International Journal of Engineering

Journal Homepage: www.ije.ir

Assessment of Structure-Specific Fragility Curves for Soft Storey Buildings Implementing IDA and SPO Approaches

F. Mohamed Nazri*[a], C. Kian Yern[a], M. Moffed Kassem[a], E. Noroozinejad Farsangi[b]

[a] *School of Civil Engineering, Universiti Sains Malaysia, Penang, Malaysia*

[b] *Department of Earthquake Engineering, Faculty of Civil and Surveying Engineering, Graduate University of Advanced Technology, Kerman, Iran*

PAPER INFO

Paper history:
Received 12 June 2018
Received in revised form 12 September 2018
Accepted 26 October 2018

Keywords:
Pushover Analysis
SPO2FRAG
Soft Storey Structure
Fragility Curve
Eurocode
Performance Level

ABSTRACT

Soft storey building is popular due to the functional and aesthetic purpose, despite its weakness in resisting seismic excitation. Nonlinear Static (Pushover) Analysis (POA) is a time saving and simple assessment procedure prosposed in Eurocode 8 (EC8). However, its reliability in designing structure still remains a question. At the first stage, seismic performance of several building models using POA in EC8 is assessed. Later on, empirical accuracy of fragility curves generated by POA (using SPO2FRAG software) is studied and verified through Incremental Dynamic Analysis (IDA) results. Four models of regular and soft storey frame of 5- and 11-storey varying heights were designed according to Eurocode 2 (EC2) and (EC8). The simulation is performed in a NL platform to carry out POA and IDA. Capacity curve obtained is served as main input in SPO2FRAG software to generate fragility curve. Then, IDA is performed to generate IDA and fragility curves. Peak ground acceleration, PGA was converted into corresponding Sa(T1) using design spectrum from EC8. Performance levels of Life Safety (LS) and Near Collapse (NC) proposed by Vision-2000 have been the main interest in this study. Results shown that the base shear calculated by using Lateral Force Method in EC8 is adequate. Fragility curve generated by SPO2FRAG, has good comformity with IDA-based fragility estimation for regular 5-storey model; however, some deviation is observed for soft storey model (5-storey). All 11-storey frames shown unsatisfactory match of fragility curves from what was generated by SPO2FRAG, compared to IDA results.

***doi**: 10.5829/ije.2018.31.12c.04*

NOMENCLATURE

F_b	Design base shear (kN)	**Greek Symbols**	
$F_{b,max}$	Maximum base shear (kN)	θ_{roof}	roof drift
$Sa(T_1)$	First mode spectral acceelration (m/s^2)	ξ	Viscous damping
SF	Safety factor	u	Logarithmic mean
PGA	Peak Ground Acceleration	σ	Logarithmic standard deviation

1. INTRODUCTION

1. 1. Soft Storey Structure

Soft storey building is prevailing across the globe, even in Malaysia. Example of vertically irregular building are hotel and shopping complex, where the ground (or more) storey is often constructed with height greater than the others, for the sake of aesthetic and functioning purpose. Consequently, there is an urgent need for earthquake engineers and experts to evaluate the capacity of building in resisting incurred damage (demand) arise from future seismic events and propose retrofitting schemes where required. The irregularity lead to building structures with irregular assignment of their mass, stiffness and strength along the height of building. In an earthquake resistant system, sudden change in strength or stiffness of the structure is undesirable. Low strength for the lateral load system elements such as weak stories is one of the main categories of seismic deficiencies [1]. Discontinuity in the rigidity of

*Corresponding Author's Email: *cefmn@usm.my (F. Mohamed Nazri)*

Please cite this article as: F. Mohamed Nazri, C. Kian Yern, M. Moffed Kassem, E. Noroozinejad Farsangi. Assessment of Structure-Specific Fragility Curves for Soft StoreyBuildings Implementing IDA and SPO Approaches. International Journal of Engineering (IJE), IJE TRANSACTIONS C: Aspects Vol. 31, No. 12, (December 2018) 2016-2021

structure, at soft story level, can be attributed to lack of infill walls or variation in floor height. It is the discontinuity that impose structural failure to multi-storey buildings when subjecting to earthquake load. Gautham and Gopi Krishna [2] in their study concluded that collapse probability is much higher for a soft storey building, which is an indication of the lack of lateral stiffness of the ground storey and results in soft storey failure mechanism.

The main objectives in this paper are to assess the adequacy of seismic resistance of regular and soft storey buildings designed by EC8 using POA and IDA, and also to develop the fragility curve through POA (using SPO2FRAG) and make comparison with IDA results.

1. 2. Performance based Seismic Engineering (PBSE) The core of PBSE is to precisely estimate seismic demand and capacity of structures [3]. It is a structural engineering paradigm that taken inherent uncertainty of ground motion, by employing probabilistic approach to evaluate structural performance in seismic prone areas [4]. The modern approach to earthquake resistant design is an attempt to design/retrofit buildings with predictable seismic performance through detreminsitic/probabilistic approach. To fulfill the objective of PBSE, logical elements has been advanced to discretize the performance assessment and design process. These elements include description, definition and quantification of earthquake intensity measures (IM), engineering demand parameters (EDP), damage measures (DM) and decision variables (DV).

Accordingly, performance objectives (or performance levels) such as Fully Operational (FO), Operational (O), Life Safety (LS) and Near Collapse (NC) are used to define the damage state of the building based on the following %drift values; <0.2, <0.5, <1.5, <2.5 and 2.5%>, respectively. Guidlines, such as Vision-2000 [5], ATC-40 [6], and FEMA-273 [7], provide performance level with corresponding drift.

1. 3. Fragility Assessment from POA In the past, the nonlinear dynamic analysis (NDA) has been used by researchers in assessing seismic fragility of buildings. Fragility assessment associated with nonlinear capacity of building to seismic response, for the sake of economic design. Nevertheless, advancement of Performance Based Seismic Engineering (PBSE) is making establishment of fragility assessment from POA possible, without seeking recourse to NDA.

In the last decade, POA-based approach such as Capacity Spectrum Method (CSM) have been used to generate fragility curves. CSM involved only the capacity curve and response spectra in the acceleration displacement response spectra (ADRS) format, which can generate fragility curves by determining the performance point, where the demand meets capacity. CSM has been improved further. Recently, SPO2FRAG software [4] has been introduced. It allows the generation of fragility curve with its special features on the basis of capacity curve as the only input.

2. MODELLING AND NONLINEAR ANALYSES

2. 1. Reinforced Concrete Moment Resisting Frame (RC-MRF) A total of 4 MRCFs, comprised of 5- and 11-storeys models for both regular and soft storey cases, have been designed according to EC2[8], and EC8[9] by identifying the combination of Permanenet load *kg* of 5.45kN/m^2 and Variable load $_k$q of 4.0 kN/m^2. Regular MRCF had identical storey height of 3.3m, while soft storey frame had 4m height at their ground level and uniform height of 3.3m for the rest of the storey which concrete compressive strength equals to 30MPa of the frame elements. Each frame had 3 bays with consistent width of 6m. They have been named as 5R, 5S, 11R and 11S models. Number 5 and 11 represented number of storey, while –R and –S represented regular and soft storey frame. Details of structural components are shown in Table 1.

2. 2. Lateral Force Method of Analysis By referring to EC8. It should be noted that design spectrum for Peninsular Malaysia is adopted. The associated values are a_{gR} = 0.08g, S = 1, T_B = 0.05s, T_C = 0.2s, T_D = 2.2s, T = 4s and q = 1.5 for regular buildings and $0.8q$ = 1.2, for soft storey cases.

2. 3. Plastic Hinges Nonlinear Modelling The structural elements (beams and columns) are modeled with concentrated plastic hinges at the column and beam faces, where the beams have only moment (M3) hinges, and the columns have an axial load and a biaxial moment (PMM) hinges. These types of hinges are considred as material inelasticity.

TABLE 1. Dimension and reinforcement design for beams and columns of MRCF used in this study

Model		5R & 5S	11R & 11S
Beam	Size	300 × 700 mm	300 × 700 mm
	Main rebar	4T16 (top) & 4T25 (bottom)	4T16 (top) &4T25 (bottom)
	Shear link	T10 – 150 c/c	T10 – 150 c/c
Column	Size	500 × 500 mm	600 × 600 mm
	Main rebar	12T20	12T20
	Shear link	T10 – 150 c/c	T10 – 150 c/c

2. 4. Structural Periods (T) This section indicates the natural periods of the frame structures according to the first three mode shapes, as illustrated in Table 2.

2. 5. Development of Fragility curves According to the previous studies [4, 10-12], the conditional probability of a structure, P to reach or exceed a specific damage state, *D*, given the first mode spectral acceelration, $Sa(T_1)$, expressed in Equation (1). Drift limits for LS and NC levels are the main focus in this study.

$$P\left[D / Sa(T_1)\right] = \Phi\left[\frac{\ln\left[Sa(T_1)\right] - \mu}{\sigma}\right] \quad (1)$$

2. 6. Nonlinear Static (Pushover) Analysis (POA) Safety factor, *SF* of POA in EC8 is determined from the ratio of maximum base shear, $F_{b,max}$ and design base shear, F_b, as shown in Equation (2). $F_{b,max}$ represents the actual capacity of building (from analysis) while F_b indicates the design capacity from EC8.

$$\text{Safety Factor, } SF = \frac{\text{maximum base shear, } F_{b,\max}}{\text{design base shear, } F_b \text{ (EC8)}} \quad (2)$$

Capacity curve is then used as core input in SPO2FRAG software. After idealization of capacity curve, input of floor masses and height, defining engineering demand parameter, *EDP* (roof drift, θ_{roof}) with associated limit states and include additional variability, fragility curves demonstrating probability of exceeding performance level as a function of $Sa(T_1)$ are estimated. Viscous damping, has been assumed as ξ=5% in this study.

2. 7. Incremental Dynamic Analysis (IDA) IDA [13] has been performed by using three different ground motions that has been scaled from low IM, which is Peak Ground Acceleration *(PGA)*, to obtain θ_{roof} until it exceeds damage state threshold defined in Vision-2000. ξ=5% has been adopted in IDA. *PGA* has been converted to equivalent building response, $Sa(T_1)$, using the design spectrum with associated values as mentioned in Section 2.2 of this study [14]. Finally, IDA curve showing $Sa(T_1)$ - θ_{roof} relationship were plotted.

TABLE 2. Structural Periods of the MRCF in Regular and Soft storey models

MRC Frames	Mode 1	Mode 2	Mode 3
5R	1.61	0.79	0.29
5S	1.74	0.82	0.32
11R	5.54	1.73	0.88
11S	5.75	1.77	0.92

Details of three ground motions chosen from Pacific Earthquake Engineering Research Center (PEER) are summarized in Table 3.

2. 8. Inter- and Cross-comparison among POA and IDA Finally, fragility curves generated from both SPO2FRAG and IDA outcomes were compared, on their median capacity at LS and NC performance levels, respectively using Equation (3). The trend of fragility curves were compared empirically.

$$\text{Percentage difference (\%)} = \frac{Sa(T_1)_{POA} - Sa(T_1)_{IDA}}{Sa(T_1)_{IDA}} \quad (3)$$

3. RESULTS AND DISCUSSIONS

3. 1. Capacity Curve from POA Capacity curves for 5 and 11 storey models are shown in Figures 1 and 2, respectively. $F_{b,\ max}$ and corresponding θ_{roof} with safety factor are summarized in Table 4. Design SF using EC8 are calculated using Equation (2).

Comparison on drift is first discussed. For 5-storey frames, 5R and 5S models successfully pushed beyond both LS and NC performance levels, at drift of 1.5 and 2.5% each. However, both 11-storey frames failed to reach 2.5% drift.

TABLE 3. Ground motion records used in this study

NGA	RSN	Event Name	Year	Mag-nitude	*PGA* (g)
NGA-West 2	60	San Fernando	1971	6.61	0.421
NGA-East	2753	MtCarmel_2008-04-18a	2008	4.64	0.104
NGA-West 2	4061	Parkfield-02, CA	2004	6.00	0.522

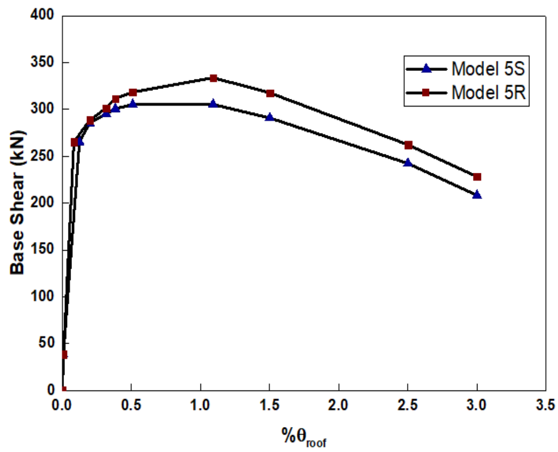

Figure 1. Capacity curves of Model 5R and 5S

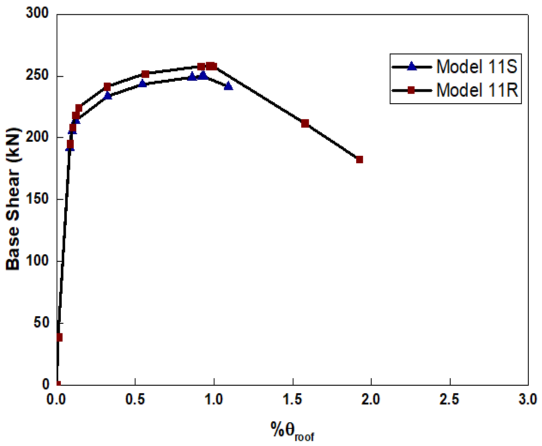

Figure 2. Capacity curves of Model 11R and 11S

TABLE 4. Maximum Base Shear, $F_{b,\ max}$ and corresponding roof drift, θ_{roof}, and Safety Factor, SF

Model	Height (m)	$F_{b,\ max}$(kN)	F_b (kN)	θ_{roof} (%)	Safety Factor
5R	16.5	321.364	145.83	1.31	2.20
5S	17.2	301.590	176.69	1.07	1.71
11R	36.3	258.422	180.59	0.97	1.43
11S	37.0	249.716	222.53	0.92	1.12

It is revealed 11R model exceeded 1.5% and failed at 1.92% drift, while 11S model failed at 1.09% before reaching 1.5% drift.

In the path of force transmission, the flexible first storey may create a critical situation during an earthquake. The stiffness discontinuity between the first and the second storey might cause significant structural damage, or even the total collapse of the building. This can be attributed to the onset formation of NC plastic hinges, which signified collapse of frame, hinder the capacity curve to further extend, according to analysis results of SAP2000.

Then, maximum base shear is discussed. For 5-storey frames, 5R model has maximum base shear, $F_{b,\ max}$ of 321.364 kN at the drift of 1.31% while 5S model is 301.59 kN at 1.07%. For 11-storey cases, model 11R and 11S attained $F_{b,\ max}$ 258.422 kN and 249.716 kN and drift of 0.97 and 0.92%, respectively. Result shows that shortest frame has highest base shear resistance. This is due to higher post-yield stiffness of low-rise structure, compared to medium-rise structure [15]. Both soft storey frames also exhibited weaker base shear resistance (or capacity) and smaller corresponding drift, compared to regular frame.

From the calculation and according to EC 8 design Base Shear, F_b for 5R and 5S models are 145.83 kN and 176.69 kN, with safety factor, *SF* of 2.20 and 1.71 each. F_b for 11R and 11S models are 180.59 kN and 222.53 kN, with *SF* of 1.43 and 1.12, respectively. Results show that soft storey frames have higher F_b than regular frame, due to presence of softness in the soft storey. Overall, EC 8 gives safe design to all frames, as maximum base shear resistance, $F_{b,max}$ exceeded the design base shear, F_b. However, special attention should be given to 11-storey with soft storey case. Going any higher (>37.0m) or adding more storey (or mass) can result in under-design situation, at the onset the maximum base shear from analysis smaller than design base shear, on the basis of POA.

In term of ductility, the ductility capacity ratio, shows the enhancement for each of Regular- over the Soft- frame structures as shown in Table 5. Based on the ductility capacity ratios, the regular structures shows much better results, wherease the difference between the (R) and (S) frames detremined as 37% in the 5-storeys frames, and 15% in the 11-storeys frames.

3. 2. Comparison of Fragility Curves produced by POA and IDA

Nonlinear Analysis of both POA (using SPO2FRAG) and IDA have generated fragility curves. Median capacity at LS and NC level are selected for comparison in this section. Corresponding percentage difference are calculated using Equation (3) and the median capacity are tabulated in Table 6. Comparison on general trend of fragility curve for LS state is presented in Figures 3 and 4, respectively. Positive percentage difference indicates overestimation on median capacity of POA over IDA, while a negative one symbolizes underestimation.

POA overestimates median capacity of regular frame, which are 5R and 5S models, in both LS and NC limit states.

TABLE 5. Ductility capacity ratio (DCR)

Model	Yielding (%Drift), ΔY	Ultimate (%Drift), ΔU	ΔU/ΔY	DCR Difference (%)
5R	0.1	1.31	13.1	37%
5S	0.13	1.07	8.23	
11R	0.17	0.97	5.71	15%
11S	0.19	0.92	4.84	

TABLE 6. Comparison on median capacity of fragility curves between POA (using SPO2FRAG) and IDA

	Median capacity, $Sa(T_1)$ at LS level			Median capacity, $Sa(T_1)$ at NC level		
Model	POA	IDA	%	POA	IDA	%
5R	1.17	1.05	+11.4	1.85	1.75	+5.7
5S	1.12	1.15	-2.6	1.80	1.91	-5.8
11R	0.90	0.31	+190.3	1.20	0.52	+130.8
11S	0.59	0.36	+63.8	-	0.61	-

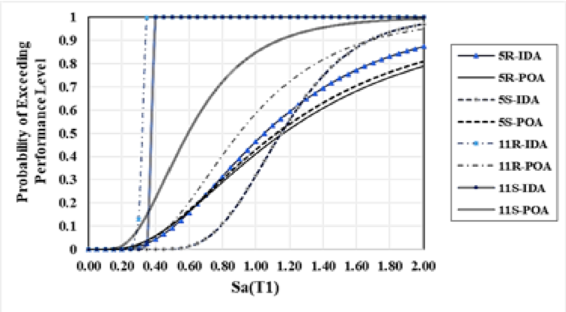

Figure 3. Fragility curves of all Modelsfor LS performance state

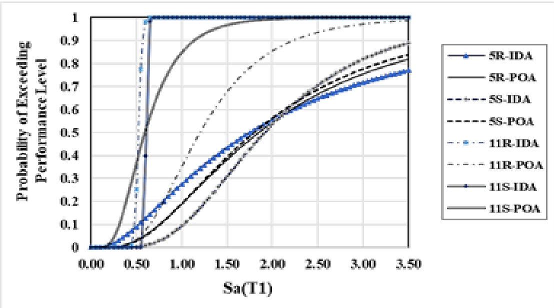

Figure 4. Fragilitycurvesof all Models for NCperformance state

The overestimation is ranging from 5.7 to 190.3%. 11R model of LS state shows the greatest overestimation.On the other hand, median capacity of model is underestimated by POA, from 2.6 to 5.8%. However, POA overestimates median capacity of 11S model, at NS state by 63.8%. The results of 11S model arenot appropriate to make comparison, due to the early failure before reaching 2.5% roof drift in Pushover Analysis, due to formation of NC plastic hinges. In general, fragility curves plotted by SPO2FRAG and IDA for 5R model shown closest match at both LS and NC states. The trend of fragility curve is also close for 5S model, with an under estimation at lower range of $Sa(T_1)$ and an over estimation in higher range of $Sa(T_1)$ for both states. Fragility curves for 11-storey frame, which are 11R and 11S models, generated by SPO2FRAG in general shows great deviation from that of IDA. In short, SPO2FRAG is unsuitable for 11-storey building.

4. CONCLUSION

Based on the results obtained, the purpose from this study is to shed the light on the response behaviour of the regular and soft storey structures under the seismic loading using nonlinear analysis. From the POA, base shear from capacity curve is compared. Regular frame has higher maximum base shear, $F_{b,max}$ compared to soft storey frame. The maximum base shear, $F_{b,max}$ is always higher than design base shear, F_b from EC8 for all models in this study, which means the actual capacity is greater than design capacity, which can be concluded that the base shear resistance designed by using Lateral Force Method in EC8 is adequate.Comparison on the trend of fragility curve produced from POA (SPO2FRAG) and IDA was made. Noticeably, for 5-storey frame, regular structure shown closest match, while soft storey structure shows deviation with some under- and over-estimation on lower- and higher-range of $Sa(T_1)$ respectively, in both LS and NC states. 11-storey structure shown poor fit for both regular and soft storey case in both LS and NC levels.

4. ACKNOWLEDGMENT

This study is financially supported by Universiti Sains Malaysia, under the Bridging Grant Scheme (6316092).

5. REFERENCES

1. El-Betar, S. A., "Seismic performance of existing RC framed buildings," ***HBRC Journal***, Vol. 13, (2017), 171-180.
2. Gautham, A. & Gopi Krishna, K., "Fragility Analysis–A Tool to Assess Seismic Performance of Structural Systems," *Materials Today:* ***Proceedings***, Vol. 4, (2017), 10565-10569 .
3. Vamvatsikos, D. and Cornell, C.A, "Direct Estimation of Seismic Demand and Capacity of Multidegree-of-Freedom Systems through Incremental Dynamic Analysis of Single Degree of Freedom Approximation1," ***Journal of Structural Engineering***, Vol. 131, (2005) 589-599.
4. Baltzopoulos, G., Baraschino, R., Iervolino, I. and Vamvatsikos, D, "SPO2FRAG: software for seismic fragility assessment based on static pushover,"***Bulletin of Earthquake Engineering***, Vol. 15, (2017) , 4399-4425.
5. Vision-2000, *Conceptual Framework for Performance Based Seismic Engineering of Buildings*: Structural Engineers Association of California (SEAOC), (1995).
6. ATC-40, "Seismic Evaluation and Retrofit of Concrete Buildings," *Applied Technology Council*, *report ATC-40. Redwood City*, (1996).
7. FEMA-273, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings*: FEMA, (1997).
8. B. S. Institution, *Eurocode 2: Design of concrete structures: Part 1-1: General rules and rules for buildings*: British Standards Institution, (2004).
9. P. Code, "Eurocode 8: Design of structures for earthquake resistance-part 1: general rules, seismic actions and rules for buildings," *Brussels: European Committee for Standardization*, (2005).
10. Ibrahim, Y.E. and El-Shami, M.M., "Seismic fragility curves for mid-rise reinforced concrete frames in Kingdom of Saudi Arabia," ***The IES Journal Part A: Civil & Structural Engineering***, Vol. 4, pp. 213-223, (2011).
11. Menasria, Y., Nouaouriaa, M. and Brahimi, M., "Probabilistic Approach to the Seismic Vulnerability of RC Frame Structures by the Development of Analytical Fragility Curves," ***International Journal of Engineering-Transactions A: Basics***, Vol. 30, (2017), 945-954.

12. Tariverdilou, S., A. Farjadi, and M. Barkhourrdari, "Fragility curves for reinforced concrete frames with lap-spliced columns,"***International Journal of Engineering-Transactions A:Basics ,*** Vol. 22 No. 3 (2009), 213-224.
13. Vamvatsikos, D. and Cornell, C.A, "Incremental dynamic analysis," ***Earthquake Engineering & Structural Dynamics***, Vol. 31, (2002), 491-514.
14. Yazdani, A., S. Razmyan, and H. Baharmast Hossainabadi, "Approximate incremental dynamic analysis using reduction of ground motion records," ***International Journal of Engineering-Transactions B: Applications***, Vol. 28, (2014), 190-197
15. Nazri, Fadzli Mohamed, and Nicholas A. Alexander. "Predicting collapse loads for buildings subjected to seismic shock", ***Bulletin of Earthquake Engineering***, Vol. 13, No. 7 (2015): 2073-2093.

Assessment of Structure-Specific Fragility Curves for Soft Storey Buildings Implementing IDA and SPO Approaches

F. Mohamed Nazri[a], C. Kian Yern[a], M. Moffed Kassem[a], E. Noroozinejad Farsangi[b]

[a] *School of Civil Engineering, Universiti Sains Malaysia, Penang, Malaysia*

[b] *Department of Earthquake Engineering, Faculty of Civil and Surveying Engineering, Graduate University of Advanced Technology, Kerman, Iran*

P A P E R I N F O

Paper history:
Received 12 June 2018
Received in revised form 12 September 2018
Accepted 26 October 2018

Keywords:
Pushover Analysis
SPO2FRAG
Soft Storey Structure
Fragility Curve
Eurocode
Performance Level

چکیده

ساختمان با طبقه نرم به علت اهمیت کاربردی و زیبایی شناخته شده است، به رغم ضعف آن در مقاومت در برابر تحریک لرزه‌ای. تجزیه و تحلیل غیرخطی استاتیکی (Pushover (POA صرفه‌جویی در وقت و روش ارزیابی ساده در Eurocode 8 (EC8) است. با این حال، قابلیت اطمینان طراحی این نوع سازه همچنان یک سوال باقی است. در مرحله اول، عملکرد لرزه‌ای چند مدل ساختمان با استفاده از POA در EC8 ارزیابی می‌شود. بعلاوه، دقت تجربی منحنی‌های شکنندگی تولید شده توسط POA (با استفاده از نرم‌افزار SPO2FRAG) از طریق تجزیه و تحلیل دینامیکی بارفزاینده (IDA) مورد بررسی قرار گرفت. چهار مدل از قاب منظم با طبقه نرم و ارتفاع ۵ و ۱۱ طبقه با توجه به Eurocode 2 (EC2) و (EC8) طراحی شده است. شبیه‌سازی در یک محیط غیرخطی برای انجام POA و IDA انجام می‌شود. منحنی ظرفیت به دست آمده به عنوان ورودی اصلی در نرم افزار SPO2FRAG برای ایجاد منحنی شکنندگی بکار گرفته شده است. سپس تحلیل دینامیکی بارفزاینده برای تولید منحنی‌های IDA و شکنندگی استفاده شده است. بیشینه شتاب زمین، PGA به (Sa (T1 مربوطه با استفاده از طیف طراحی EC8 تبدیل شده است. سطوح عملکرد ایمنی جانی (LS) و آستانه فروریزش (NC) پیشنهاد شده توسط Vision-2000 مورد توجه این مطالعه بوده است. نتایج نشان داد که برش پایه محاسبه شده با استفاده از روش نیروی جانبی در EC8 کافی است. منحنی شکنندگی تولید شده توسط SPO2FRAG، دارای سازگاری خوب با برآورد شکنندگی مبتنی بر IDA برای مدل معمول ۵ طبقه است. با این حال، تا حدودی اختلاف در سازه با طبقه نرم (۵ طبقه) مشاهده شده است. نتایج تمامی قاب‌های ۱۱ طبقه نشان‌دهنده‌ی عدم مطلوبیت منحنی‌های شکنندگی تولیدی با SPO2FRAG در مقایسه با نتایج واقعی تحلیل IDA است.

doi*: 10.5829/ije.2018.31.12c.04*