

## Proposal of lateral load pattern for pushover analysis of RC buildings

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### Abstract

The proposal lateral load pattern for pushover analysis is given in two forms for symmetric concrete buildings:  $1-(X/H)^{0.5}$  for low-rise and mid-rise buildings, 2-  $\text{Sin}(\Pi X/H)$  for high-rise buildings. These two forms give more realistic results as compared to conventional load patterns such as triangular and uniform load patterns. The assumed buildings of 4, 8, 12, 16, 20 and 30 story concrete buildings are special moment frame which have been designed according to 2800 standard. Then using conventional load patterns and proposal load patterns, the pushover analysis has been done and results have been compared with the outcomes of nonlinear time history analysis. Results show the accuracy of proposed load pattern in comparing to the load patterns proposed by standards such as FEMA356.

**Keywords:** Pushover analysis; Performance-based seismic design; Lateral load pattern; Nonlinear time history analysis.

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### 1. Introduction

In the last ten years, much attention has been paid to performance-based seismic design in earthquake engineering research. This new method requires designing a building for several expected performance levels associated with different earthquake hazard levels. To meet this objective, a more rational design procedure based on inelastic displacement rather than elastic force is needed. At present, the method has been suggested in some recommended or guidance codes and documents [1].

An important step in performance-based design is to estimate the nonlinear seismic response of buildings. There are two procedures: nonlinear time history analysis and simplified nonlinear analysis, herein referred to as pushover analysis. The nonlinear time history analysis can provide more realistic results for a given earthquake ground motion. However, such analytical methods tend to be highly sensitive to the earthquake input. It is difficult to provide suitable earthquake time histories as earthquake motion for general design use in codes. Pushover analysis is not as complicated as nonlinear time history analysis and

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can use response spectrum as demand diagram to estimate the seismic response of structures [2]. Therefore it is generally recommended in performance-based design.

In pushover analysis, the first step is to suppose a certain lateral load pattern, then perform a static analysis of the structural model under this pattern. The load pattern is applied step by step until a predetermined target displacement is reached. Thus, the relationship between base shear and roof displacement is obtained, which is referred to as the capacity curve of building. It is clear that different load patterns will result in different capacity curves. If the curve over-or-underestimates the seismic capacity of the building, then the steps used to estimate the displacement response based on this curve and design demand diagram would not be realistic. Therefore, the selection of a reasonable lateral load pattern is particularly important in pushover analysis [3].

Several lateral load patterns have been suggested. They are: (1) inverted triangle distribution (modal pattern); (2) uniform distribution [4]; (3) load distribution based on linear elastic dynamic analysis or response spectrum analysis of the building [5]; (4) the adaptive distribution, which is varied as the inter story resistance changes in each load step [6]; (5) distribution proportional to the product of the mass and fundamental mode shape, which is used initially until the first yielding takes place. Then the lateral forces are determined based on the product of the current floor displacement and mass at each step [7]; (6) a distribution based on mode shapes derived from secant stiffness at each load step [8]. The last three distributions are adaptive patterns, which try to establish equivalent lateral load distribution based on a certain theoretical basis. However, their superiority over the simple fixed load patterns has not been demonstrated.

It was also noted that the first two patterns might result in the lower and upper bound of pushover curves, respectively [9]. In present paper, numerous time history analyses are carried out for 4, 8, 12, 16, 20 and 30 story concrete buildings, which were selected to represent a variety of structures, to obtain the capacity curves of these buildings under earthquake excitations. Then, pushover analyses are conducted under different load patterns including conventional and proposed load patterns, the obtained capacity curves are compared with those obtained from time history analysis, the effectiveness of different load patterns is examined and suitable load patterns are suggested for different types of structures. RC buildings have been designed according to Iranian earthquake standard. Then pushover and nonlinear time history analysis are applied to each building by means of FEMA356.

Pushover analysis is done by applying of triangular load, uniform load as well as proposed load patterns then the building capacity curve is drawn for each pattern. These curves are compared with those obtained from time history capacity of the building.

The best lateral load pattern can be given by comparison of building's capacity curve while applying of different lateral load patterns with exact capacity curve obtained from time history nonlinear analysis.

## **2. Introducing of records and buildings**

### *2.1. Characteristics of buildings*

The used design standards for 4, 8, 12, 16, 20, and 30-story buildings are introduced in this section. The load standard NO.6 of building national standard [10], Iranian seismic standard [11], and Iranian Concrete Regulation [12] have been used for design and analysis of buildings. The height of each story has been assumed as 3 meters. Dead and live loads are supposed as  $650 \text{ kg/m}^2$  and  $200 \text{ kg/m}^2$  respectively. In addition, live load for the roof is assumed  $150 \text{ kg/m}^2$ . Lateral resisting system is considered special moment frame. Plan of structures, based shear and type of the soil are presented in Figure 1 and Table 1 respectively.

Table 1. Characteristic of buildings.

Story	Soil	C	V (Ton)
4	II	0.11	99.5
8	II	0.08	142.3
12	II	0.04	135.5
16	II	0.04	214.7
20	III	0.04	188.7
30	II	0.02	259.7

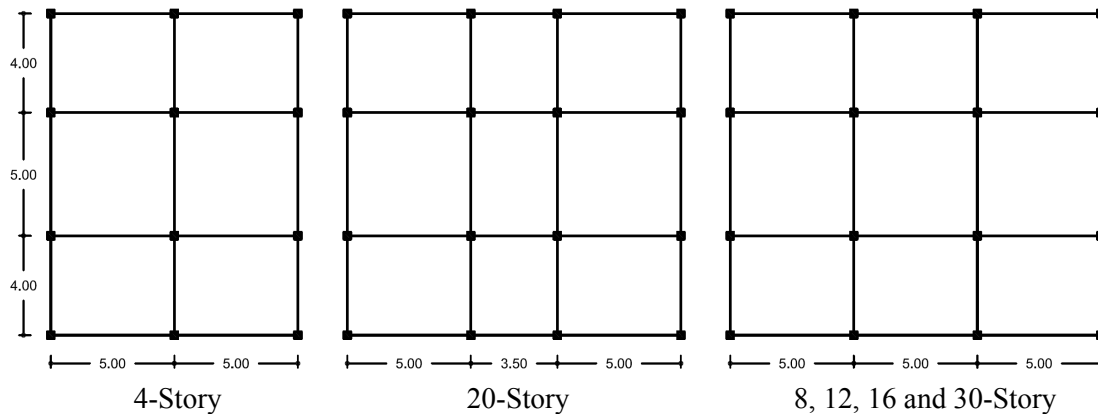


Figure 1. Plan of buildings.

## 2.2. Used earthquakes

Seven earthquake ground motions have been considered for each building. The characteristics and specifications of used records are in accordance with type of the soil. The specification of the used records is listed in Table 2. The spectrum relating to some used records is given in Figure 2. In this study, we assumed that the earthquake record does not affect the trend of the results obtained.

## 3. Results

### 3.1. Comparison of pushover and nonlinear time history analysis

In this section the capacity curve of conventional pushover, triangular and uniform load patterns, and nonlinear time history analysis have been given. For extracting of building's dynamic capacity curve, the nonlinear time history analysis should be carried out by multiply different coefficients to the earthquakes. After determining the response of nonlinear time history analysis for each used coefficient, the maximum displacement and base shear is extracted. Therefore, it is obvious that for drawing of building's dynamic capacity curve of a record, different nonlinear time history analysis should be performed. Each point of capacity curve can be obtained by performing a nonlinear time history analysis using a ground motion record. The dynamic capacity curves obtained from mentioned records are shown in Figure 3.

Table 2. Characteristics of used records [13].

abbreviations	Name of records	Date	Station	Soil type	PGA (g)
LADSP	Landers	06/28/92	Desert hot springs	B	0.171
LPAND	Loma prieta	10/18/89	Anderson dam downstream	B	0.242
LPGIL	Loma prieta	10/18/89	Gilroy gabilan coll	B	0.357
LPSTG	Loma prieta	10/18/89	Saratoga aloha ave	B	0.512
MHGO	Morgan hill	04/24/84	Gilroy array	B	0.355
NRORR	Northridge	01/17/94	Castaic old ridge rt	B	0.514
IPLVY	Imperial valley	5/19/40	El centro array	B	0.308
TABAS	Tabas	09/16/78	Tabas	B	0.836
KOBE	Kobe	01/16/95	Takarazu	B	0.689
MENDOCINO	Cape mendocino	04/25/92	Cape mendocino	B	0.494
NORTHRIDGE	Northridge	01/17/94	Rinaldi receiving sta	C	0.838
IMPERIAL VALLEY	Imperial valley	5/19/40	El centro array #9	C	0.308
LOMA PRIETA	Loma prieta	10/18/89	Capitola	C	0.442
MENDOCINO	Cape mendocino	04/25/92	Petrolia	C	0.662
MORGAN HILL	Morgan hill	04/24/84	Gilroy array #2	C	0.212
HOLLISTER	Hollister	11/28/74	Hollister city hall	C	0.175
TURKEY	Turkey	11/12/99	Duzce	C	0.535

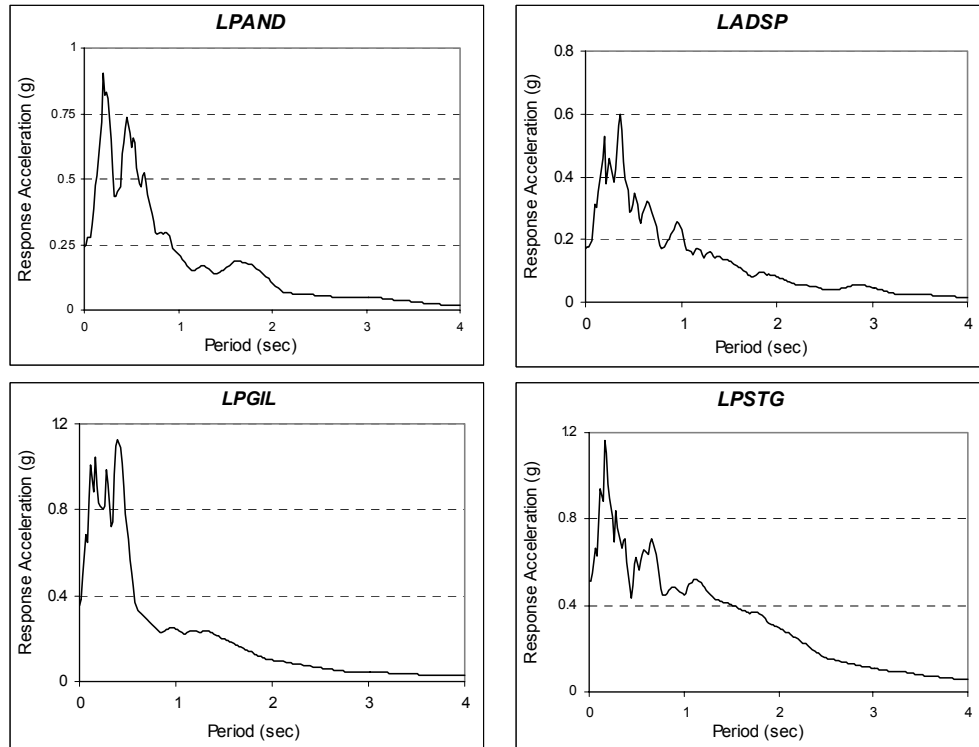


Figure 2. Response spectra of some records.

In this research, dynamic capacity curves have been drawn under seven earthquakes as well as average capacity curve, amongst these seven dynamic capacity curves, which is called the real capacity curve of building, is extracted. The capacity curve obtained from triangular and uniform load patterns is evaluated by comparing to real capacity curve of each building (Figure 4).

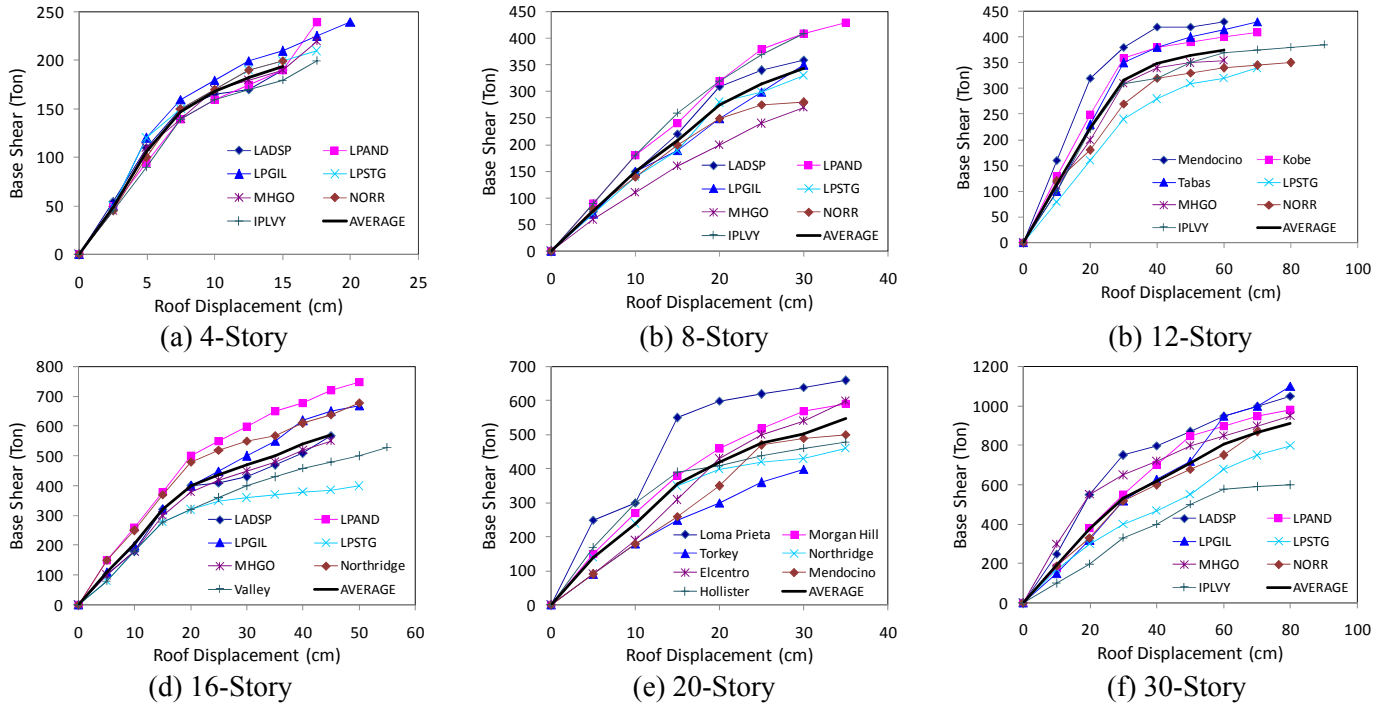


Figure 3. Dynamic capacity curves of buildings.

Considering the previous figure, the error induced by using conventional load pattern instead of nonlinear time history analysis is demonstrated.

The dynamic capacity curve is located between two capacity curves obtained from uniform and triangular load patterns for both 4 and 8-story buildings. In 12, 16, 20 and 30 story buildings the dynamic capacity curve is located above the two mentioned capacity curves. With regard to these graphs, using the uniform load pattern is unsuitable for low-rise buildings at all as it overestimates the capacity of the building from its real capacity. Using this load pattern for high-rise buildings would lead to a considerable error. Especially 30 story building in contrast to uniform load pattern the triangular load pattern is more reliable as it always underestimates the capacity of building from its real capacity. Therefore, using a new load pattern which gives a more realistic view can result in a more economic design.

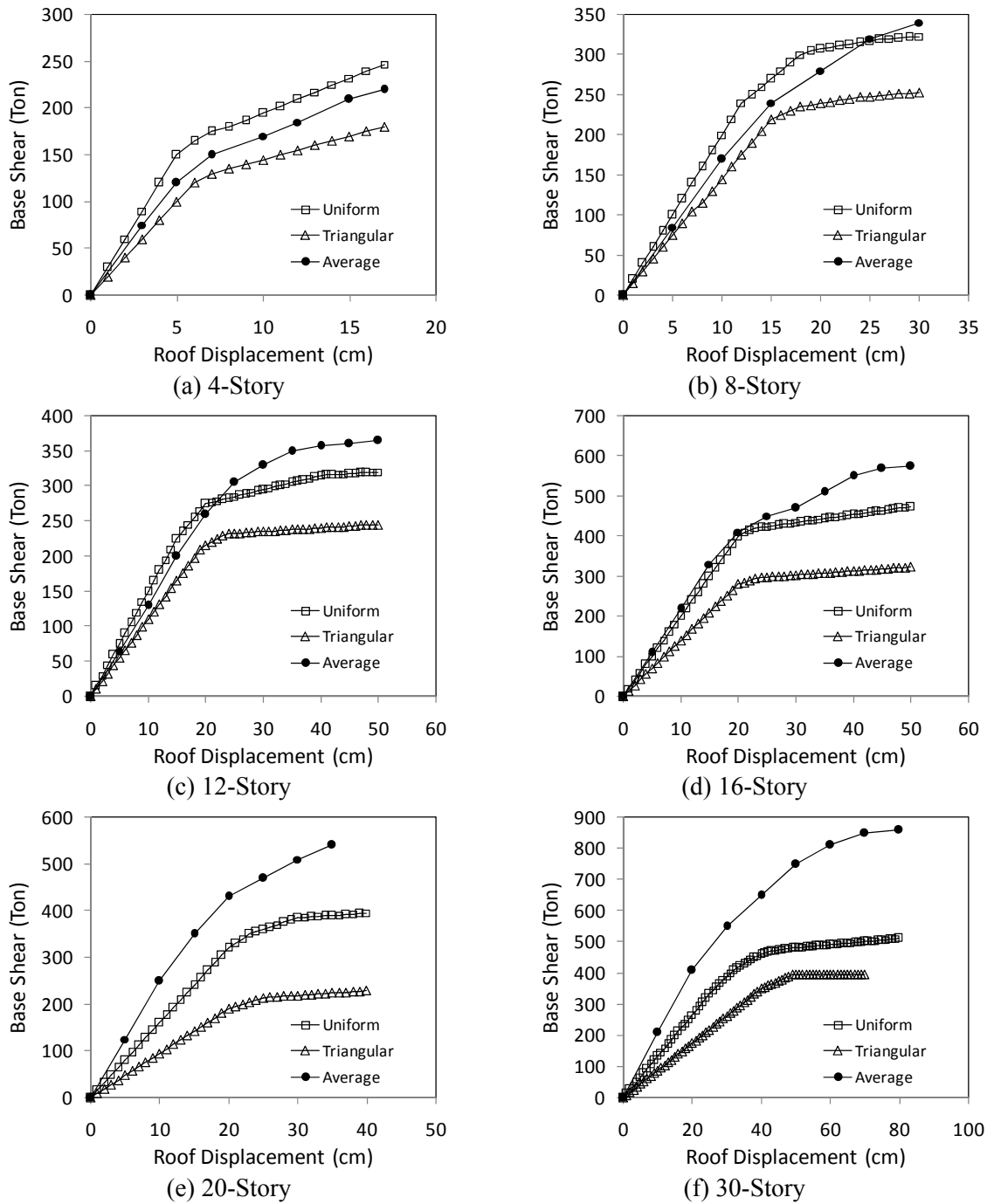


Figure 4. Comparison of dynamic capacity curve with triangular and uniform capacity curves.

### 3.2. New proposed load patterns

Different mathematical functions as a load pattern can be used for paving the way to be closer to real capacity curve. Then the best load pattern can be obtained by comparing the building capacity curve under the suggested applied patterns and the real capacity curve.

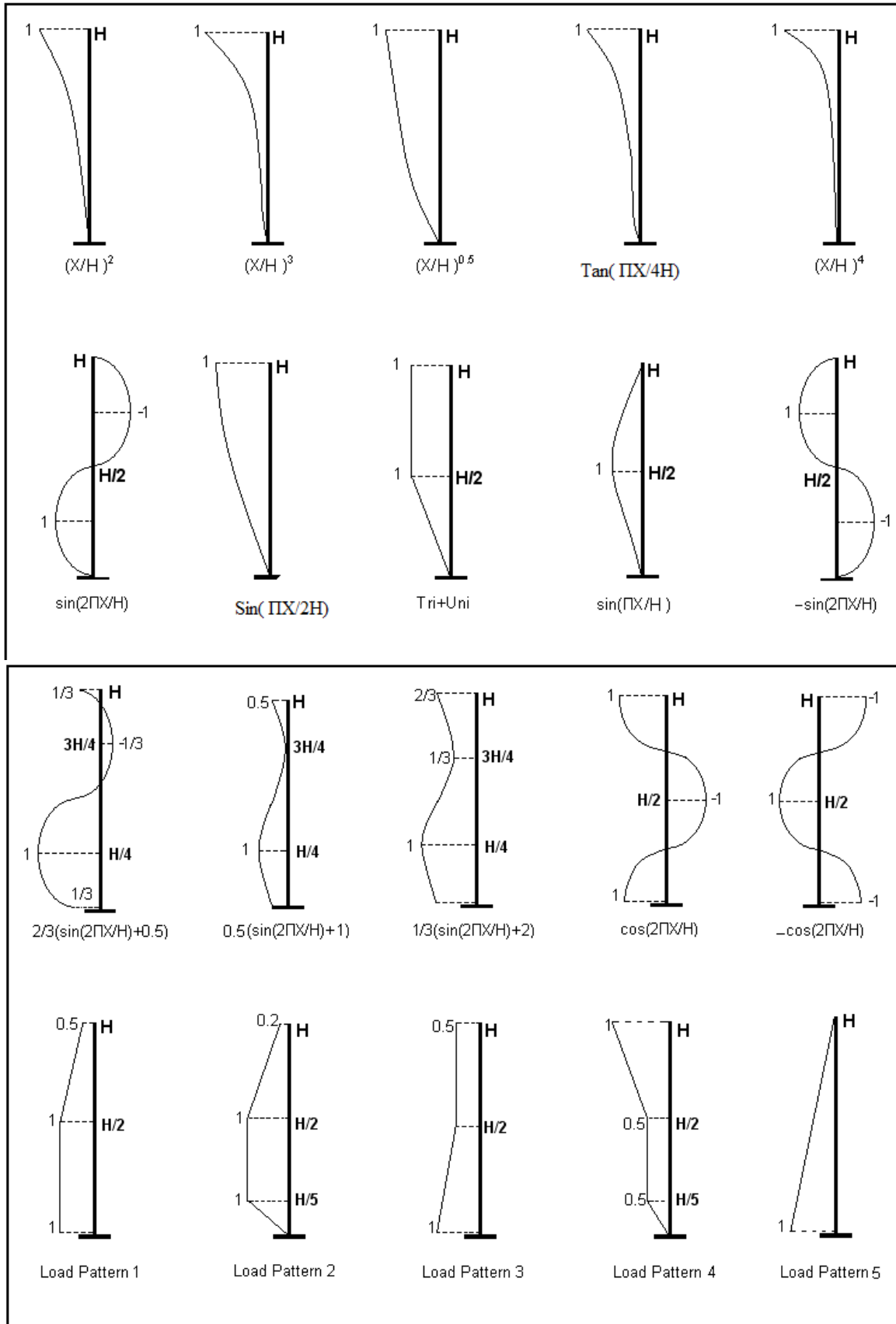


Figure 5. Proposal load patterns.

In this investigation, many different load patterns have been applied to the buildings by means of different mathematical functions. Some of the applied patterns are exhibited in Figure 5. It is obvious that each load pattern gives different capacity curve as compared with other presented patterns. By drawing the capacity curve for each load pattern and comparing it with dynamic capacity curve, the important factor is the center of the load pattern which is the contact point of the applied lateral load resultant under the same pattern (X). The applied patterns to 4 and 8-story buildings are as follows:

- |                  |                     |
|------------------|---------------------|
| 1- $(X/H)^{0.5}$ | 5- $Tan(\pi X/4H)$  |
| 2- $(X/H)^2$     | 6- $Sin(\pi X/2H)$  |
| 3- $(X/H)^3$     | 7- <i>Tri + Uni</i> |
| 4- $(X/H)^4$     | 8- $Sin(\pi X/H)$   |

### 3.2.1. Capacity curves

The capacity curve corresponding to the above load patterns for 4 and 8 -story buildings are illustrated in Figure 6a and Figure 6b in the same order.

Considering this figure, the capacity curves obtained from load patterns 2 to 5 are located under the capacity curve of triangular load pattern. Beside it, the capacity curves corresponding to load patterns 6, 1, and 7 are located between two capacity curves of triangular and uniform load patterns.

Keeping in mind the factor mentioned in previous section it is apprehended that the value of X for patterns 2 to 5 is more than the value of X for triangular patterns.

In the same way, the value of X for load patterns 1, 6 and 7 is located between this value for triangular and uniform load patterns.

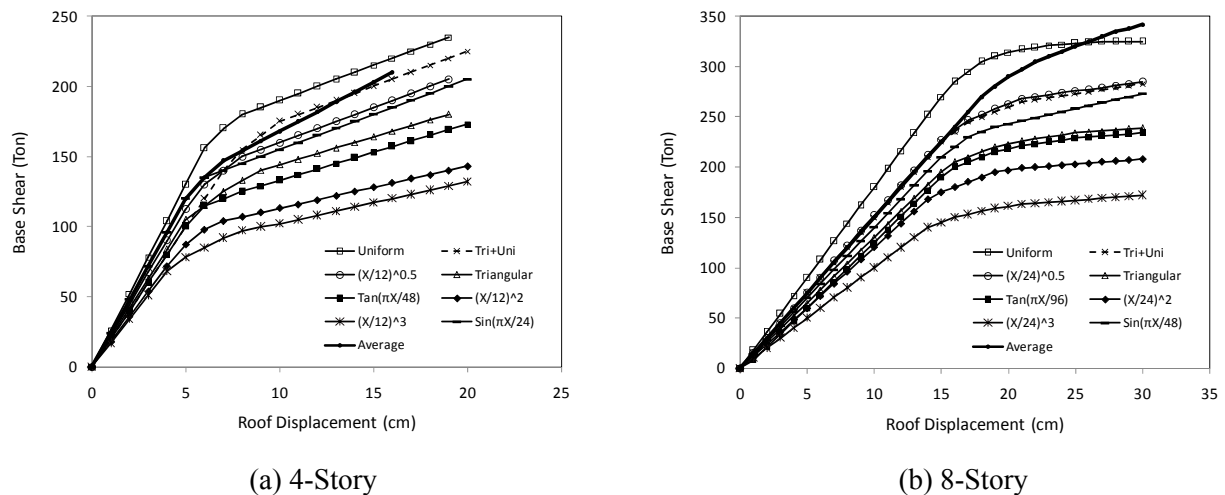


Figure 6. Various obtained capacity curves.

We come to conclusion that the higher value of X (point of lateral load resultant), the lower the position of its capacity curves on the scale. On the other hand, the lower the contact point of lateral load resultant in a load pattern, the higher position of its curve on the scale. To determine the best lateral load pattern, the time history capacity curve or real capacity curve of the building is used. According to Figure 7, the load patterns  $(X/H)^{0.5}$  and *Tri+Uni* show the best accordance to the real capacity curve of the building.



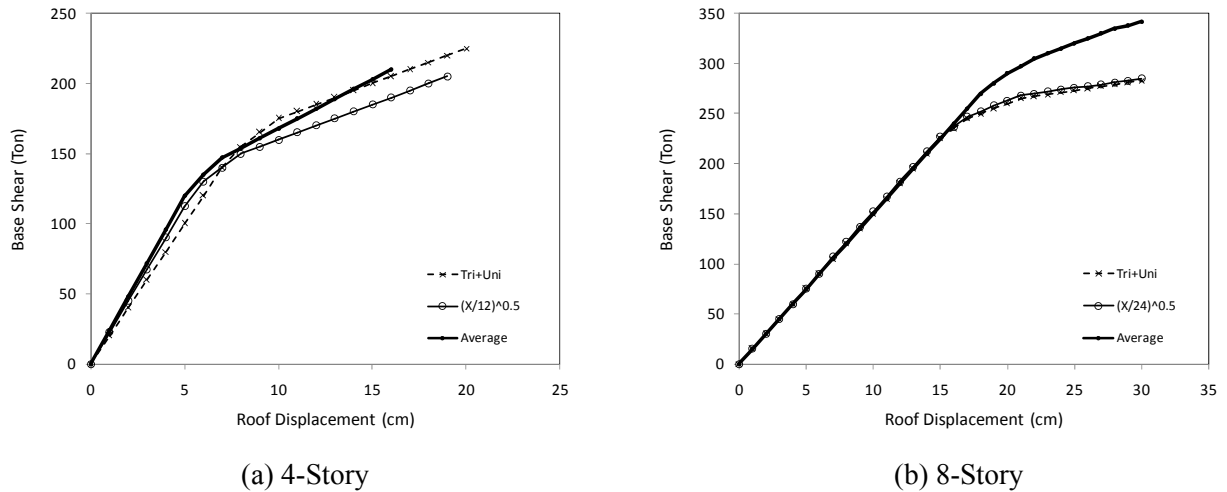


Figure 7. Capacity curves corresponding to proposed load patterns.

According to the Figure 4 the capacity curves of high-rise buildings are located in higher position with comparing to uniform and triangular capacity curves. It is confirmed that using uniform load pattern for high-rise buildings shows accurate results as compared with triangular load pattern. Therefore, it is better to convert the lateral load distribution pattern from triangular to uniform by increasing the height of the building.

Achieving new lateral load patterns for high-rise buildings, with regard to the represented solution for 4-story building in the previous section, we should use patterns the lateral load resultant's contact point is located in lower height as compared with uniform load pattern. As a result, the load patterns in Figure 8 are used for tall buildings. The capacity curves of proposed load patterns are shown in Figure 9.

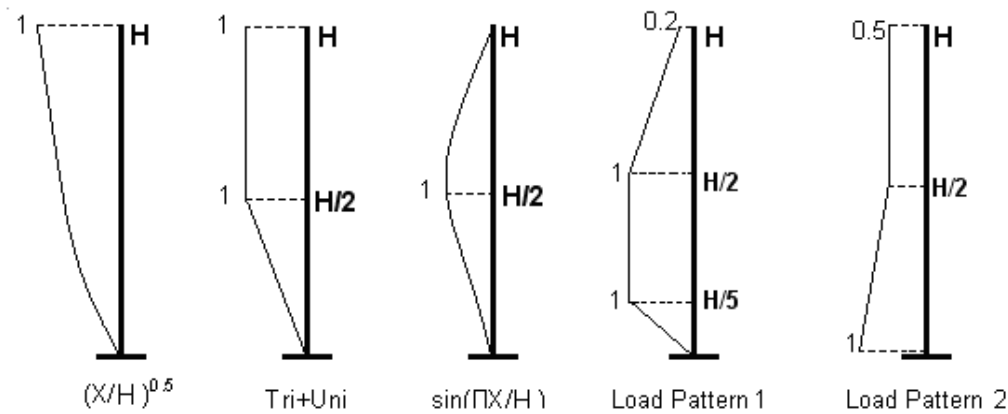


Figure 8. Applied load patterns to tall building.

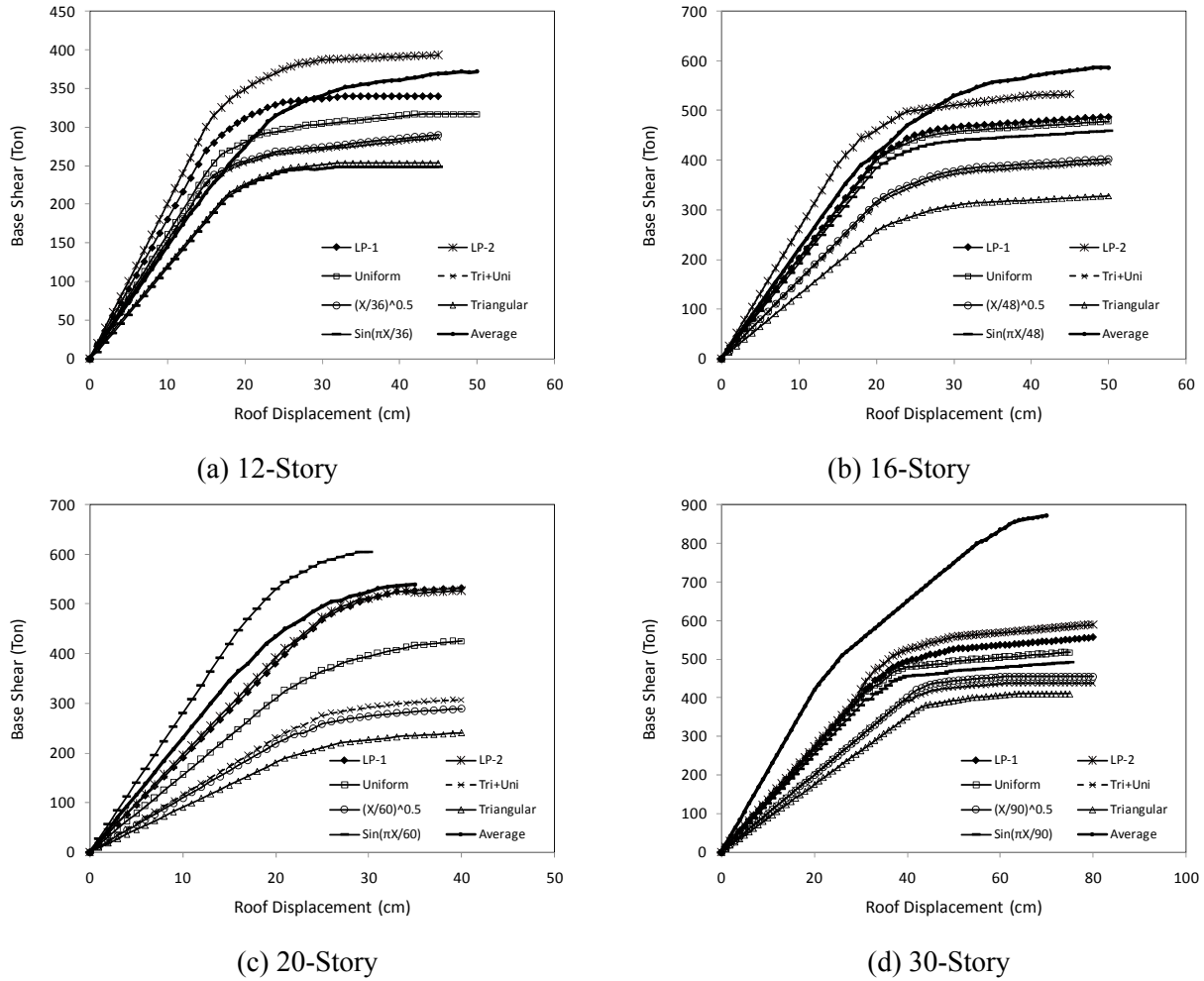


Figure 9. Various capacity curves obtained for tall building.

The dynamic capacity curve, real capacity curve, is utilized to determine the best lateral load pattern. According to Figure 10, the proposed load patterns 1 and  $Sin(\pi X/H)$  along with uniform load pattern get the best capacity curves for 12 and 16-story buildings. It is obvious that for 20-story building the capacity curve of uniform pattern presents inappropriate response of building, while the curves relating to proposed patterns 1 and 2 merely close to dynamic capacity curve.

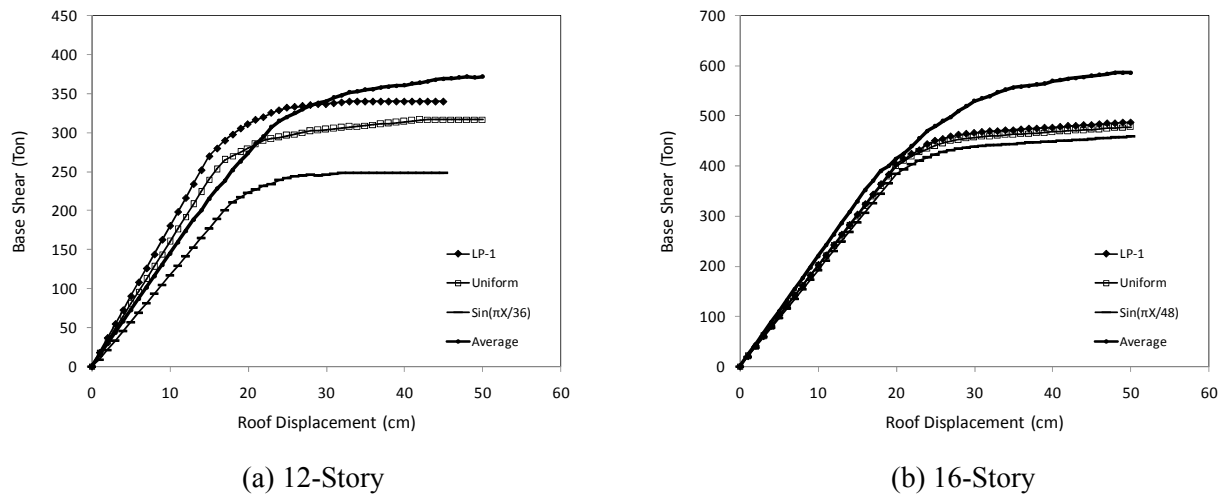


Figure 10. Comparison of dynamic capacity curves of the proposed load patterns.

According to Figure 11(b) the patterns 1 and 2 exhibit better behavior for 30-story building. However; there is still a considerable difference between its capacity curve and the dynamic capacity curve. This difference is due to higher modes effects. This would lead to significant error in results of pushover analysis comparing to nonlinear time history analysis as the number of stories increase.

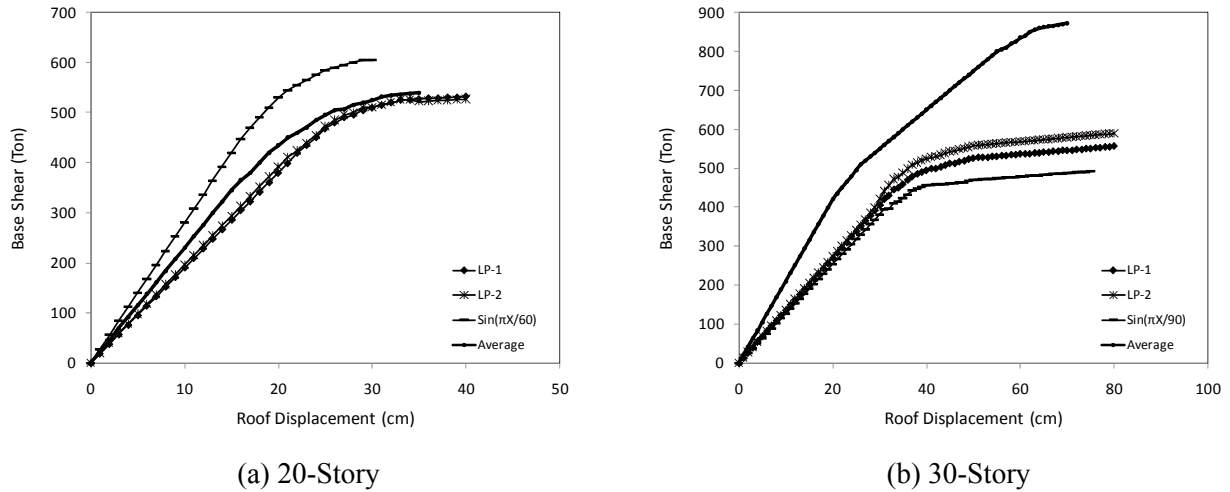


Figure 11. Comparison of capacity curves obtained from proposed and the real capacity curve.

### 3.2.2. Performance points

For better verification of proposed lateral load patterns, performance point of the buildings under the proposed load patterns is obtained and compares them with the average of maximum nonlinear dynamic displacement (Figure 12).

It is noted that the performance point was obtained with intersection of capacity curve and demand spectrum as explained in FEMA 356 document.

This figure illustrates that not only capacity curve is influenced highly by different lateral load distribution but also the performance point is affected in the same way. Therefore, the responses of building including capacity curve and performance point are significantly depended on the lateral load pattern.

Two proposed load patterns *Tri+Uni* and  $\sqrt{(X/H)}$  show better accuracy than triangular load pattern in estimating the performance point for both 4-story and 8-story buildings. Therefore, applying these two patterns is appropriate for determining the performance point of low-rise and mid-rise buildings. Proposed load pattern *Sin ( $\pi X/H$ )* is the most precise load pattern to determine the performance point of a 16-story building as compared with other patterns. But it is unsuitable for determining the performance point of 12-story building. For determining the performance point of 20-story and 30-story buildings the load pattern 2 exhibits the most accurate result among other load patterns.

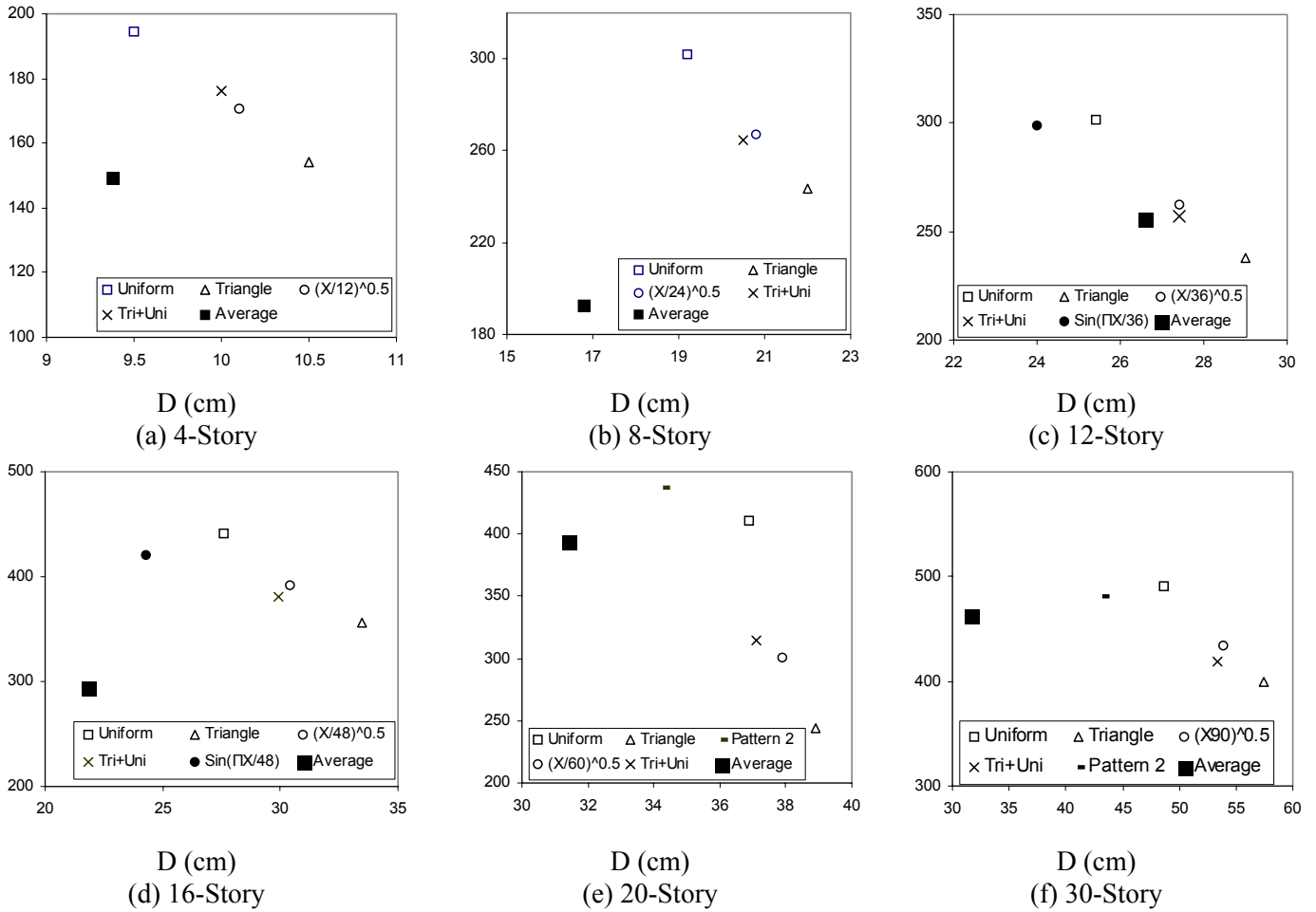


Figure 12. Verification of performance points (vertical axis is base shear (ton)).

### 3.2.3. Verification of displacement criterion

One of the parameter for verification of performance levels of buildings is to determine story drift of buildings. Figure 13 presents drift of various buildings using different load patterns and time history analysis as an exact solution.

For this purpose, the values of relative displacements of the buildings at performance point are obtained and compared to them with the results obtained from nonlinear time history analysis (Figure 13).

The figure shows how various load patterns can induce different drifts and result various performance levels. In addition, the accuracy of proposed load patterns can be approved by comparing to the nonlinear time history analysis, regarding to the performance levels.

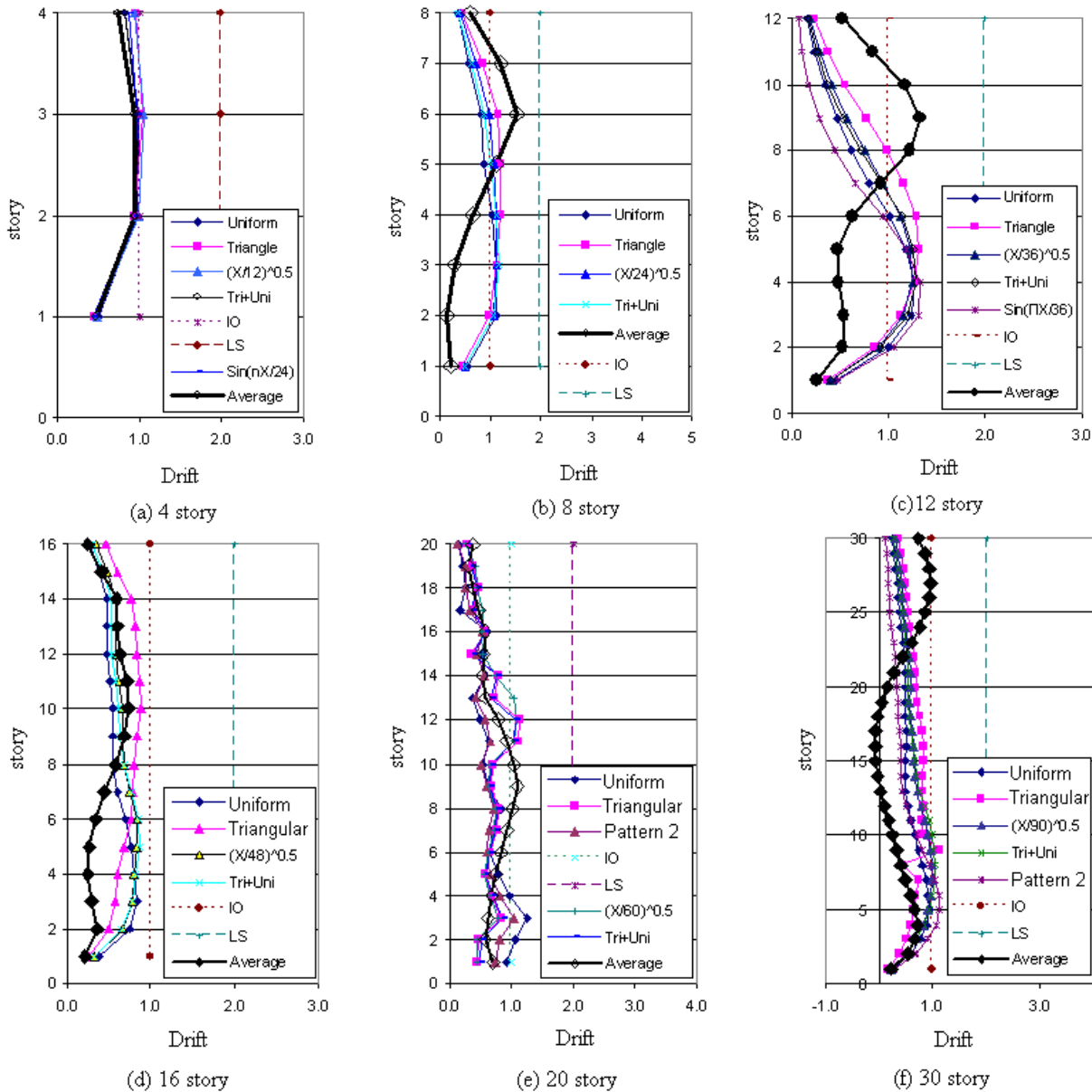


Figure 13. Verification of performance levels.

#### 4. Conclusion

In the current paper, new load patterns for symmetrical reinforced concrete buildings have been proposed. Numerous pushover analysis using conventional load patterns and proposed load patterns as well as nonlinear time history analysis as an exact solution were performed. The obtained results can be summarized as follows:

1. It is inappropriate to use uniform load pattern for determining the capacity curve of low-rise and mid-rise buildings. The capacity curve obtained from uniform load pattern is located higher than it corresponding to dynamic capacity curve and therefore it is not reliable. The reliable pattern is triangular load pattern as it underestimates the capacity of the building. On the other hand the triangular load pattern does not show the real capacity of the building and it is not economic too. Using two proposed load patterns  $\sqrt{(X/H)}$  and componential pattern *Tri+Uni* (which

is a combination of triangular and uniform patterns) removes the mentioned shortcoming and gives a precise capacity of the building.

2. Applying triangular load pattern would lead to significant errors in capacity curve as the height increases. It underestimates the capacity of the building. The uniform load pattern gives better results for mid-rise building. The capacity curve obtained from uniform load pattern differs slightly from dynamic capacity of the building. Applying this pattern for high-rise buildings is more realistic. In addition, the proposed load pattern 2 gives accurate capacity curve, as a result, proposal load pattern is even better than uniform load pattern according to obtained results for 20 and 30-story buildings. There are two other proposed load patterns  $Tri+Uni$  and  $(X/H)^{0.5}$  which could improve the results as compared with triangular load pattern and the curves obtained from the two patterns are more precise than capacity curve of triangular load pattern.
3. Load pattern  $Sin(\pi X/H)$  for 12 and 16-story buildings is more accurate than it corresponding to triangular and uniform load patterns. For 20-story building, the proposed lateral load pattern number 2 shows the least error in determining the capacity curve of building. Therefore, the proposed pattern for 12 and 16-story buildings is  $Sin(\pi X/H)$  and for 20-story, load pattern number 2 is suggested.
4. The shortcoming of all load patterns for determining of the capacity curve of 30-story building is demonstrated. Although the proposed pattern 2 has improved the condition in some extends, none of the proposed and existing load patterns represent an appropriate estimation of the building capacity curve. It is due to increasing of participation of higher modes and weakness of existing load patterns.
5. In high-rise buildings, before formation of the plastic hinges on the upper stories the hinges in lower stories turn to life safety (LS) and even collapse prevention (CP). That is the reason for differences between pushover capacity curve and dynamic capacity curve for high-rise buildings. It means that in pushover analysis of high-rise buildings the capacity of the upper stories is not considered. By using particular load patterns in which the direction of the lateral loads changes, the necessary drift for formation of plastic hinges in upper stories is provided. Overall, a load pattern which can apply the influence of different modes to the building, can give more reliable results.
6. Comparing dynamic maximum displacement with performance point, we find that different load patterns overestimate the results of pushover analysis. We should keep in mind that the records used in nonlinear time history analysis highly affect the determination of maximum displacement.

In this study we assumed the earthquake record does not affect the trend of the results obtained, further studies are needed to demonstrate the effects of different earthquakes with various sources such as far field and near field (with fling step or forward directivity) on the lateral load patterns.

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