Reliability Engineering and Resilience 1-1 (2019) 42-54

Contents lists available at **RER**

Reliability Engineering and Resilience

Journal homepage: www.rengrj.com

Developing a Lateral Load Pattern for Pushover Analysis of EBF System

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https://doi.org/10.22115/RER.2019.184387.1009

ARTICLE INFO

Article history:
Received: 05 May 2019
Revised: 09 June 2019
Accepted: 09 June 2019

Keywords:
Eccentric bracing,
Nonlinear dynamic analysis;
Incremental analysis;
Absorbed energy;
Load pattern.

ABSTRACT

Finding an appropriate system to absorb the intended energy of the earthquake is of great importance in seismic region. The eccentric bracing frame (EBF) is one of the structural systems that reveal proper behavior during earthquakes phenomenon. In doing so, design codes attempt to optimize EBF seismic behave to avoid failure of the earthquake regarding a set of the criteria. Indeed, the dynamic nonlinear approaches are the most powerful methods which solve the motion equations based on the time history of the ground motion. However, the dynamic nonlinear methods require a rigorous effort to nail the structural responses. Therefore, there is a need to develop a simplified approach such a pushover method which is based on the non-linear static analysis. The main attempt of this research is to present a simplified push overload pattern for EBF system to sufficiently divulge the structural performance subjected to the seismic loadings. In this investigation, three models of the middle rise and tall rise, 10, 20, 30 stories of buildings are considered, which are designed according to the available codes. Accordingly, several different load patterns are developed. The idea behind of each proposed load patterns inspired by the deflection of a rod subjected to the flame. Herein, the meaning of the flame refers to the region of the structures which is subjected to the plastic hinges.

How to cite this article: Dorri F, Ghasemi SH, Nowak AS. Developing a lateral load pattern for pushover analysis of EBF system. Reliab. Eng. Resil. 2019;1(1):42–54. https://doi.org/10.22115/RER.2019.184387.1009.

1. Introduction

Earthquake on average leads to about 10,000 deaths yearly (Figure 1) [1]. Due to the seismicity of Iran, the importance of seismology is evident, as earthquakes cause many casualties and damages year to year. The first investigation in seismology was carried out by Irish engineer Robert Malt in the south of Italy following the 1857's earthquake. Earthquake engineering might be estimated to be developed in the twentieth century. In the first 60 years of the twentieth century, when accelerograph systems were invented and installed, between 60's and 70's decade, researchers tried to develop a logical relation between old and new results. They suggested R factor. This factor makes a link between old knowledge based on engineering perception and new knowledge on the basis of the nonlinear ability of structures. At the beginning of 80 decades, American earthquake code presented a new concept of earthquake load. In the 70 decades, Structural Engineer Association of California (SEAOC) constituted Applied Technology Council (ATC) to modify last code and preparation a new code minute. Consequently, new concepts like elastic earthquake force and behavior factor were considered for the first time [2]. ATC criteria were considered by other countries very soon.

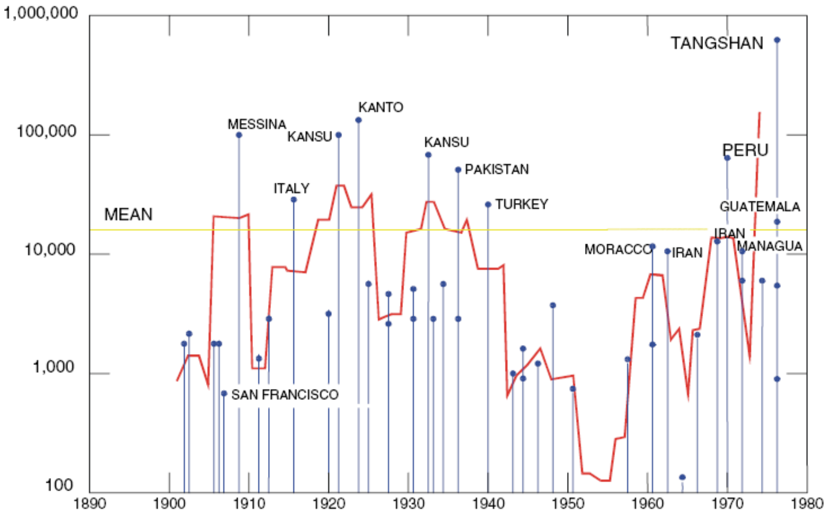

Fig. 1. casualtiesof intensive earthquake after 1890 [1].

In order to increase the structural withstand-ability, several types of lateral resistance frames have been developed. Indeed, because of the proper energy dissipation of the earthquake violation, the eccentrically braced steel frames (EBFs) have been pleasantly utilizing for steel structures. Popov and Engelhardt (1988) conducted a study to evaluate EBFs seismic performance [3]. Accordingly, this kind of moment frame system has been widely used and many studies have been led to investigate the decency-behavior of EBFs (Koboevic (2000) [4]). For instance, Chao and Goel (2005) probed the seismic performance of eccentrically braced frames using target drift and yield mechanism with regard to the performance-based design [5]. However, the nonlinearity performance of EBFs subjected to the seismic loadings with different structural configuration (number of the stories) is still opened to discussion. Defects-deficiency of the linear static method caused that engineers attempt to find a logical method instead of traditional methods.

Consequently, in the 90 decades, a new evaluation-revolution and design method based on performance were presented for structures. This approach caused various structural design and evaluation studies based on deflections and use of nonlinear analysis to reach more accurate structure behavior evaluation-assessment under varied levels of the earthquake. In this method, ductility and nonlinear deformation control are considered instead of preference to force control. All of these methods were presented as ATC-40, FEMA273, FEMA356 and FEMA440 guidelines [6–9]. Nowadays nonlinear static analysis which is called pushover has been developed as a powerful tool in seismic design based on the structural performance. It might provide useful nonlinear behavior information of structures, plastic hinges locations, and the process of distribution of forces that is not possible by static analysis method.

In general, conditions to perform pushover analysis methods, specifications of materials are directly entered in modeling. Then the structural model is imposed by incremental lateral load pattern until it reaches objective displacement and amount of internal deformations and forces are measured. During the process, the sequence of fractures, plastic hinges forming and structural member damages can be depicted easily. This process should be continued until structural displacement reaches the objective point or the structure collapses. In this method, the objective displacement is determined to be equal to the maximum displacement of the structure during the probable earthquake. It is worth mentioning that based on the concept of the random vibration and critical excitation the probable earthquake can be derived [10,11]. In fact, in order to evaluate the structural performance level using pushover analysis, the capacity spectrum of the structure can be compared with the demand spectrum of the structure.

The procedure of pushover analysis has been explained in [12–14] and other references. It should be noted that besides all available methods to define the performance levels, the probabilistic approaches can be considered as the state of the art to estimate the required performance level of the system using the reliability analysis [15–19].

Although the pushover procedure has been precisely explained FEMA-273 [7] and its descendant FEMA-356 [8], numerous debates have been investigated to investigate the hypotheses and limitations of pushover analysis. Krawinkler and Seneviratna (1998) presented a detailed document to stipulate the advantages and drawbacks of a pushover analysis [20]. One of the major debates has been always relating to the load pattern of the pushover analysis. Several researchers have been attempted to figure out the adaptive force using different approaches. After a discussion on the limitations of the pushover analysis by Gupta and Kunnath (2000), they proposed an adaptive modal pushover analysis to account for to rationally express the response of the system [21]. Yun et al. (2002) evaluated the seismic performance of steel moment frames they provided a solution for multiple-objective optimization problems for using an evolutionary genetic algorithm to minimize the structural construction costs [22]. Bosco et al. [23] proposed modifications to the design provisions of Eurocode for buildings with split K eccentric braces. In addition, Bosco et al. [24] investigated the influence of modeling of steel link beams on the seismic response of EBFs. Montuori et al. [25] conducted a study to evaluate the seismic performances of MRF-EBF dual systems with regard to the influence of the bracing scheme. Mastrandrea et al. [26] investigated the failure mode of EB-using pushover and IDA analyses.

Ordinary pushover analysis has the capability of estimating the total seismic response for buildings with low and middle height accurately. However, they are not absolutely exact in estimating the seismic response of high, irregular buildings and in some cases provides misleading results. In recent years, many studies have been conducted to modify and develop pushover methods.

This investigation is an attempt to find the best load pattern for pushover analysis for EBF systems. The idea behind the load patterns stems from the distribution of the hinges in the height of the structures. Therefore, the main focus of this research is dedicated to EBF system for various tall-rise buildings, concerning the structural capacity, story drifts, and plastic hinges. The correctness of the proposed load patterns for the EBF systems are validated using the nonlinear dynamic analysis.

2. Case study

2.1. Studied models and reason of choosing them

The models are 3 buildings with EBF system includes 10-, 20- and 30-stories. The reasons for choosing the models are as follows:

- To study the effect of the height of building on seismic behavior of the structure, models with the different stories number is selected
- The models are selected with different heights to study the effect of load pattern on building on the different stories.
- The plan and elevation of models are shown in Figure 2.
- The buildings have 3 bays in each direction. All the beams and braces attach to the corresponding element with hinge connection and do not resist bending moment.

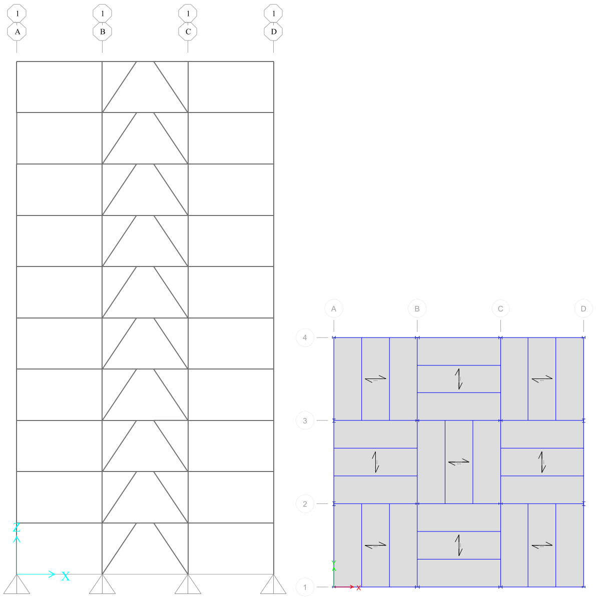

Fig. 2. The plan and elevation of 10-story building

2.2. Geometric characteristics of models

For modeling of SAP-2000-14.2.4 is used [27] and all structures are 2D. The structural system is EBF the panel width are 5 meters and height of all stories are 3 meters. In building with joists, composite or two-way slab ceilings, due to the high rate in plate rigidity in special conditions the floors can be assumed rigid diaphragm. In this case, there is no displacement between two ends of beams; which can be concluded as a no presence of axial force. Therefore, all nodes which are in the same height form a rigid diagram and are restrained together. Therefore, in SAP 2000 software, the end offset tab is activated for all members and conservatively a factor equal 0.5 assigned to them which are applied for IPE all sections such as columns, and braces box sections are used.

2.3. The specifications of steel

The used steel in this research is made of ST-37 and its mechanical properties are tabulated in Table (1).

Table 1
The mechanical properties of steel in the analysis and design

Weight (kg/m3)	E Elasticity module (kg/cm2)	Poisson's ratio	Fy Yielding tension (Kg/cm2)	Fu Ultimate tension (kg/cm2)
7850	2039000	0.3	2400	3700

2.4. Calculation of gravity loads

Due to two-dimensional frame models and one-way load distribution in the joist, it is assumed that the load is imposed on the studied frame. The sixth section of the national code [28] is used to loading and the models are considered as residential buildings. According to the sixth section of national code, live load for residential buildings is 200 kg/m^2. Live load for the roof was considered similar to the stories and the dead load is also considered 500 kg/m^2.

2.5. Calculation of earthquake lateral load

To calculate earthquake lateral load the seismic design guideline, 2800 standard code [12] is considered. For further investigation distribution of mode shape 1, static lateral load, and spectrum acceleration which is the combination of at least 3 modes for 10 stories building are shown in Figure 3.

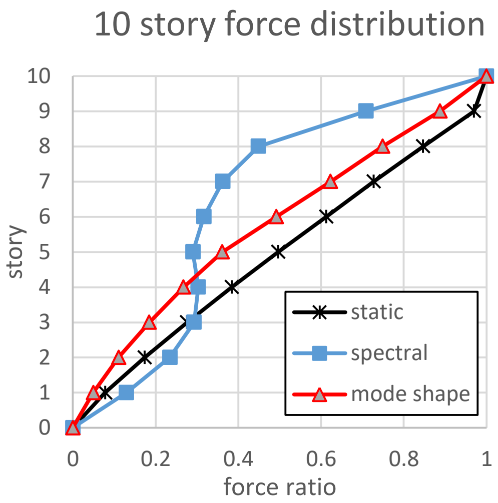

Fig. 3. Force distribution of static, spectral and mode shape 1.

2.6. Design of buildings

Design of buildings have been done according to the tenth section of the national code [13]. Link beams design to yield at shear force prior to other elements. The design is based on the LRFD procedure and final sections are listed in Table 2.

Table 2
Structural sections.

Buildings	10-story			Stories	20-story			Stories	30-story		
Stories	beam	brace	column		beam	brace	column		beam	brace	column
1	PG4	Box16	Box32	1-2	PG5	Box18	Box50	1	PG5	Box18	Box70
2-3			Box28	3-5			Box45	2-6			Box60
4-5			Box24	6-7	PG4	Box16	Box40	7-10			Box50
6-8	PG3	Box12	Box20	8-9			Box36	11-13			Box45
9-10	PG2	Box10		10-11			Box32	14-16			Box40
				12-13			Box28	17-19			Box36
				14-15			Box24	20-22	PG4	Box16	Box32
				16-18	PG3	Box12	Box20	23-25			Box28
				19-20	PG2	Box10		26-28	PG3	Box14	Box24
								29-30	PG2	Box12	Box20

In Table 2. columns and braces with the name of Box are HSS sections. The dimension of BoxAA means its width and heights are equal; also its thickness is one-tenth of its width. Moreover, link beams with the name of PG are wide flange a section that their height and width of the flange are varies from 200 mm to 300 mm.

2.7. Ground motions selection

The earth acceleration is determined based on accelerographs condition. Every two accelerographs are simultaneously imposed in orthogonal main directions of the structure and the structural responses are then determined as a function of time. The final response of structure at each moment is the maximum response of analysis for three couples of accelerographs. In this method, it is possible to use seven couples of accelerographs instead of three couple and the final response could be the average of results. In time history analysis the structural behavior could be assumed as linear or nonlinear. In this paper, seven couples of accelerographs are considered. The final response is an average of seven couples of accelerographs. Table (3) represents the considered earthquakes' records Figure (4) shows the schematic of average pseudo acceleration based on the considered earthquakes.

Table 3
Specifications of used accelerograph.

row	accelerograph	year	Soil type	PGA(g)
1	Chi Chi	(1999)	B	0.413g
2	Loma Prietta	(1984)	B	0.233g
3	Superstition Hills	(1987)	B	0.455g
4	Manjil	(1990)	B	0.505g
5	Morgan Hill	(1984)	B	0.423g
6	Kern county	(1954)	B	0.178g
7	Duzce	(1999)	B	0.134g

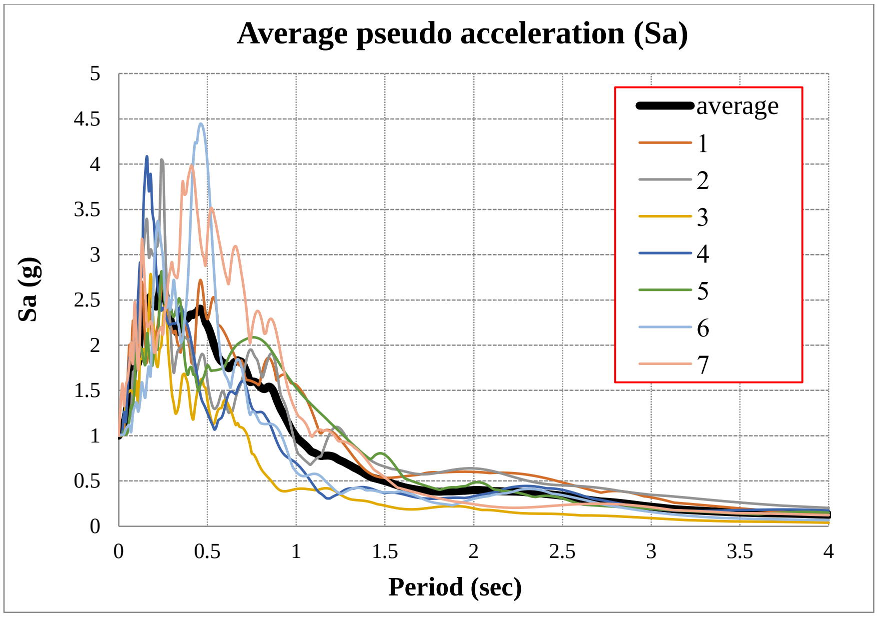

Fig. 4. Acceleration records spectrum of the considered earthquake with 5% damping.

3. Suggested load patterns for pushover analysis

As it mentioned earlier, the selection of the load pattern for tall-rise buildings is still questionable. Generally, three suggested load patterns are proposed in Figure (5). It should be noted that although the amount of load is not vital, the pattern and form of the load is indispensable. Therefore, in triangular pattern No.2, the amount of height is not important. In the trapezoidal pattern, the length of the longer base is considered twice more than another base.

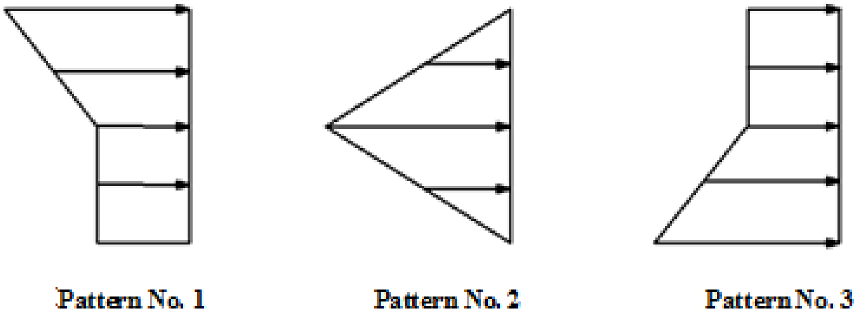

Fig. 5. Suggested load patterns.

The idea behind each load patterns has constructed the base on the possible structural deformations which are inspired by deflection of a rod subjected to the flame. The meaning of the flame refers to the region of the structures which is the most possible to occur the plastic hinges. The load Patten No. 1 reminds the loading scenarios which the flames (the possible crucial region of plastic hinges) are started from the middle to the end of the rod. The load Patten No. 2 indicates the loading scenarios which the flames (plastic hinges) are just focused at the middle of the rod. The load Patten No. 3 denotes the flames (plastic hinges) are started from the outset of the rod to its middle.

4. Incremental dynamic analysis

To perform an incremental dynamic analysis (IDA), each accelerograph is induced to the structures with 0.1g scale factor and continued with 0.1g incremental steps. The loading protocol continues until the scale factor of 2g applied to the structures. In each step, the maximum base shear is recorded versus the maximum displacement of the roof. Accordingly, ID Analyzed structure capacity diagram is achieved. The obtained curves of capacity using IDA with consideration of the different earthquakes are shown in Figure (6). The curves show the following outcomes:

- Although the stiffness decreases by increasing the height, the strength level of the system increases.
- Due to the elastic structure, the diagrams are linear in low slope PGA.
- In these PGAs because of forming plastic hinges in all of the elements, the secondary capacity curves drops toward zero.

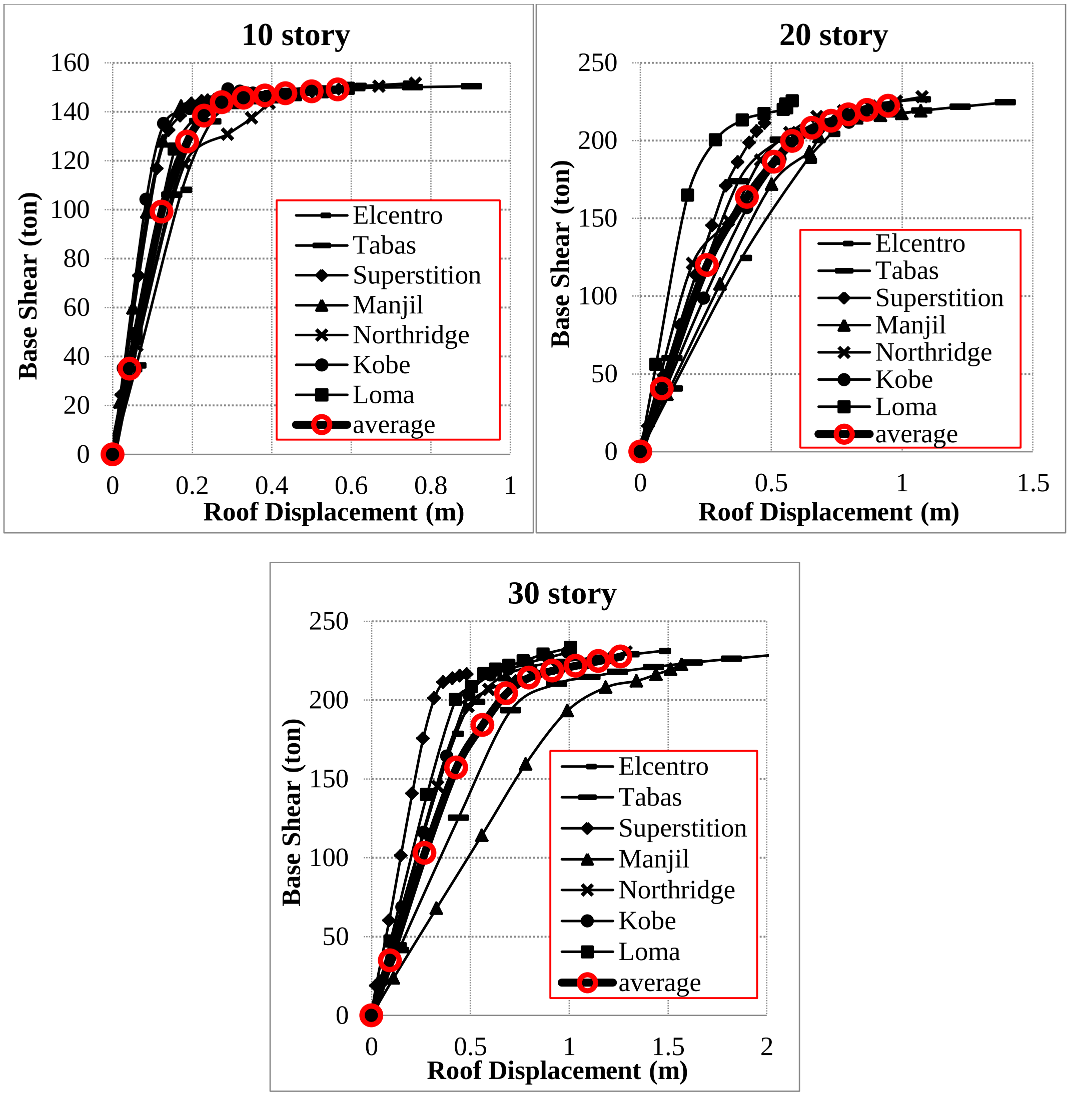

Fig. 6. Capacity curve using IDA based on the different earthquakes.

5. Capacity curve of structure comparison

In Figure (6) the capacity of analyzed models with pushover load patterns and IDA are compared. The comparison of the model capacity based on the different analysis including load pattern No. 3, pushover load pattern and IDA is shown in Figure 7. Accordingly, the following statement can be derived using the mentioned comparison.

- Structure capacity obtained based on the IDA is far higher than what was obtained using the existing pushover analyses.
- The proposed load pattern (No. 3) is the best load pattern to estimate the dynamic capacity of the structures.
- For tall-rise building the difference between IDA analysis and existing pushover analyses is far more considerable.

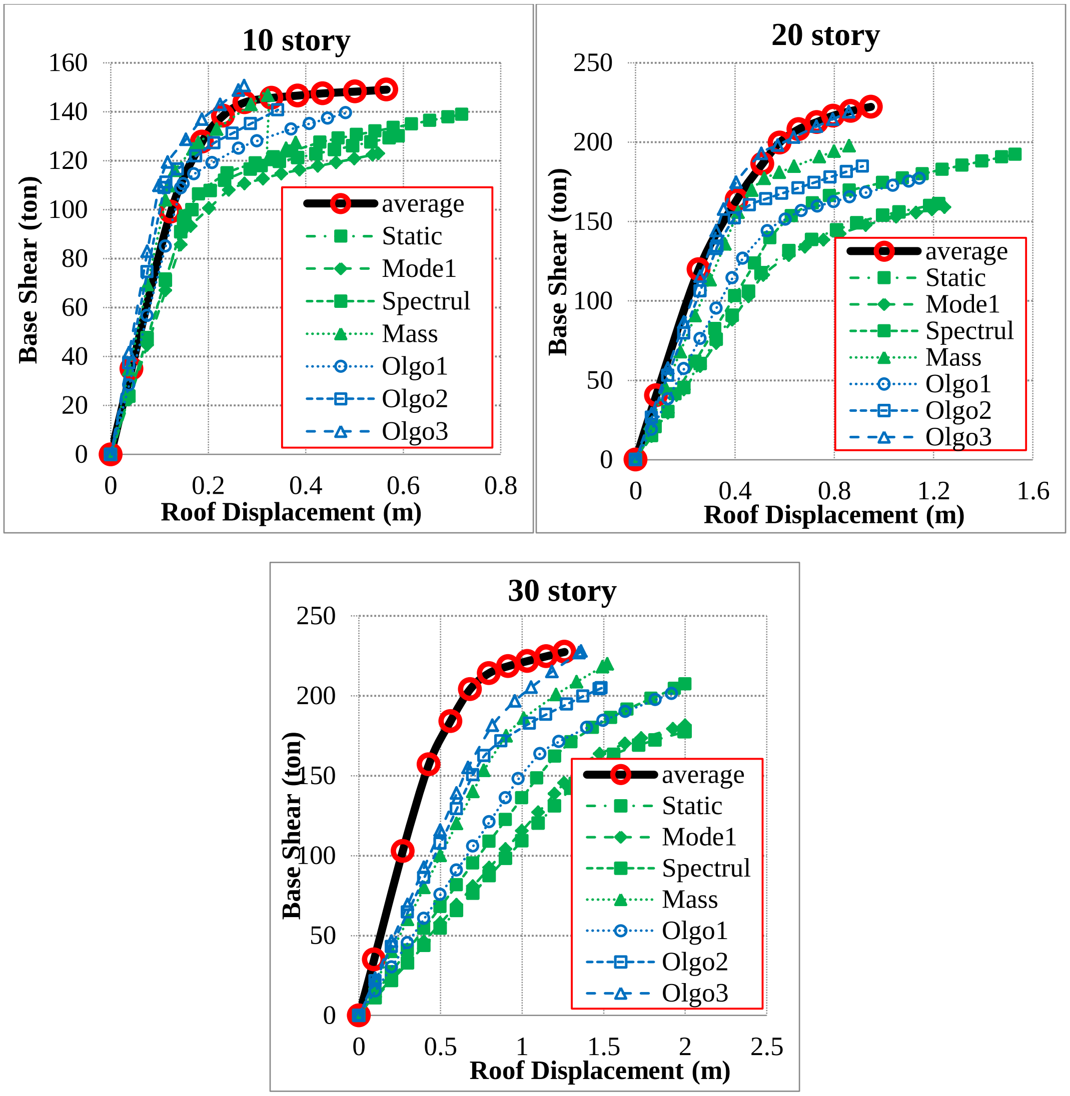

Fig. 7. Base Shear capacity from pushover of different patterns.

6. Drift story comparison

In Figure (8) the pushover analysis drift based on the different load patterns, the average of scaled dynamic analysis drift, the story drift of spectral load pattern and the average of IDA drift are compared. Based on the observation the following comment can be provided.

- The maximum discrepancies of the investigated methods refers to the of the upper stories drift.
- The best load pattern to estimate the structural drift behavior is the spectral method.
- For tall-rise buildings, the spectral pattern is more similar to the dynamic pattern and reach acceptable to an estimation.

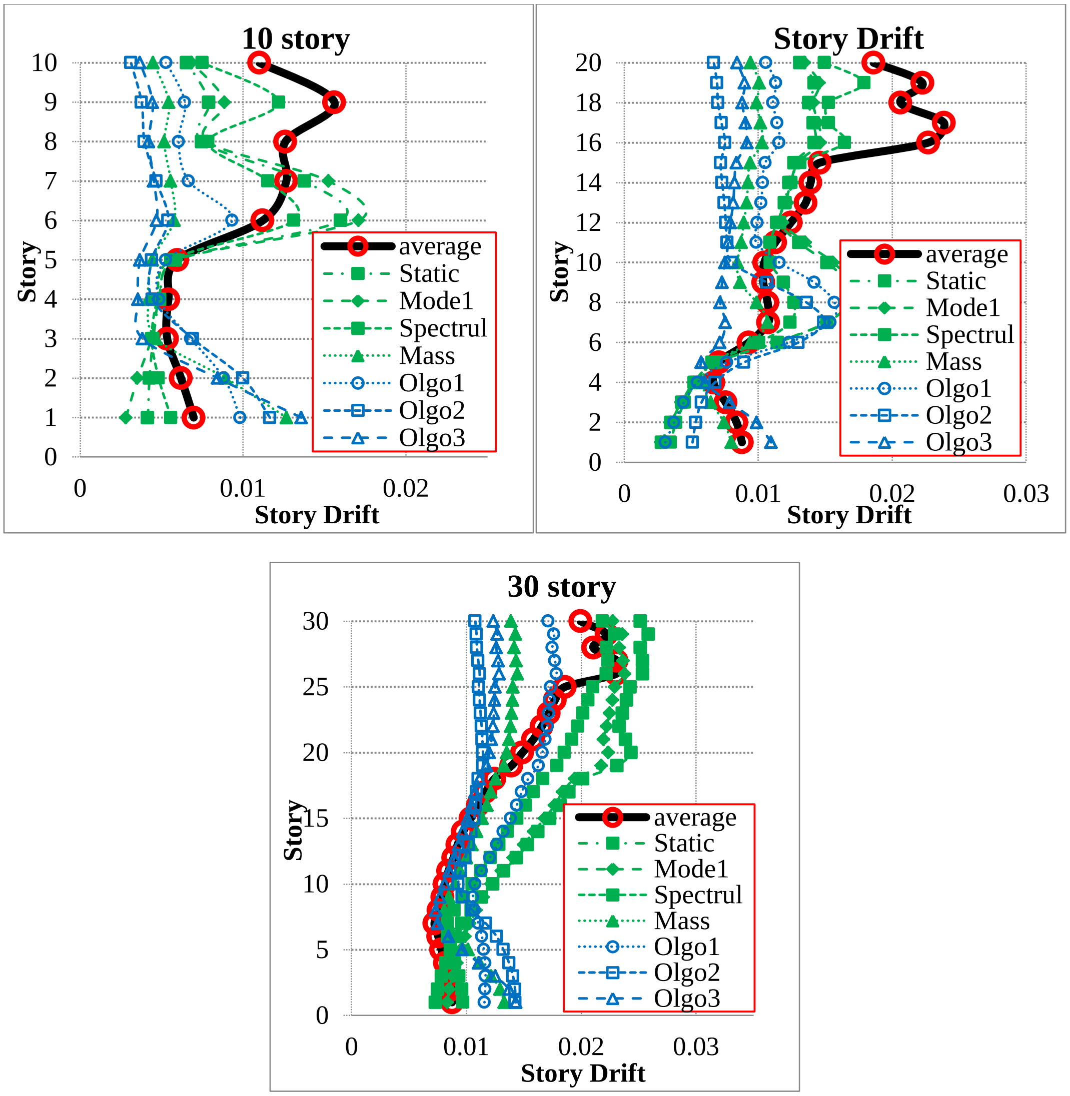

Fig. 8. Load patterns story drift and scaled dynamic analysis displacement average comparison.

7. Conclusions

In this research, the best pushover lateral load pattern for tall-rise buildings using EBF lateral stiffness system was investigated. The existing load pattern and several new loading patterns were deliberated to propose the best load pattern for low-, mid-, and tall-rise buildings. The inspection of the proposed load patterns is ignited from the possibility of the hinges distribution all over the structures' height. Several models with different stories were created and the optimum design criteria of the shear link were applied. Then the behavior of the structures in pushover analysis scaled nonlinear dynamic analysis and incremental dynamic analysis were studied. Accordingly, it was observed that although using the spectral load pattern can provide the proper estimation for the structural drift behavior, the structural based shear capacity cannot be appropriately estimated using the mentioned load pattern or any considered existing load patterns. However, the proposed load pattern No 3. can provide an accurate estimation concerning the shear capacity of the structures. As a general conclusion, it could be stated that for tall-rise building if drift and performance level are taken into consideration, the spectral load pattern is appropriate and if the share capacity of the structure is taken into consideration, load pattern No. 3 leads to the proper results.

Acknowledgement

This research is based in part upon work supported by the Iranian Science Foundation under Grant No. 96000065.

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