ADAPTIVE PUSHOVER ANALYSIS OF REINFORCED CONCRETE STRUCTURES

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ABSTRACT

Nonlinear static analysis, commonly referred to as pushover analysis, is a powerful tool for assessing the seismic response of structures. A suitable lateral load pattern for pushover analysis can bring the results of this simple, quick and low-cost analysis close to the realistic results of nonlinear dynamic analyses. In this research, four samples of 10- and 15-story [two- and four-bay] reinforced concrete frames were studied. The lateral load distribution patterns recommended in FEMA 273/356 guidelines were applied to the sample models in order to perform pushover analyses. The results were then compared to the results obtained from several nonlinear incremental dynamic analyses for a range of earthquakes. Finally, a lateral load distribution pattern was proposed for pushover analysis of medium-rise reinforced concrete buildings based on the results of nonlinear static and dynamic analyses.

INTRODUCTION

In recent years, performance-based design methods have been proposed as new concepts and have been extensively used in the seismic design and evaluation of structures (Ghaffarzadeh et al., 2013). This design approach is primarily concentrated on meeting various performance objectives matching the desired level of the service of the structure. Among such methods, nonlinear static analysis is considered to be the basic notion of performance based seismic design. The effectiveness of nonlinear static analysis and its computational simplicity brought this procedure in to several seismic guidelines and design codes in last few years. However, many researches have shown that conventional methods which are usually based on load patterns restricted to the fundamental mode shape include many deficiencies that can result in responses totally different from those obtained through dynamic analyses (Paret et al., 1996; Goel and Chopra, 2004).

Therefore, various procedures as well as load patterns have been proposed in order to overcome some of these shortcomings. Moghadam and Tso (2002) provided a multimode approach in which the seismic response of the structure corresponding to each mode was calculated and the overall responses were then obtained on the basis of modal participation factors for each mode. Chopra and Goel (2002) developed another method of analysis named modal pushover analysis. In this method, a series of independent analyses was performed with the lateral load patterns consistent to the mode shapes. The produced modal responses were then combined together using quadratic modal combination rules. Despite the higher mode effect considerations, however, the continuing changes in the dynamic properties of the structure due to the inelastic behaviour are not considered in computing the applied load pattern in this type of pushover analysis (Mao et al., 2008).

In order to overcome this defect, the adaptive pushover procedure was introduced where the lateral force distribution is evaluated and adjusted as necessary based on the nonlinear behaviour of the structure (Gupta and Kunnath, 2000; Antoniou and Pinho, 2004; Abbasnia et al., 2013). Besides, many researchers have also developed improved modal methods in which the structures are pushed with combined modal forces. In other words, the modal combination conception is used to identify the load pattern rather than to combine the nonlinear responses for each mode (Matsumori et al., 1999). In addition, adaptive forms of these methods have been proposed, wherein the load pattern is firstly defined by the combination of instantaneous modal loads, and is then applied to the structure through a single pushover analysis (Antoniou and Pinho, 2004).

In this paper, an attempt is made to explore the effects of applying different lateral load distribution patterns recommended by seismic rehabilitation codes on the structural response, specially their influence on the capacity curve of four 10- and 15-story, having two and four bays, reinforced concrete frames. It also draws a comparison between the results of this analysis and the results of the nonlinear incremental time history analyses for three different earthquakes in Iran.

MODELLING AND ANALYSIS

Models studied in this research consist of four reinforced concrete frames including two 10-story frames [two- and four-bay] and two 15-story frames [two- and four-bay]. All frames have story height of 3.2 m and equal bays of 5.0 m. Gravity and seismic loads were assigned to the frames based on the criteria in the 6th section of the Iranian National Building Code (INBC-06, 2006)and the Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800, third edition). Moreover, the frames were designed according to the design criteria for special moment resisting frames according to the 9th section of the Iranian National Building Code (INBC-09, 2009). The buildings are characterized as an ordinary building having residential occupancy, and are supposed to be built in a site with conditions matching ground type II. The construction site is also located in a region of high seismicity. This is also noteworthy that in order to simulate the nonlinear behaviour of materials, the Takeda Model has been adopted. The specifications of the beams and columns used in the structures under study are presented in Fig.1 and Table1.

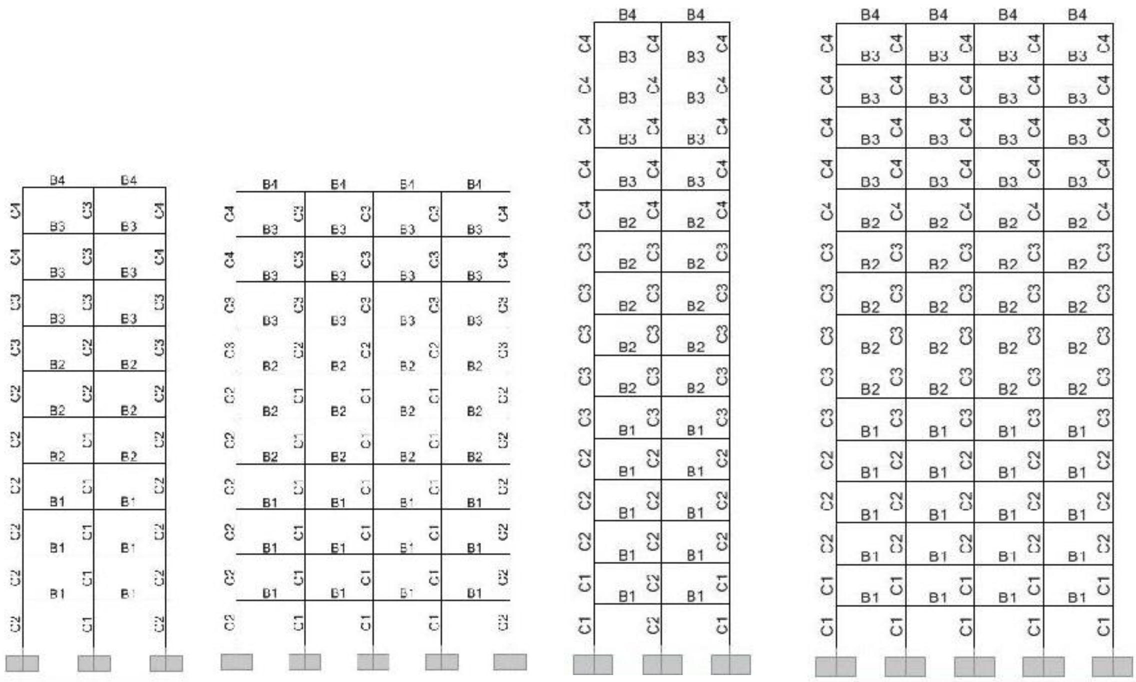


Figure 1. Schematic view of 10- and 15-story frames

Table 1. Beams and columns used in 10- and 15-story frames

Frame	Member	Section name	Dimensions (cm)	Longitudinal reinforcement (cm^2)	Transverse reinforcement (cm^2/cm)
10-story frame	Beams	B1	55 × 55	48.3	0.314
		B2	50 × 50	45.8	0.314
		B3	45 × 45	33.1	0.235
		B4	40 × 40	20.3	0.235
	Columns	C1	60 × 60	61.1	0.791
		C2	55 × 55	50.9	0.678
		C3	50 × 50	40.7	0.769
		C4	45 × 45	30.5	0.804
15-story frame	Beams	B1	60 × 60	48.3	0.392
		B2	55 × 55	45.8	0.392
		B3	50 × 50	40.7	0.314
		B4	45 × 45	25.4	0.235
	Columns	C1	65 × 65	61.1	0.791
		C2	60 × 60	61.1	0.791
		C3	55 × 55	50.9	0.678
		C4	50 × 50	40.7	0.769

International building codes contain various lateral load patterns for pushover analysis that give a more simplified representation of earthquake loadings. In this research, the most common lateral load distributions are employed for performing a more precise analysis of the effect of different lateral load patterns on the structural response as well as introducing a new lateral load distribution. These load distribution patterns are asfollowing:

- Uniform Lateral Force Distribution Pattern (ULF)
- Equivalent Lateral Force Distribution Pattern (ELF)
- Lateral Force Distribution according to the First Mode Shape (Mode 1)
- Lateral Force Distribution according to the CQC Method (CQC)

Besides, in order to perform nonlinear time history analyses, three ground motion records including Tabas Earthquake, Kahak Earthquake, and Zarand Earthquake were used. All the selected accelerograms were far field ground motions and had been recorded on soil type II (Table 2).

Table 2. General specifications of earthquakes

Region	Date	Time	Magnitude			Database
			Ml	Ms	Mw	
Kahak	18/06/2007	14:29:50	5.7	-	-	BHRC
Zarand	22/02/2005	02:25:26	-	-	6.2	NEIC
Tabas	16/09/1978	15:35:56	-	7.7	-	USGS

The acceleration time histories of considered ground motions as well as their corresponding response spectrum with 5% damping ratio are shown in Fig. 2.

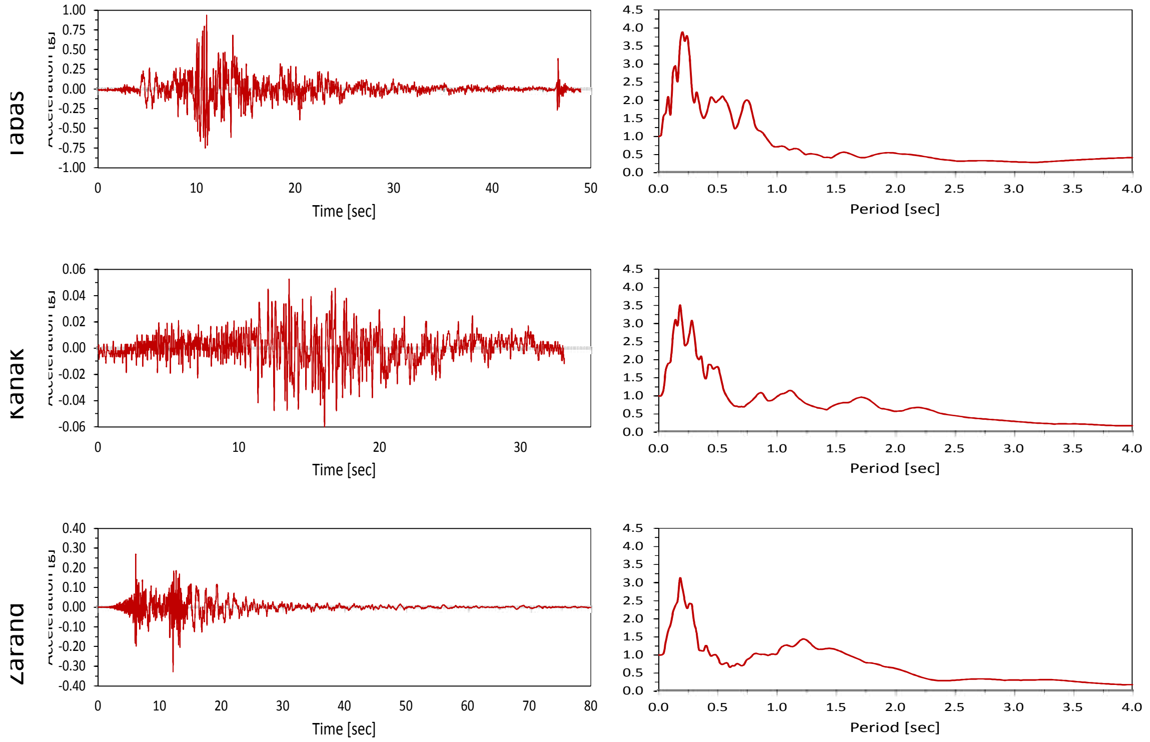
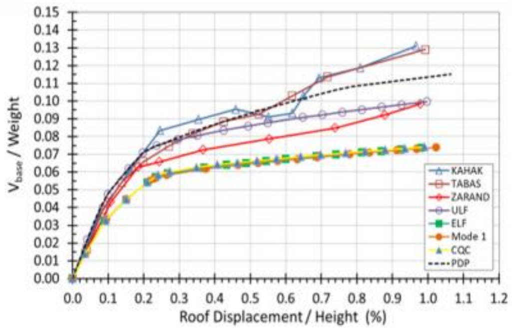


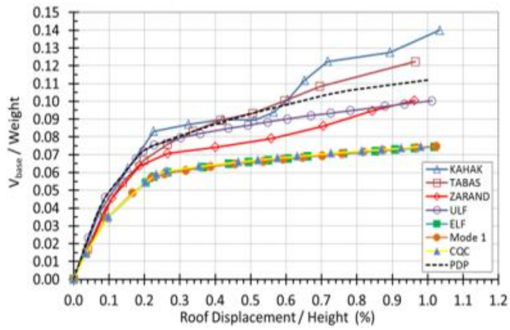
Figure 2. Acceleration time history and response spectrum of earthquakes

RESULTS OF ANALYSES

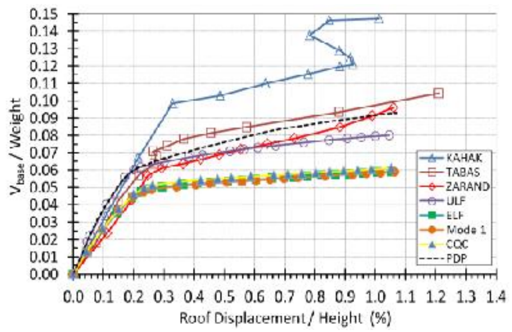
Comparison of results obtained from incremental static and dynamic analyses has been shown in Fig. 3 (in these figures, proposed distribution pattern is shown with PDP). It should be noted that due to high dispersion in the results of time history analyses, the capacity curves were compared up to the vicinity of the target roof displacement.



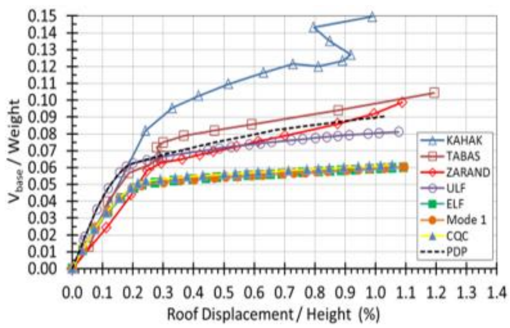
10-story frame with two bays



10-story frame with four bays



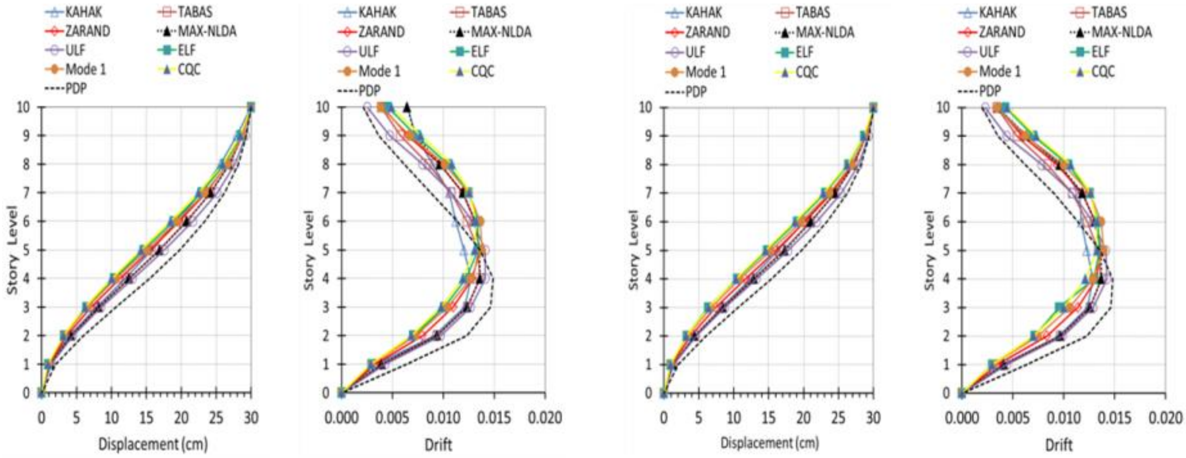
15-story frame with two bays



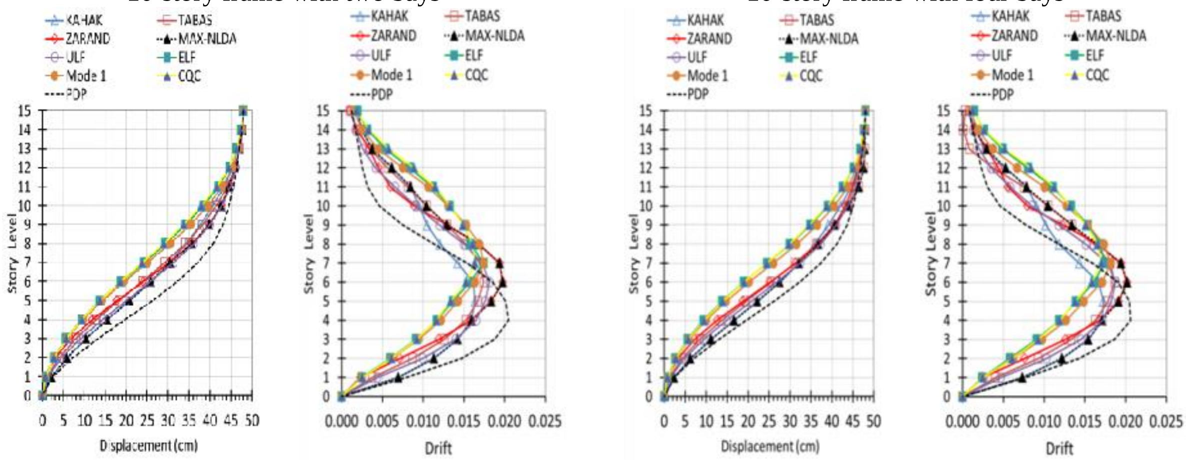
15-story frame with four bays

Figure 3. Comparison of capacity curves of frames

Moreover, Fig. 4 shows the maximum displacement and story drift of the structures (in these figures, maximum response for nonlinear dynamic analysis is shown with MAX NLDA). It should be noted that the values of these quantities are compared when the roof displacement values of the 10- and 15-story frames are 30 and 48 cm, respectively (close proximity to the target displacement).



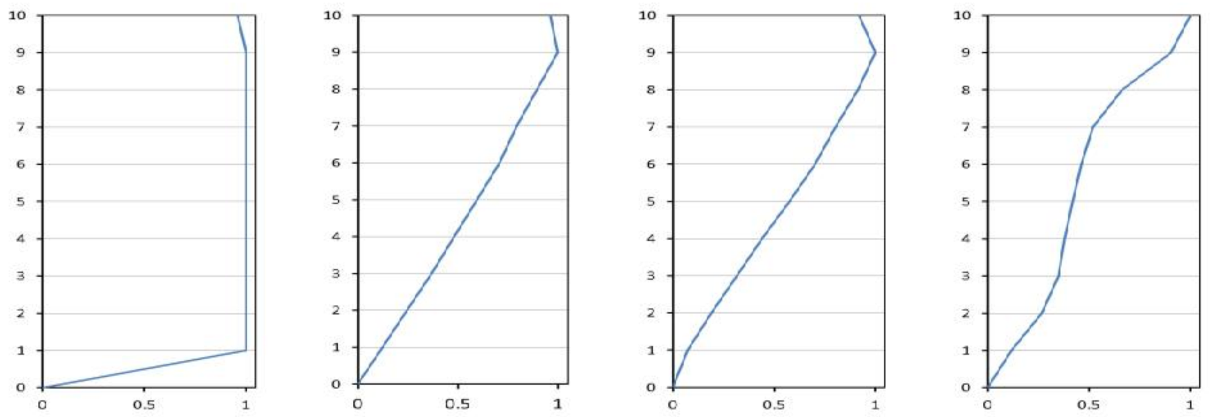
10-story frame with two bays
10-story frame with four bays



15-story frame with two bays
15-story frame with four bays

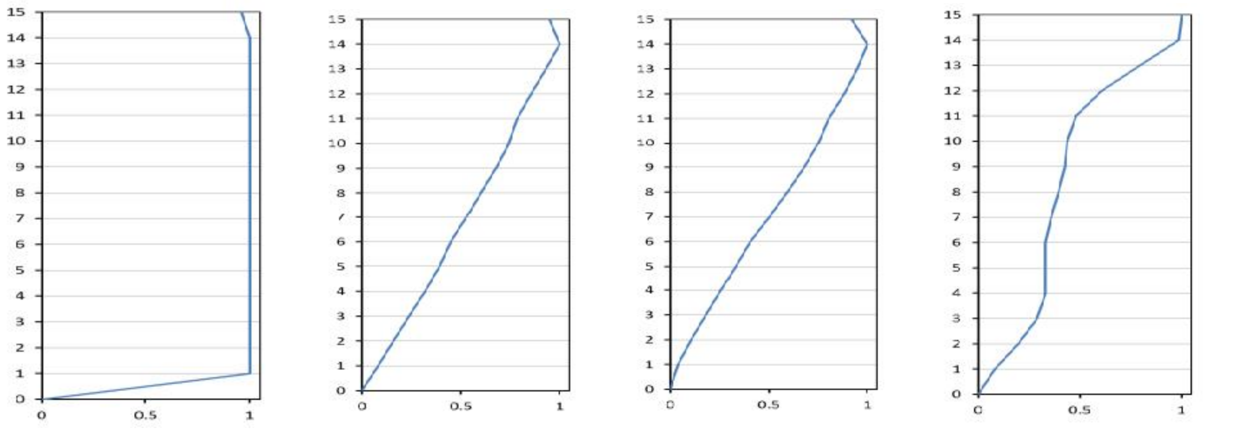
Figure4. Maximum floor displacement and story drift of frames

The common lateral load distribution patterns used in pushover analysis of the structures under study were calculated as shown in Figs. 5 and 6 for structure 10- and 15-story, respectively.



Uniform Pattern (ULF)
Equivalent Pattern (ELF)
First Mode Pattern (Mode 1)
Modal Combination Pattern (CQC)

Figure5. General shape of lateral load distribution patterns employed in 10-story frames



Uniform Pattern (ULF) Equivalent Pattern (ELF) First Mode Pattern (Mode 1) Modal Combination Pattern (CQC)

Figure 6. General shape of lateral load distribution patterns employed in 15-story frames

PROPOSED DISTRIBUTION PATTERN

Regarding the nonlinear static and nonlinear dynamic time history analyses of the reinforced concrete frames under study, it is deduced that in the linear regions of the capacity curve, the response values obtained from pushover analysis of medium-rise frames using common lateral load distribution patterns are remarkably consistent with the responses resulted from nonlinear dynamic time history analyses. In nonlinear regions, however, little consistency is seen due to dynamic effects, particularly the effects of higher modes. In these areas, lateral load distribution is highly disordered and unpredictable, and forces concentrate on a number of stories due to the onset of damage and yield in some structural members.

Concerning the results mentioned above, in the elastic regions of capacity curve of the medium-rise reinforced concrete frames, the uniform force distribution pattern (ULF) is used until the performance point reaches 25% of the target displacement. And then, with the continuing increase in the lateral forces, the load pattern obtained from the combination of the first three modes in proportion to their effective mass (L_n^2 / M_n) is employed, where *Ln* represents the modal participation factor for each mode (Eq. 1). The force distribution pattern derived from the summation of the first three modes and the general shape of proposed load distribution pattern applied to the 10- and 15-story frames are shown in Figs. 7 and 8, respectively.

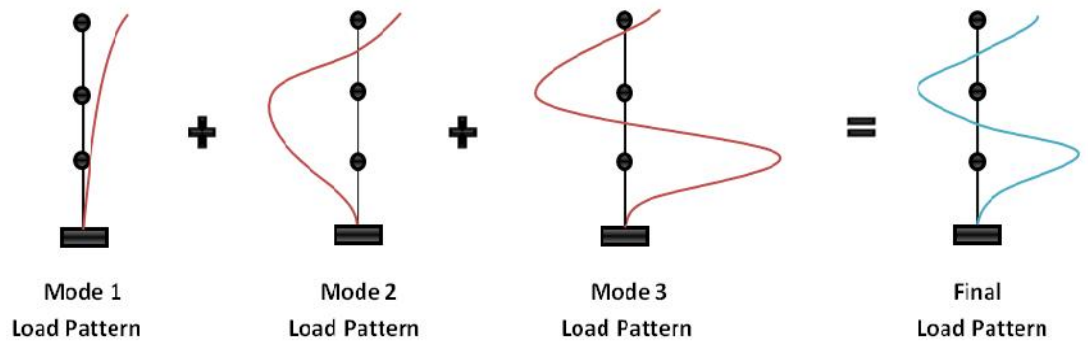
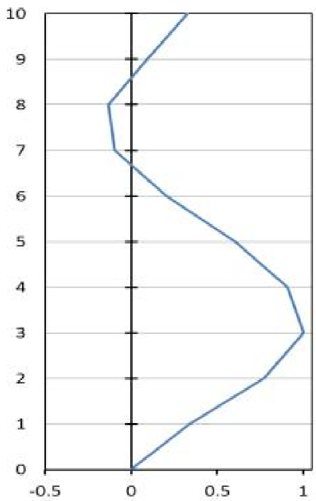
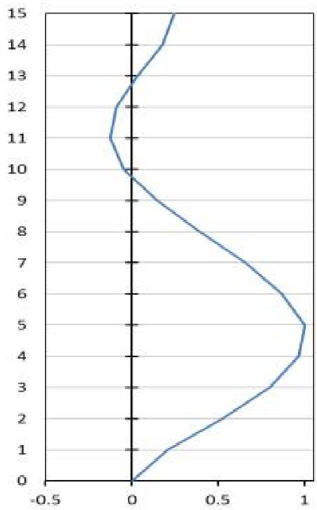


Figure 7. The process of determining the proposed lateral load pattern during nonlinear behavior of the structure

$$\Delta F_i = \left\{\frac{L_1^2}{M_1}\right\} * \Delta F_{1i} + \left\{\frac{L_2^2}{M_2}\right\} * \Delta F_{2i} + \left\{\frac{L_3^2}{M_3}\right\} * \Delta F_{3i} \tag{1}$$



PDP for 10-story structure



PDP for 15-story structure

Figure8. General shape of proposed distribution patterns (PDP) applied to the structures

CONCLUSIONS

Based upon the results obtained from pushover and nonlinear incremental time history analyses of the structures under study, it can be stated that:

- In 10- and 15-story frames, applying uniform or proposed lateral force pattern instead of other patterns leads to a more precise performance for obtaining the overall capacity curve of the building.
- When utilizing at least two different load patterns, response quantities are estimated more accurately. In addition, when uniform force pattern is used as one of the lateral load patterns, more decisive results are produced in general.
- Values of the maximum displacement and story drift obtained through analyses using the proposed load pattern rather than the other patterns seem to be more reliable.
- In general, the number of bays in frames causes insignificant and negligible effect on the results of this research.

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