Evaluating the Accuracy of Lateral Load Patterns in Pushover Analysis

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Abstract: Pushover analysis is important because of its feasibility and operation speed such that it can estimate seismic behavior of structures with more significant acceptable accuracy in comparison with non-linear complicated dynamic analyses. It has been tried in this study that having investigated various methods of pushover analysis and that of lateral load, their advantages and limitations are separately identified. Lateral load patterns are including inverted triangular, uniform, first mode and story stiffness patterns. Studied structures are 5, 7 and 9-story steel moment-resisting frames. Pushover analysis has been conducted with regard to above load patterns on the frames and the results have been compared with non-linear dynamic analysis results. Finally, the accuracy of lateral load patterns has been evaluated from comparisons. SAP2000 software has been used for non-linear analyses.
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1. Introduction

In recent years, several studies have been published for the accuracy of various patterns of lateral load in pushover analysis. Among these studies, it can be indicated to Kallkan and Kunath (2004) studies [1]. The main debate in these paper is devoted to applications, limitations, advantages of these methods as well as their comparison with that of linear and non-linear methods. Pushover methods in these papers are classified into two, conventional and advanced classes. Conventional methods of pushover analysis are performed using uniform and triangular loading patterns. These patterns are gradually increased during the analysis and continued up to achieve non-linear stage in the structure. Fajfar (2000) from University of Ljubljana, Slovenia, was one of the researchers who have conducted studies on pushover analysis methods using N2 method [2]. Because of limitations of conventional pushover analysis method, advanced ones have been developed. However, conventional pushover methods are still popular among the engineers. Recently, many endeavors have been made towards resolving the shortcomings and problems with the pushover method. With an overview on these activities, their results can be divided and provided into two templates:

1. Adaptive pushover analysis methods and
2. Modal pushover analysis methods

Gupta and Kunnath (2000) presented an adaptive load pattern that considered the effect of higher modes on pushover analysis. In this pattern, applied load pattern is continuously changed based on dynamic temporal system characteristics, the forces are independently applied in each mode and loading stage, analysis is undertaken and at the end of each stage, the responses from each mode are combined [3]. Papanikolaou and Elanshai (2005) studied different methods of adaptive and conventional pushover analysis by Zenus-NL software in Mid-America Earthquake (MAE) Center. Their results are as follows:

Adaptive pushover analysis is no longer free of limitations, the most important of which is how to combine different modal effects. Different applicable combinational modal methods are including the square root sum of the squares (SRSS) and the complete quadratic combination (CQC) methods in which negative values are eliminated because of quadratic terms to obtain ever positive responses. It is clear that during an earthquake, modal vector components of structure are no longer ever positive but different values of displacements with different signs are created all over the structure height. When the responses of 3D structures are studied, the effects of torsional modes are generally eliminated and their shares are ignored in resultant force because the signs of modal displacements are removed in CQC and SRSS methods [4].

Chopra and Goel (2001) presented modal pushover analysis (MPA) method based on multi-mode pushover (MMP) static analysis and using the concepts of elastic spectral analysis. In this method, it assumed that modal responses remain still independent in the inelastic state. Therefore, structural seismic response in each mode is achieved independent of pushing the structure by constant load distribution pattern resulted from inertial forces of the mode until the target displacement is obtained [5].

Chopra and Goel (2003) investigated modal pushover method. In this study, they compared the results from modal and FEMA356 pushover methods with the results from non-linear dynamic analysis. It is observed that modal pushover method provides and overestimates a relatively acceptable estimate of general response parameters such as displacements and drifts of the stories than proposed FEMA356 pushover analysis methods with constant loading. Above proposed methods underestimate story drifts cause to unacceptable responses with high errors. By the way, modal pushover method has have no good accuracy to calculate local response quantities including plastic rotations, although this is one of characteristic problems with all pushover methods and is not specific to modal pushover method. However, this method is appropriate in which the relations between ductility and damping are completely provided. Because of these, it has been taken significant considerations by the researchers [6].

This study is aimed to investigate different patterns of lateral load in the pushover analysis and compare the accuracy and applicability of this method to estimate structural response. For this, having applied lateral load patterns to the studied structures, each of them was analyzed by pushover method such that lateral load patterns were applied increasingly step by step to the structure. This was continued until the roof displacement was reached the target displacement. Therefore, the structure enters the non-linear stage and its performance can be evaluated from structure behavior. Structural performance evaluation during the earthquake is one of the most important purposes of earthquake engineering ad this is undertaken using pushover analysis with acceptable accuracy. Recently, extensive studies has been conducted on the accuracy evaluation of pushover method, results of which are pushover analysis methods with different lateral load patterns but most of the studies are devoted to regular structures at specific heights and less is dealt with irregular ones. Therefore, this study deals more with the accuracy of lateral load patterns in pushover analysis concerning to irregular-in-height structures. For this, the studied structures are at firs designed irregular in height and then are analyzed by pushover method. In the next step, irregular conditions in the structure height are created by changing the mass and stiffness of the structure stories and then the structure is reanalyzed by the pushover method. Having compared the results of these two stages with the results of non-linear dynamic analysis, the accuracies of different lateral load patterns can be investigated for irregular buildings.

2. Methodology

At first, the studied structures are designed by ETABS 2000 software. Then, the modeling structures are exported to SAP 2000 software in which modal and nonlinear static analyses of the frames are conducted. Capabilities of this software for pushover analysis are more than other nonlinear software. ANSYS software was used to undertake non-linear dynamic analyses because of the ability of time history nonlinear dynamic analyses. In this case, geometrical nonlinearity is implemented in the form of large deformations-small strains and material nonlinearity is defined in the form of strain-stress diagram with 5% strain hardening by Von-Mises criterion. In order to obtain initial pushover diagram, the structure is analyzed under pushover. Pushover analysis at this stage is conducted using load control and inverted triangular lateral load pattern. With initial pushover diagram, elastic structural stiffness (K_i) and idealized slope of structure diagram (K_e) are obtained. These two parameters are used to determine the target displacement by coefficients method. Having determined the target displacement, the structure is again analyzed by pushover method. The analysis is undertaken by displacement control and continues up to achieve the displacement of the highest point of the structure. At this stage, lateral load patterns include inverted triangular load, uniform load, first mode, and story stiffness patterns. Afterwards, pushover diagram and displacement response values concerning to pushover analysis was obtained for each of lateral load patterns. Displacement responses from pushover analysis are including:

1. Structure deformation profile;
2. Lateral displacement between the stories; and
3. Average rotations of plastic hinges in the story beams and columns, separately.

In all nonlinear analyses, damping and strain hardening are 5% and story diaphragms are considered solid. This is accompanied by fixing horizontal displacements of story nodes with regard to a node on the story. P-Δ effect and large deformations are considered in all analyses. Pushover analysis principles and different stages to obtain capacity diagram are illustrated in Figure 1.

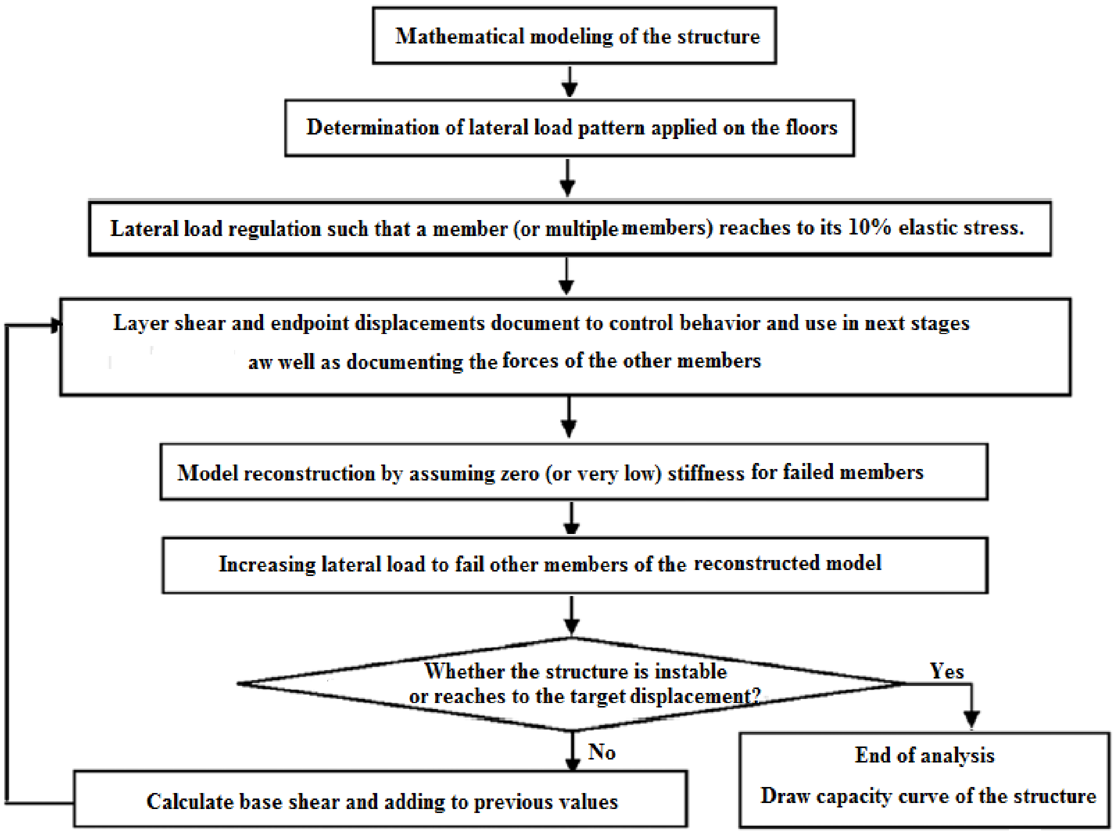


Figure 1: Flowchart of different stages of pushover analysis

3. Study structures

The structures in this study were 5-, 7- and 9-story steel frame buildings. Their lateral resisting system was of moment-resisting frame type. In order to consider irregularity effect in the structure height, the mass and stiffness of the stories are differently selected. This is in order to investigate the effect of stiffness and mass changes on the structure height. By the way, irregularity effect on the structure height is evaluated in different lateral load patterns and the results from pushover analysis are investigated and studied. Each of frames is separately analyzed within three stages. At the first stage, the frame is considered regular in height. At the second stage, changing the stiffness and mass of different frame stories, irregularity effects are studied on the structure height such that the stiffness of structure stories are changed in a way that irregularity conditions are provided at the structure height and then the frame is analyzed. At the final stage, changing story masses, irregularity conditions are provided on the structure height and after that, nonlinear static and dynamic analyses are conducted on the structure. Therefore, the effects of stiffness and mass irregularity on the structure height can be investigated. Comparing nonlinear static and dynamic analysis results, the accuracy of lateral load patterns are evaluated in pushover analysis. 5-story frame characteristics have been shown in Figures 2 and 3.

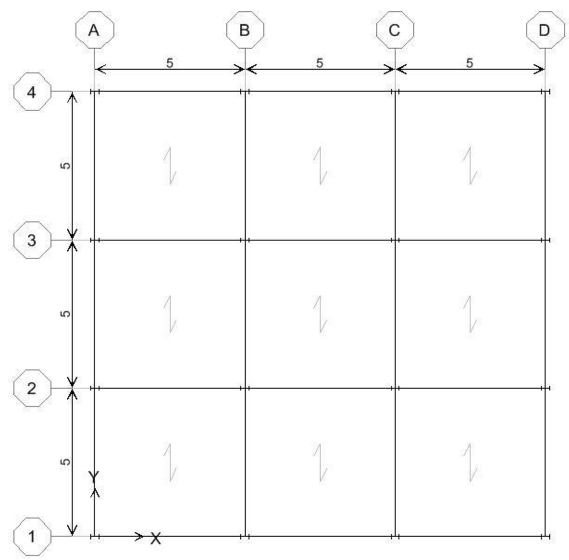
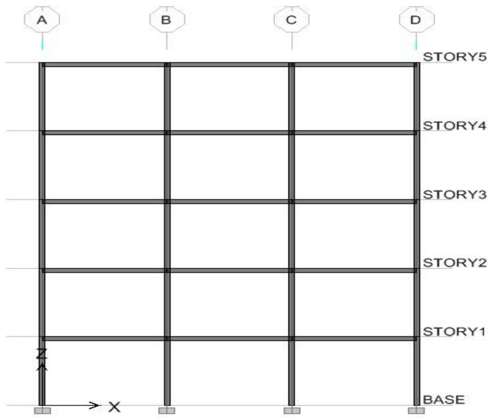


Figure 2: Study building plan



Stories	Beam section	Column section
5	IPE300	BOX25x6
4	IPE330	BOX25x8
3	IPE330	BOX30x8
2	IPE360	BOX30x10
1	IPE360	BOX30x10

Figure 3: 5-story moment-resisting frame

4. Lateral load patterns

Instructions used in loading the study structures were sixth issue of National Building Regulations and guidelines for seismic rehabilitation. Assumptions for seismic loading are as follows:

- Design base acceleration with the assumption of constructing the buildings in an area with relatively high risks is a = 35/0.
- The buildings are residential with average importance coefficient (1l).
- Considering that structural system is steel moment-resisting frame, structure behavior coefficient equals to 7R.
- Building site is of II type based on which other seismic features are described as follows:

T_0=0.1
T_S=0.5
S=1.5

Regarding the assumptions, building seismic coefficients along x direction for 5-, 7- and 9-story frames are calculated C_x= 0.0816, 0.0925 and 0.1095, respectively. Dead (D) and live (L) loads of the stories are 627kg/m^2 and 200 kg/m^2, and for 7- and 9-story frames 600 kg/m^2 and 200 kg/m^2, respectively.

5. Inverted triangular load pattern

This load pattern is proportional to lateral load distribution in linear static method. The relation used to calculate load pattern is based on sixth issue of National Building Regulations (Eq. (1)):

$$F_i = (V - F_t)\frac{W_i h_i}{\sum_{j=1}^{n} W_i h_i} \qquad (1)$$

where:
F_i: Lateral load at story i level;
V: Shear force at base level;
T: Min time period of oscillation;
W_i: Story i weight including ceiling weight, a portion of overload, half of total weight of the walls and the columns located above and below the ceiling;
h_i: Level i height from the base level;
n: The numbers of the building stories from base level upwards; and
F_t: Extra lateral load on story n ceiling level which is determined by Eq. (2):

$$F_t = 0.07\,TV \qquad (2)$$

F_t should be no more than 0.25V and whereas T≤ 0.7s, it can be equal to zero.

Uniform load pattern

In this pattern, lateral load distribution is applied to the structure proportional with story masses at every level. This load pattern is determined based on Eq. (3) and (4):

$$\{F\} = [m] \qquad (3)$$

$$\boldsymbol{F_i = m_i} \qquad (4)$$

where:
F_i: Lateral load at story i level; and
m_i: Story I mass.

First mode load pattern

Lateral load distribution in this pattern is proportional with every story mass multiplied with modal vector component of the respective story. The values obtained for the stories are normalized with regard to the respective value at roof level. The load distribution is according to Eq. (5) and (6):

$$\{F\} = [m]\{\Phi\} \qquad (5)$$

$$F_i = m_i \varphi_i \qquad (6)$$

where:
F_i: Lateral load at story i level;
m_i: Story I mass; and
φ_i: Modal vector component at the level i.

6. Stiffness pattern

In preliminary analyses it has been observed that if the structure mass or stiffness at one or multiple stories were significantly changed, the pushover results from load patterns proposed in seismic instructions would more deviated from the results of nonlinear dynamic analysis. Therefore, it seems require more involvement of story stiffness and mass distribution to determine lateral load pattern. For this, the pattern used in this section is as Eq. (7):

$$F_i = \frac{m_i.|\varphi_i|.h_i.k_i}{\sum m.|\varphi|.h.k}(\sum|m\varphi|) \qquad (7)$$

whereas m is story mass, φ is nodal vector component at level i, k is story stiffness and h is respective story height from the base. Story stiffness is determined with regard to the assumption of diaphragm rigidities for the storys based on Eq. (8):

$$k = \sum \frac{12EI_c}{h^3} \quad (8)$$

where I_c is column inertial moment, h is respective story height and E is elasticity modulus of the materials used for the columns.

Earthquake records for nonlinear dynamic analysis

In order to conduct nonlinear dynamic analyses for 5-, 7- and 9-story frames, three accelerations related to El Centro, Tabas and Northridge earthquakes have been used as strong ground motion time histories. To normalize, design spectrum of type II Regulations 2800 has been used. Acceleration records and their properties have been presented in Table 1.

Table 1: Normalized PGA with type II soil in Iranian regulatory spectrum

Earthquake duration (s)	PGA (g)	Earthquake component	Yera	Records	Num.
53.73	0.31288	N-S	May 1940	Elcentro	**1**
	0.21478	E-W			
50	0.93312	N16W	Sept. 1978	Tabas	**2**
	0.87878	S74E			
60	0.51646	E-W	Jan. 1994	Northridge	**3**
	0.41578	N-S			

With nonlinear dynamic analysis, the responses for the displacements of studied respective structures have been obtained for each of PGAs. The responses should be averaged according to FEMA356 recommendation. Averaging methods make calculations reduced. Popular method for averaging is arithmetic method in which total responses are divided by their number and each response share is assumed to be the same in average. This is the case to estimate linear methods but because of very complicated nature of the responses in nonlinear dynamic analysis, this may seems very accurate at all. Therefore, there is another method known as exponential averaging method. As it is known, converting complicated parameters to logarithmic coordinates causes to make their variations approach to linear state which is very popular in earthquake engineering. Thus, in this study, exponential averaging method has been used to average nonlinear dynamic analysis responses from every PGA. The relations used for exponential and arithmetic averaging methods have been illustrated in Eq. (9) and (10), respectively.

$$\overline{D}_{(n)} = \frac{\sum_{i=1}^{n} D_i}{n} \quad (9)$$

$$\overline{D}_{(n)} = \exp\left[\frac{\sum_{i=1}^{n} \mathrm{Ln}(D_i)}{n}\right] \quad (10)$$

7. Analytical results

In this section, the responses from the analyses for the studied structures have been illustrated. The results from nonlinear dynamic and pushover analyses have been presented graphically for each of inverted triangular, uniform, first mode and stiffness load patterns. These results include displacement values for 5-story frame (Figures 5, 10 and 15), drift ratios (Figures 6, 11 and 16) and rotations of beam-to-column connections (Figures 5, 12 and 17). Other results presented in this section are structure deformation profile, its plastic hinges (Figures 4, 9 and 14) and pushover diagram related to each of studied structures (Figures 8, 13 and 18).

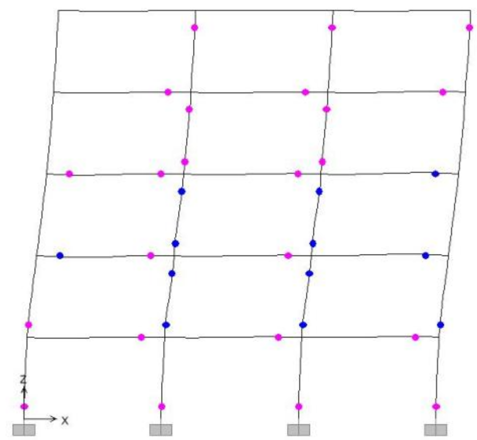


Figure 4: Plastic hinges in 5-story frame

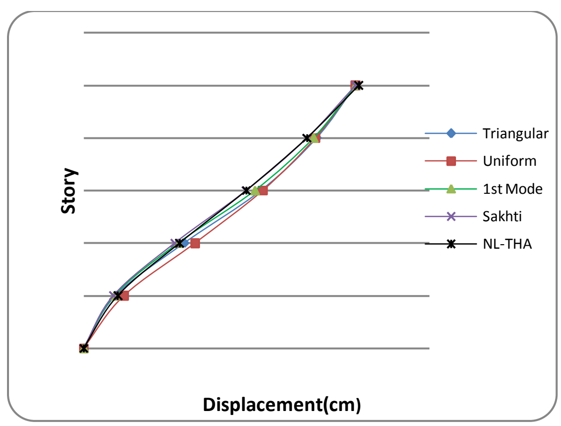


Figure 5: Displacement values for 5-story frame

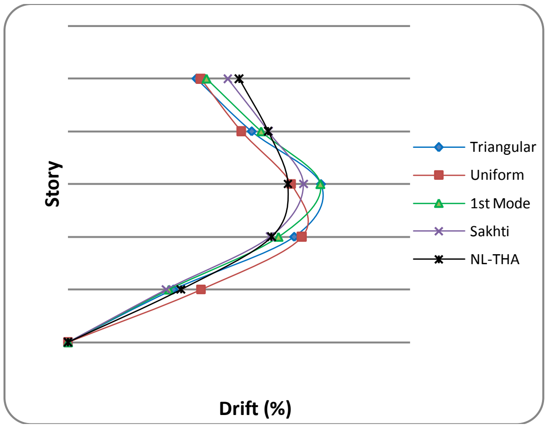


Figure 6: Drift values for 5-story frame

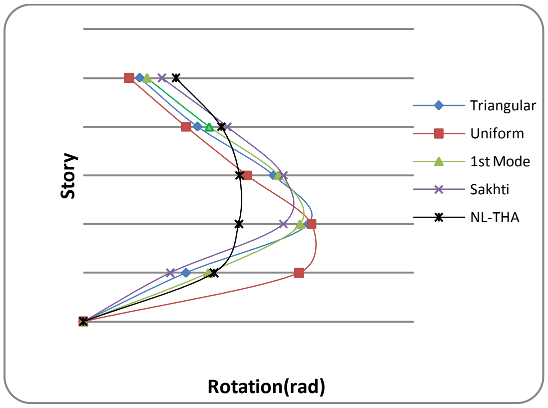


Figure 7: Beam-to-column rotations for 5-story frame

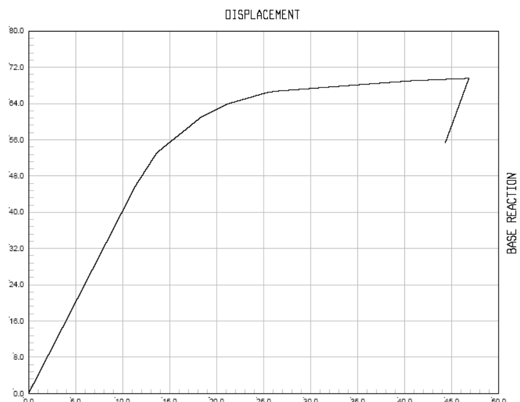


Figure 8: Pushover diagram for 5-story frame

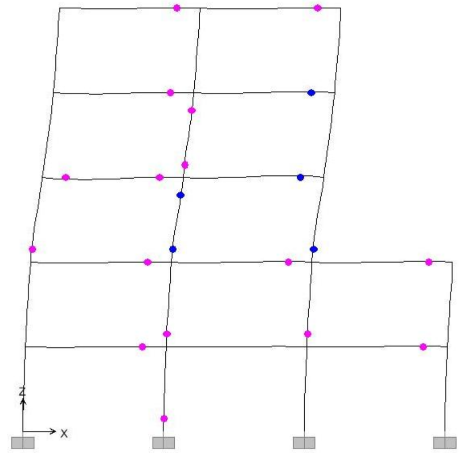


Figure 9: Plastic hinges in irregular (stiffness) in height 5-story frame

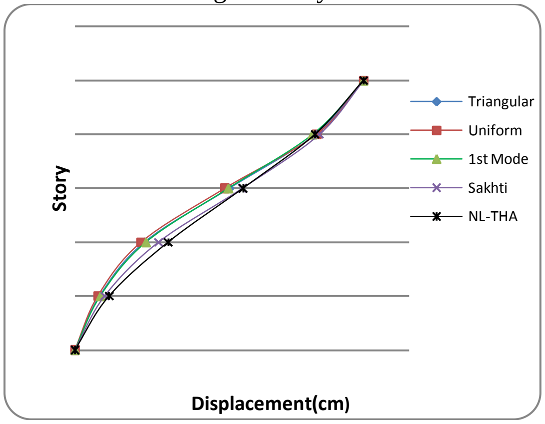


Figure 10: Displacements for irregular (stiffness) in height 5-story frame

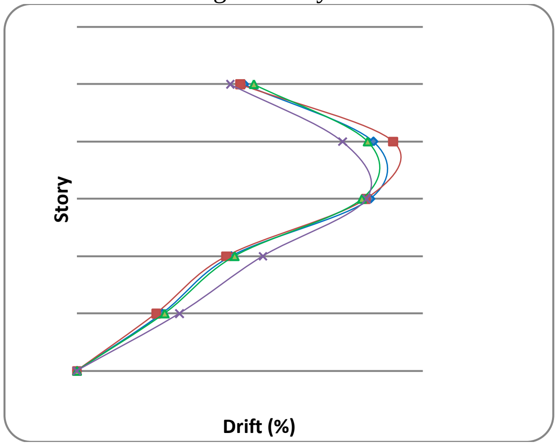


Figure 11: Drift values for the stories of an irregular (stiffness) in height 5-story frame

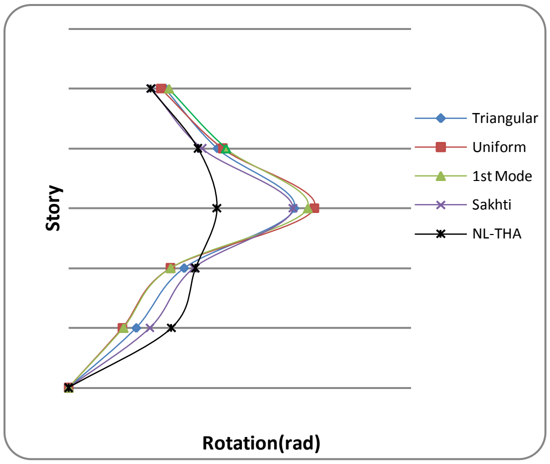


Figure 12: Beam-to-column connection rotations for an irregular (stiffness) in height 5-story frame

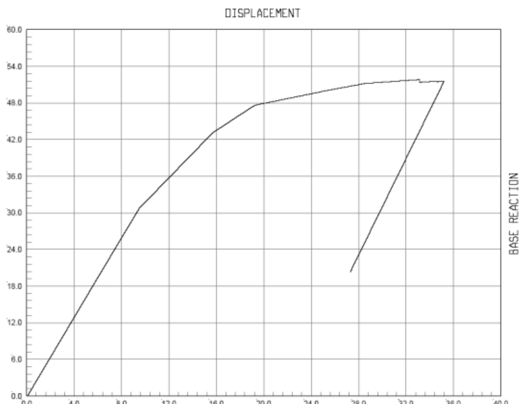


Figure 13: Pushover diagram for an irregular (stiffness) in height 5-story frame

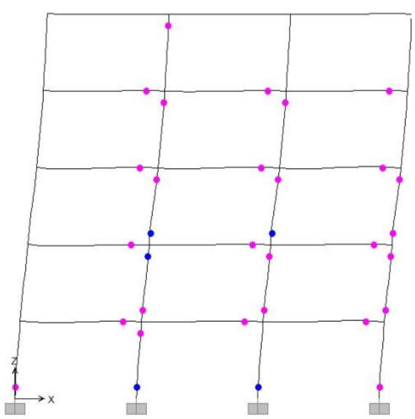


Figure 14: Plastic hinges in irregular (mass) in height 5-story frame

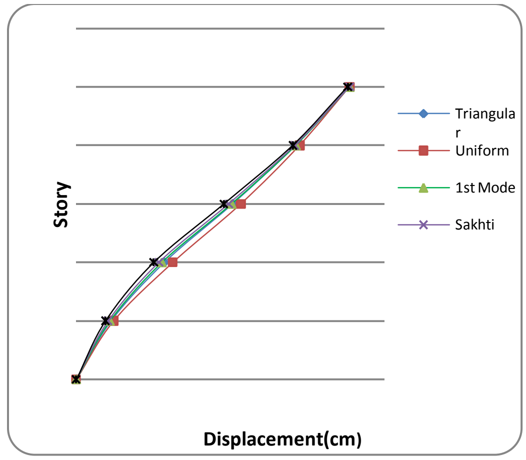


Figure 15: Displacements for irregular (mass) in height 5-story frame

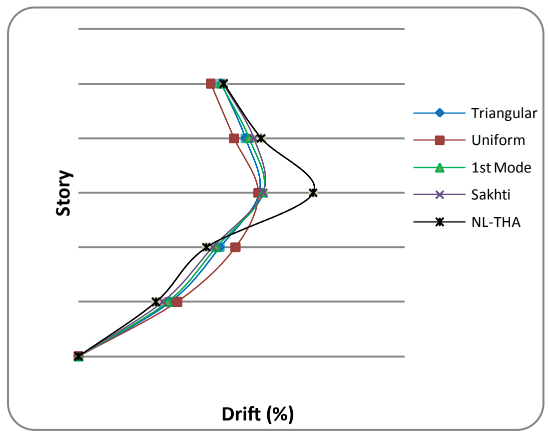


Figure 16: Drift values for the stories of an irregular (mass) in height 5-story frame

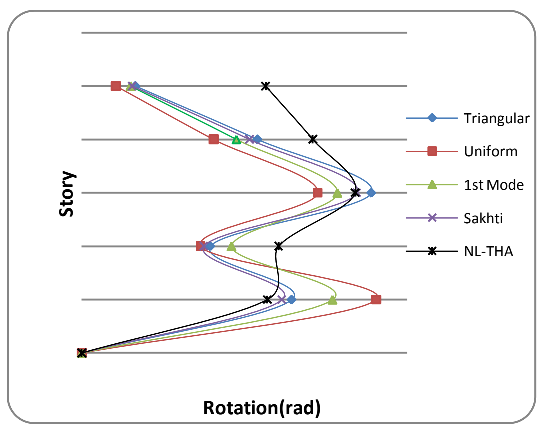


Figure 17: Beam-to-column connection rotations for an irregular (mass) in height 5-story frame

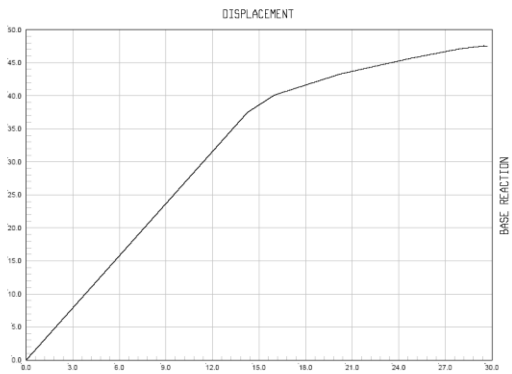


Figure 18: Pushover diagram for an irregular (mass) in height 5-story frame

8. Estimating the accuracies of different lateral load patterns

In this section, the accuracy of pushover analysis results is evaluated for any lateral load patterns. For this, the pushover results are compared with nonlinear dynamic analysis results and the deviation (error) of every lateral load pattern is calculated in percent. Therefore, the accuracy and capability of every lateral load pattern is investigated against structure response. Following this, the results for errors are presented for each of lateral load patterns in every frame in Tables 2, 3and 4 and Figures 19, 20 and 21.

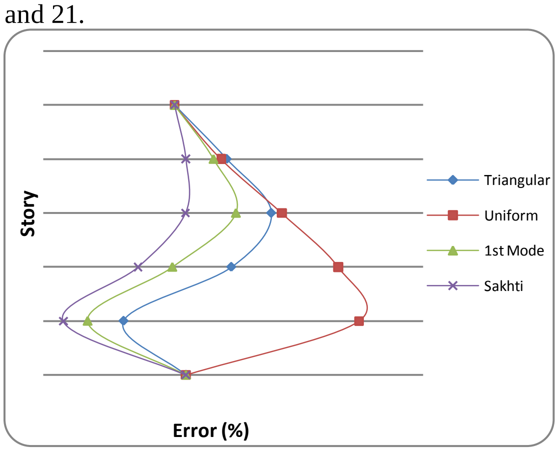


Figure 19: Estimation error for the 5-story frame displacement (%)

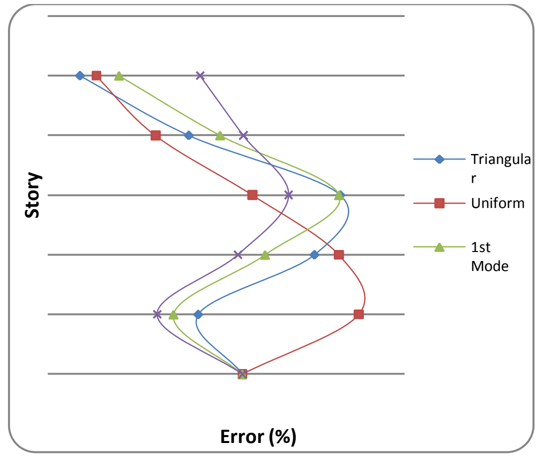


Figure 20: Estimation error for the 5-story frame drift (%)

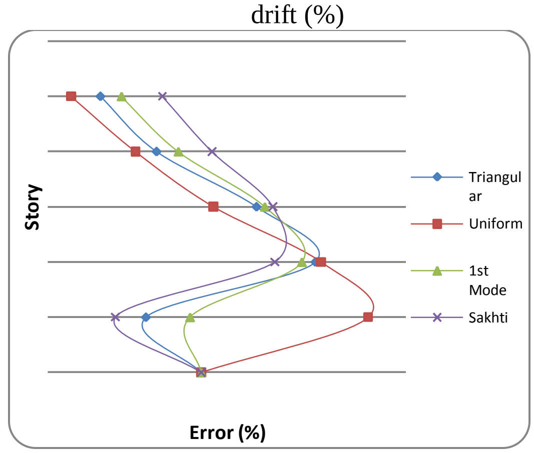


Figure 21: Estimation error for the 5-story frame beam-to-column connection rotation (%)

Table 2: Average error calculated for estimation of maximum displacements of the stories (%)

Pattern / **Frame**	**Inverted triangular**	**Uniform**	**First mode**	**Inverted triangular**
5 story	5.17	9.86	4.24	3.84
Irregular (stiffness) in height 5 story	12.31	14.68	11.90	5.13
Irregular (mass) in height 5 story	8.10	13.54	6.65	4.09
7 story	7.50	10.30	7.01	5.42
Irregular (stiffness) in height 7 story	8.68	15.16	9.61	5.00
Irregular (mass) in height 7 story	7.82	10.22	6.68	5.77

9 story	8.22	11.04	9.23	9.87
Irregular (stiffness) in height 9 story	13.79	15.42	16.53	10.09
Irregular (mass) in height 9 story	13.07	16.90	9.56	6.86

Table 3: Average error calculated for estimation of maximum drifts of the stories (%)

Pattern / Frame	**Inverted triangular**	**Uniform**	**First mode**	**Inverted triangular**
5 story	13.24	14.04	10.29	5.52
Irregular (stiffness) in height 5 story	16.91	20.13	16.19	9.74
Irregular (mass) in height 5 story	12.43	19.40	10.54	7.80
7 story	11.56	13.52	10.96	12.48
Irregular (stiffness) in height 7 story	13.15	19.31	12.85	8.58
Irregular (mass) in height 7 story	7.38	10.43	10.20	8.56
9 story	19.23	11.82	16.92	17.02
Irregular (stiffness) in height 9 story	31.74	15.25	33.30	23.16
Irregular (mass) in height 9 story	19.72	14.97	21.86	13.25

Table 4: Average error calculated for estimation of maximum beam-to-column connection rotations of the stories (%)

Pattern / Frame	**Inverted triangular**	**Uniform**	**First mode**	**Inverted triangular**
5 story	28.91	38.68	21.78	21.94
Irregular (stiffness) in height 5 story	25.70	32.94	34.25	15.60
Irregular (mass) in height 5 story	29.71	47.30	34.43	29.31
7 story	25.81	34.79	25.01	20.97
Irregular (stiffness) in height 7 story	27.38	27.57	31.83	16.74
Irregular (mass) in height 7 story	31.86	44.38	26.89	29.64
9 story	36.91	59.13	33.67	59.09
Irregular (stiffness) in height 9 story	31.95	43.02	33.68	37.86
Irregular (mass) in height 9 story	43.76	65.91	22.80	30.66

9. Conclusions

The accuracy of uniform load pattern to estimate floor displacements and drifts parameters is lower than other lateral load patterns in the study. This pattern accuracy decreases by increasing the number of stories.

The results from pushover analysis with uniform load pattern to estimate seismic demands are more overestimated than nonlinear dynamic analysis results. Thus, applying uniform lateral loading provides a conservative estimation of the structure capacity and this is because of rapidly increasing local damages at lower stories of the studied structures.

The accuracy of story stiffness load pattern to displacements and drifts of estimate regular and irregular in height frames is evaluated more appropriate than the others. Therefore, in irregular in height structures, where there are considerable changes in stiffness and mass of some stories, this pattern is a suitable option to evaluate the structure performance using pushover analysis.

Having investigated the distribution of plastic hinges in the studied frames, it is identified in this study that the structures which are seismically designed based on sixth issue of National Building Regulations and guidelines for seismic rehabilitation using linear static method have sufficient life safety performance. In the other words, the purpose defined in the sixth issue, that is designing the constructions to achieve sufficient life safety performance, is satisfied in these structures.

Generally speaking, the accuracy of lateral load patterns in the study is low in estimation of plastic hinge rotations in the place of beam to column connection. Of course, considering Chopra and Goel [6] studies, this one of characteristic problems governing on all pushover analysis methods and no longer is specific to this study.

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