking[7-11], therefore, Seismic fragility curves represent the probability of exceeding predefined performance damage states as a result of various levels of ground motion intensity.Fragility can be represented by the conditional probability statement

Fragility = P (DS^{+} | IM)equation (2)

Where DS^{+} represents the condition that some damage state of the structure has been met or exceeded as related to some predefined limit state and IM signifies an intensity measure of a given ground motion.

Damage probability matrices (DPMs): This method is presented for the empirical vulnerability assessment of typical building types, based on processing of a large set of statistical data, using the standard empirical procedure. The direct use of data in terms of repair to replacement cost ratios is recommended (for loss assessment) [12-14]

Pushover Analysis: A nonlinear pushover analysis is carried out for evaluating the structural seismic response. The pushover analysis consists of the application of gravity loads and a representative lateral load pattern. The lateral loads were applied monotonically in a step-by-step nonlinear static analysis. The applied lateral loads were accelerations in the x direction representing the forces that would be experienced by the structures when subjected to ground shaking,(ATC 40,Council 1996)[15-20].

Capacity spectrum method (CSM): can be used for a variety of purposes such as rapid evaluation of a large inventory of buildings, design verification for new construction of individual buildings, evaluation of an existing structure to identify damage states, and correlation of damage states of buildings to various amplitudes of ground motion. The procedure compares the capacity of the structure (in the form of a pushover curve) with the demands on the structure (in the form of response spectra). The graphical intersection of the two curves approximates the response of the structure. Its concept has been introduced in several US guidelines for seismic evaluations such as the ATC-40 [Applied Technology Council, 1996][21-23].

At the present paper, the capacity spectrum method is justified for the application to reinforced concrete buildings through robust database to handle both buildings and earthquakes. Stock of previous earthquakes with different characteristics is stored in the database from which any combination can be customized in the development of demand spectrum used in the vulnerability assessment. On the other hands, main buildings information is stored in the database including the capacity spectrum in form of force –displacement and spectral acceleration – displacement relationship. The capacity spectrum method is applied to any of the buildings stored in the database using the response spectrum generated using any combination of earthquakes. The performance point is then estimated for which the vulnerability category can be identified. The system developed is then applied to example buildings with different characteristics showing the effect of these characteristics on thebehavior and the seismic categorization of buildings.

2. Capacity Spectrum Method

The capacity curve is determined by statically loading the structure with realistic gravity loads combined with a set of lateral forces to calculate the roof displacement Δ_R and base shear coefficient $C_{B=V/W}$ that defines first significant yielding of structural elements. The curve is created by superposition of each increment of displacement and includes tracking displacement at each story (ATC 40). This procedure is sometimes referred to as the pushover analysis. For added sophistication, at each increment beyond yielding, the forces may be adjusted to be consistent with the changing deflected shape [25]. The stiffness is assumed to reduce to an equivalent global secant modules measured to the maximum excursion along the capacity curve for each cycle or motion. The Δ_R vs V/W coordinates are converted to spectral displacement Sd and spectral accelerations Sa , respectively by use of modal participation factors $PF1\varphi_{R1}$ and effective modal weight ratios ($\propto_1$) as determined from dynamic characteristics of the fundamental mode of structure [24].These values change as the displaced shape changes. An equivalent inelastic period of vibration (T_i) at various points along the capacity curve are calculated by use of the secant modulus (i.e., h

$$T_i = 2\pi \sqrt{S_{di}/S_{ai}g}).$$

Now the capacity spectrum curve can be plotted with the same coordinates as a response spectrum [26].

$$PF_1 = \frac{[\sum_{i=1}^{N}(wi\emptyset_{R1})/g]}{[\sum_{i=1}^{N}(wi\emptyset_{R1}^2)/g]} \text{eq. (3)}$$

$$\propto_1 = \frac{[\sum_{i=1}^{N}(wi\emptyset_{R1})/g]}{[\sum_{i=1}^{N}wi/g]\,[\sum_{i=1}^{N}(wi\emptyset_{R1}^2)/g]} \text{eq. (4)}$$

$Sa = (V/W)/\propto_1$eq. (5)

$Sd = \Delta_R/PF_1\emptyset_{R1}$eq. (6)

Where;

PF_1= modal participation factor for the first natural mode.

$\propto_1$= modal mass coefficient for the first natural mode.
wi/g=mass assigned to level i.
$\emptyset_{R1}$= amplitude of mode 1 at level i.
N= level N, the level which is the uppermost in the main portion of thestructure.
V= base shear.
W= building dead weight plus likely live loads.
Δ_R= Displacement at the top of the structure.

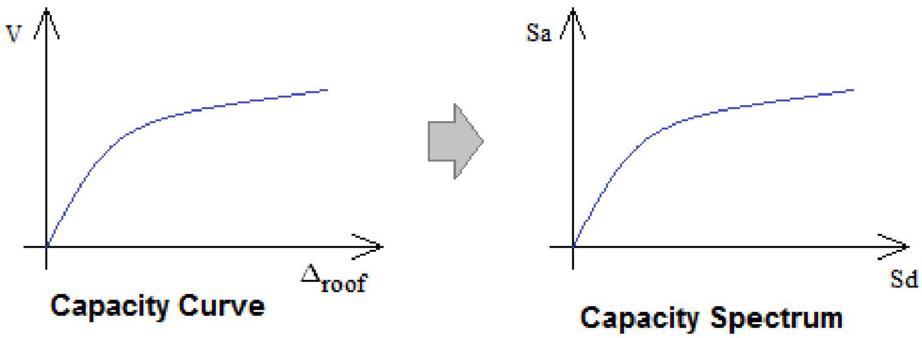

Figure (1)Conversion from the Capacity Curve to the Capacity Spectrum

3. Proposed Database

The database proposed for vulnerability assessment of Building Structures (VABS) is composed of two main components, namely earthquakes and buildings. As illustrated in the Entity Relation Diagram, ERD, shown in Figure 2, earthquakes are stored with their components which have acceleration records. One or more earthquakes can be combined to give design spectrum using any combination technique such as average, maximum, or average plus standard deviation. This combined response spectra represents the seismic demand used in the capacity spectrum analysis performed.

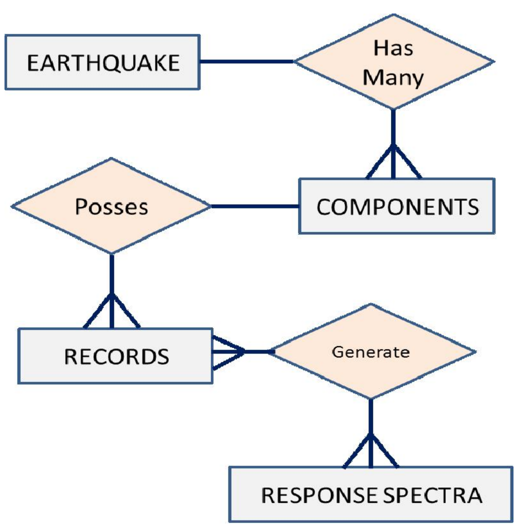

Figure (2) Main ERD of Earthquake Database

On the other hands, the building database includes building information which are used to generate the capacity spectrum of the building using separate commercial computer program and stored in the database. The ERD shown in Figure 3 shows the main entities of such database while intermediate entities are not shown. Such capacity spectra are used in combination with the demand spectra to give the performance point. The database contains as many as 300 earthquake components and capable of store huge number of earthquake components and records.

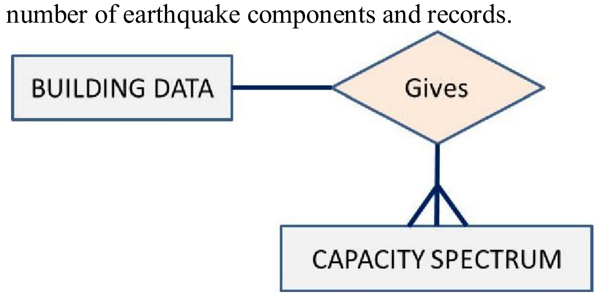

Figure (3) Main ERD of Building Database

4. Vulnerability Assessment Procedure

The capacity spectrum method is incorporated into a system customizing the database for seismic vulnerability assessment of buildings. The flow chart of the proposed system is shown in Figure 4 at which the user controls the process assisted by the database stored and external modules. One or more earthquake components can be selected from the huge database of earthquake records from them response spectra are generated. Building capacity curve is generated using external commercial structural analysis program.

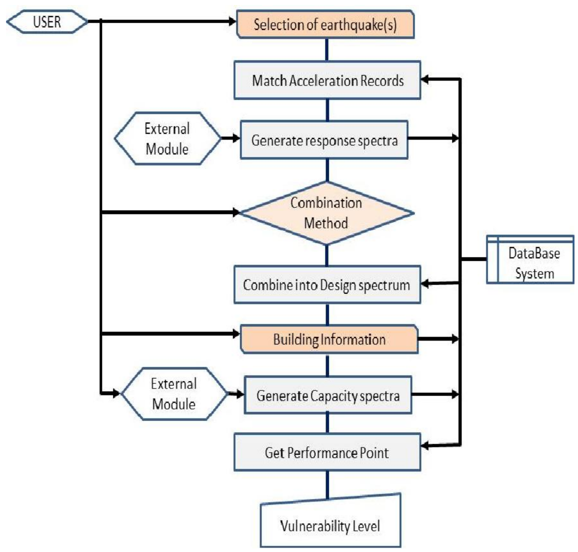

Figure (4) Process Flowchart of the Proposed Procedure

The vulnerability level assessed from the system is categorized as classified in the ATC 40 [24] to Immediate occupancy (IO), Life Safety (LS), and Collapse prevention (CP). Such levels are described in the ATC and FEMA manual and can be represented by the plot [27] shown in Figure 5.

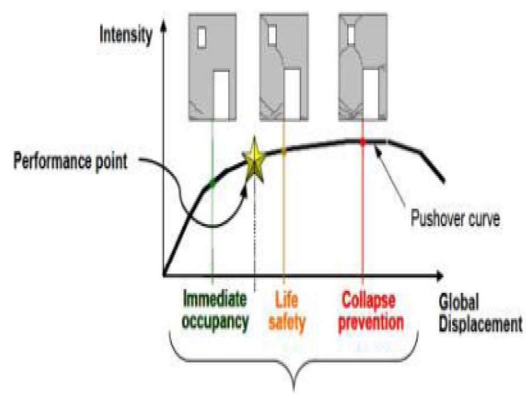

Fig (5): Performance levels described by pushover curve

5. Working Examples

To evaluate the proposed procedure customizing the developed database, five examples of existing residential reinforced concrete building structureswere selected. Table (1) shows a summary of the studied buildings. All structures which represent that commonly encountered in the construction industry were designed according to the Egyptian code and their analysis was performed using the ETABS commercial structural analysis software [30].

Table 1: Characteristics of Example Buildings

Building	Stories	Structural system	Total area
1	2	Flat slab & columns	250
2	3	Flat slab, columns& wall	500
3	3	Flat slab, columns	500
4	6	Flat slab & columns	500
5	7	Flat slab, columns& wall	600

All the above-mentioned buildings were analyzed and evaluated [29], while selected results will be discussed herein.

6. Description Of Earthquakes

The selection of ground motions plays one of the most important roles for use in seismic response analysis. About one hundred sixteen (116) earthquake or more acceleration records were incorporated in the database. Selected groups of these earthquakes normalized to the PGA of 0.2g which represents the common seismicity level in the rejoin are applied to the selected buildings. Table 2 shows sample of the most popular earthquake in the database while Figure 8.a shows the Frendaleearthquake acceleration record normalized to the PGA discussed and Figure 8.b shows the response spectrum of Frendaleearthquake plotting the spectral acceleration against time period. It is shown that the maximum spectral acceleration (0.7) when the time period at (0.45 sec). The values of spectral acceleration are stabilized when the time period reaches (2sec).

Table 2: Sample Information of Ground Motions

No.	Ground motion	Duration	Country	Year	PGA
1	El Centro	50 sec	San Diego	1940	0.35 g
2	EL Centro array	60 sec	BORREGO MOUNTAIN	1942	0.60 g
3	Nelson Ranch	30 sec	OROVILLE	1975	0.24 g
4	SANROCC	40 sec	Italy, Friuli	1976	0.28 g
5	Frendale	55 sec	Humbolt	1937	0.16 g
6	Summit AVE	40 sec	OROVILLE	1975	0.28 g

7	San Juanecapistran	60 sec	SAN FERNANDO	1971	0.28 g
8	Isabella Dam	50 sec	SAN FERNANDO	1975	0.35 g
9	Lahollywood	37 sec	Kren county	1952	0.36g
10	PACOIMA DAM	20 sec	SAN FERNANDO	1971	0.48 g
11	Hollister	15 sec	City Hall, USA	1974	0.12 g
12	Sanluis	20 sec	Parkfield	1966	0.63 g

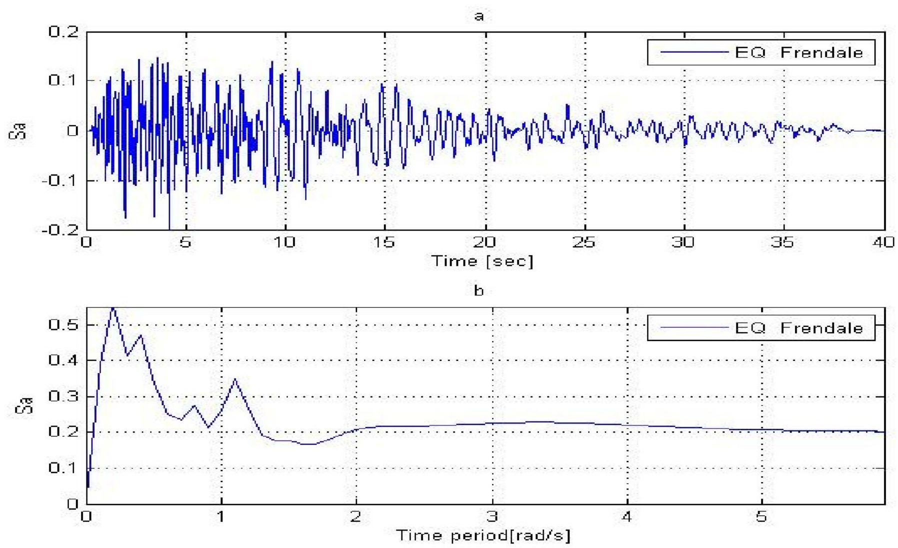

Figure (6) Frendale earthquake (a) Earthquake record (b) Response spectrum.

7. Results

To apply the Capacity Spectrum Method on the studied buildings, the capacity curve of these buildings are compared with the response spectrum of many earthquakes. The earthquakes are categorized into five groups.Combinations of buildings and earthquake groups (first and five) are discussed here.

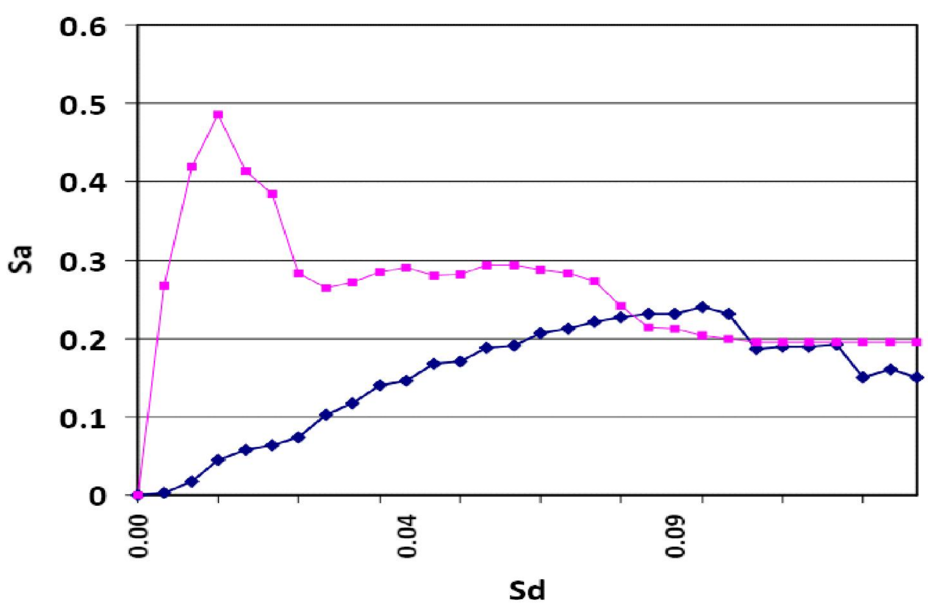

Figure (7) performance point for first buildingUnder Earthquakegroup (1)

Figure (7) showsis the Evaluation of building example number 1 subjected to the first group of earthquakes for which the spectrum curve is generated as maximum spectrum among one earthquake records.Intersection of capacity curve of building with demand curve of earthquake group is the performance point that indicates the vulnerability category of building. As shown, the performance point for this evaluation is at sd =0.0798, sa =0.225. From the location of performance point the building has been identified of the category (LS) which mean that this building will be Moderate damage (slight structural damage, moderate non-structural damage), cracks in columns and beams of frames when subject to these earthquakes.

Figure (8) shows in is the Evaluation of building example number 1 subjected to the five group of earthquakes for which the spectrum curve is generated as average spectrum among five earthquake records.Intersection of capacity curve of building with demand curve of earthquake group is the performance point that indicates the vulnerability category of building. As shown, the performance point for this evaluation is atsd =0.083, sa =0.235. From the location of performance point the building has been identified of the category (CP) which mean that this building will be Substantial to heavy damage (moderate structural damage, heavy non-structural damage), cracks in columns and beam column joints of frames at the base,Spalling of concrete cover, buckling of reinforced rods when subject of these earthquakes.

Figure (9) shows is the Evaluation of building example number 5 subjected to the first group of earthquakes for which the spectrum curve is generated as average spectrum among one earthquake records.Intersection of capacity curve of building with demand curve of earthquake groupis the performance point that indicates the vulnerability category of building. As shown, the performance point for this evaluation is at sd =0.018, sa =0.223. From the location of performance point the building has been identified of the category (IO) which mean that this building will be Negligible to slight damage (no structural damage, slight non-structural damage),fine cracks in plaster over frame members or in walls at the base, when subject of these earthquakes.

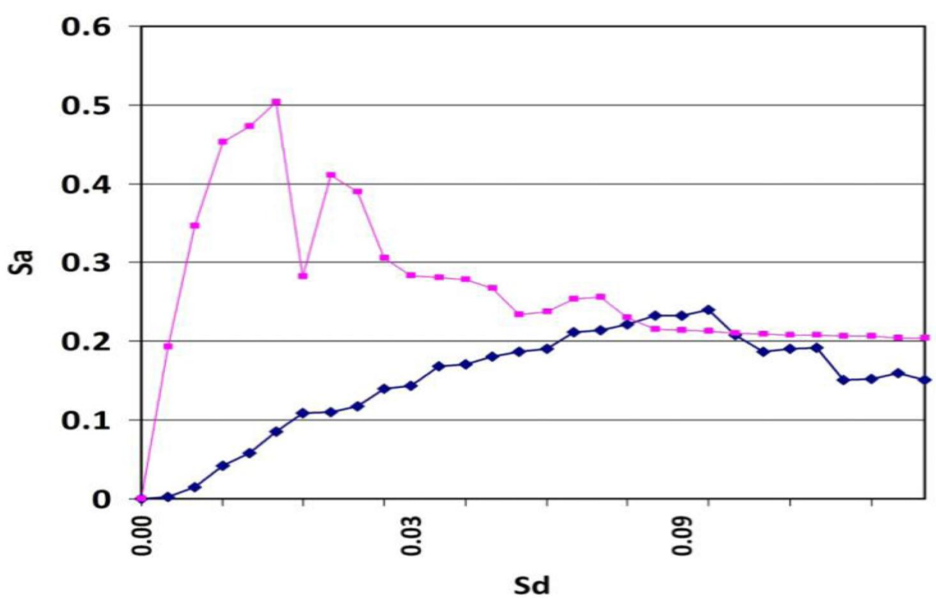

Figure (8) performance point for first building under Earthquakegroup (5)

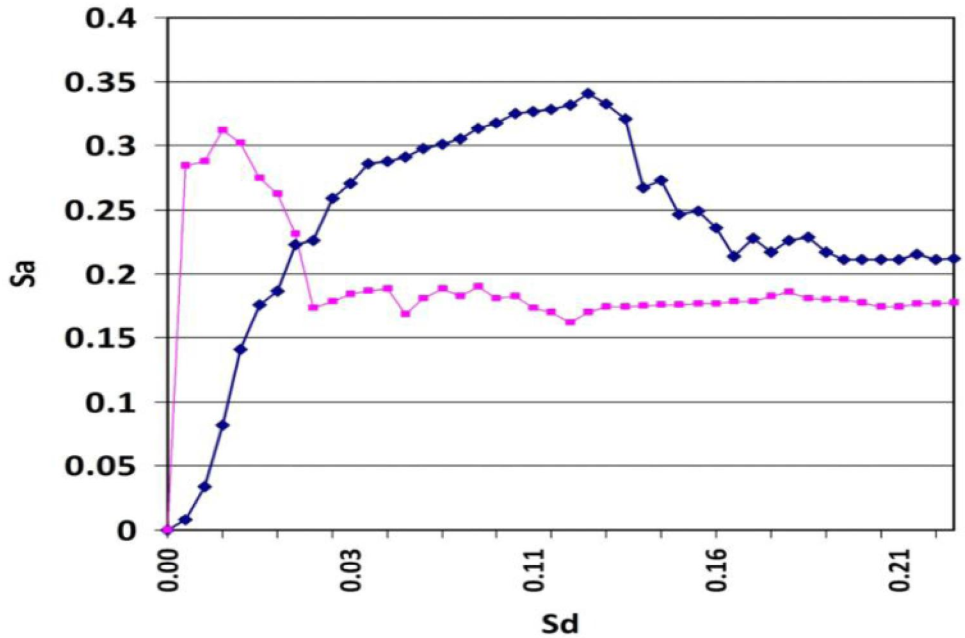

Figure (9) performance point for fifth building under Earthquakegroup (1)

8. Conclusion

The proposed procedure for seismic vulnerability assessment of buildings was applied to example buildings with practical structural systems and common configurations and dimensions. The method is based on nonlinear static analysis, customizes the capacity spectrum method and supported by the developed database of earthquakes and buildings. Investigating the results of the analysis and evaluation of the buildings, the following conclusions can be derived

- The proposed procedure is simple allowing the evaluation of a larger number of buildings without neglecting important features such as the nonlinear deformation capacity of the buildings. The existence of large number of earthquakes stored in the database allows the variety of demand requirements.
- It is based on mostly well-known engineering models and applied through common structural analysis software; and hence, it can be applied by practicing engineers without large pre-requirements.
- The proposed procedure enable deeper look on the capacity-demand relations leading to the capability of tuning of building slightly from any undesirable vulnerability category to better one. In a further step, it is also possible to consider certain upgrading strategies by an appropriate change in the capacity curve of the building.
- The results of the evaluation method can be therefore regarded with some confidence. The proposed method is rather more detailed than other analytical approaches developed for the evaluation of a whole building population. This is due to a lack of experience with earthquake damages requiring a more precise analysis which allows a better understanding of the behavior of the buildings under seismic action.
- The applications of the proposed procedure applied to practical examples illustrated the applicability of the method and how can the selected earthquakes and the building structural systems affect the vulnerability category of the building.

References

[1] **A. M. AElkady, 2011"**Variability and Uncertainty in Probabilistic Seismic Hazard analysis for the island of Montréal" a Thesis Presented to University Of McGill.

[2] **A. Karbassi, 2010 "**Performance –based seismic vulnerability evaluation of existing building in old sectors of Quebec" a Thesis Presented to University Of QUÉBEC.

[3] **S. Cozzi, S. Menoni and F. Pergalani, 2007** "Seismic vulnerability assessment: from physical to systemic and organizational aspects" Web page http://www.prometeo.polimi.it/SCOP/SCOPing/Articolo_Grecia_definitivo.

[4] **T. Srikanth, R. Pradeep and A. Pratap, 2010 "**Earthquake vulnerability assessment of existing

buildings in Gandhidham and Adipur Cities Kachchh, Gujarat (India)" European Journal of Scientifc Research, 41(3): 336-353.

[5] R. Giribone and B. Valette, 2004"Principles of failure probability assessment (PoF)" International Journal of Pressure Vessels and Piping 81, 797–806.

[6] I. Iervolinoa, G. Manfredi and M. Polese, 92007 "Seismic risk of R.C. building classes" Engineering Structures 29:813–820.

[7] A. Martinelli, G. Cifani and G. Cialone, 2008 "Building vulnerability assessment and damage scenarios in Celano (Italy) using a quick survey data-based methodology" Soil Dynamics and Earthquake Engineering 28,875– 889.

[8] A. Saeidi, O. Deck and T. Verdel, 2009 "Development of building vulnerability functions in subsidence regions from empirical methods" Engineering Structures 31,2275-2286.

[9] E. Dumova-Jovanoska, 2000 "Fragility curves for reinforced concrete structures in Skopje (Macedonia) region" Soil Dynamics and Earthquake Engineering 19,455-466.

[10] M.B.D. Hueste and Jong-WhaBai, 2007 "Seismic retrofit of a reinforced concrete flat-slab structure: Part II —seismic fragility analysis" Engineering Structures 29, 1178–1188.

[11] A.K. Eleftheriadou and A.I. Karabinis, 2008 "Damage probability matrices derived from earthquake statistical data" 14th World Conference on Earthquake Engineering, Beijing, China.

[12] H. Yalciner, S. Sensoy and O. Eren, 2012 "Time-dependent seismic performance assessment of a single-degree-of-freedom frame subject to corrosion" Engineering Failure Analysis 19,109–122.

[13] M. Dolcea, A. Kappos and A. Masi, 2006 "Vulnerability assessment and earthquake damage scenarios of the building stock of Potenza (Southern Italy) using Italian and Greek methodologies" Engineering Structures 28,357–371.

[14] R. Hasan, L. Xu and D.E. Grierson, 2002 "Push-over analysis for performance-based seismic design" Computers and Structures 80,2483–2493.

[15] Barbara Borzi, RuiPinho, Helen Crowley, 2008 "Simplified pushover-based vulnerability analysis for large-scale assessment of RC buildings" Engineering Structures 30, 804–820.

[16] H. Duan and M.B.D. Hueste, 2012 "Seismic performance of a reinforced concrete frame building in China" Engineering Structures 41,77–89.

5/25/2013

[17] A. Kadid and A. Boumrkik, 2008 "pushover analysis of reinforced concrete frame structures" Department of Civil Engineering, University of Batna, Algeria, Asian journal of civil engineering (building and housing) VOL. 9, NO. 1, pp 75-83.

[18] A. Benavent-Climent and R. Zahran, 2010 "An energy-based procedure for the assessment of seismic capacity of existing frames: Application to RC wide beam systems in Spain " Soil Dynamics and Earthquake Engineering 30, 354–367.

[19] G.M Verderame, M. Polese and C. Mariniello, 2010 "A simulated design procedure for the assessment of seismic capacity of existing reinforced concrete buildings" Advances in Engineering Software 41,323–335.

[20] Peter Fajfar, 1999 "Capacity spectrum method based on inelastic demand spectra" Earthquake engineering and structural dynamics. 28, 979-993.

[21] Kaspar Peter and Marc Badoux, 2000 "Application of the capacity spectrum method to R.C. building with bearing walls" Web page: http://www.iitk.ac.in/nicee/wcee/article/0609.

[22] A.H. Barbata, L.G. Pujadesb and N.Lantada, 2008 "Seismic damage evaluation in urban areas using the capacity spectrum method: Application to Barcelona" Soil Dynamics and Earthquake Engineering 28,851–865.

[23] Applied Technology Council "Seismic evaluation and retrofit of concrete buildings".ATC-40, Redwood City, California, 1996.

[24] Sigmund A. Freeman, 31 May-June 4, 1998 "Development and use of capacity spectrum method" 6th US NCEE Conference on Earthquake Engineering/EERI.

[25] César Fajardo and Carlos Zavala, June 2012 "Seismic Performance Model of an Important Building in Peru Evaluation of a Hospital Structure" the international symposium for cismid 25th anniversary, pp no. TS-2-3.

[26] M.Mouzzoun1, O. Mostachi and A. Taleb, Jan. Feb. 2013 "Seismic performance assessment of reinforced concrete buildings using pushover analysis" IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 5(1),pp. 44-49.

[27] Federal Emergency Management Agency (FEMA); NEHRP Guidelines for the Seismic Rehabilitation of Buildings, FEMA 273, 1997.

[28] Sajad Kareem Hasham, 2013 "Characterization of Seismic Risk of Structures through Robust database Framework" Zagazig University.

[29] ETABS manual, November 2005 "Integrated Building Design Software" Computers and Structures, Inc. Berkeley, California, USA.