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EVALUATION OF THE HIGHER MODES CONTRIBUTION IN THE SEISMIC DEMANDS OF BUILDINGS SUBJECTED TO FAR-FIELD AND NEAR-FIELD GROUND MOTIONS

M. H. Vafaee[1] and H. Saffari[1,*]
[1]Department of Civil Engineering, Faculty of Engineering, Shahid Bahonar University of Kerman, Kerman, Iran

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ABSTRACT

Instead of the complicated non-linear response history analysis (NL-RHA), engineers are more likely to use simplified non-linear static procedures (NSPs). Because of various deficiencies of the conventional pushover procedures, different researchers presented advanced NSPs. Some of these advanced NSPs used first two modes of the structure and the others offered using more than first two modes. In this study, the higher mode contributions in the structural responses are investigated through NSPs including modal pushover analysis (MPA) and modal shear-based pushover (MSP) procedures for far-field and near-field ground motions. Finally, the optimized number of considered modes for different situations is suggested.

Keywords: Response history analysis; non-linear static procedure; higher mode effects; modal contribution ratios; far-field ground motion; near-field ground motion.

1. INTRODUCTION

In conventional pushover procedures, the seismic demands are obtained using a non-linear static analysis of the structure subjected to monotonically increasing lateral forces until a predetermined target displacement is reached [1-3]. These procedures have been shown to provide good estimations of the deformation responses when structures are governed primarily by first mode response. To overcome this main drawback of the conventional pushover procedures, various investigations have been made to present NSPs which are capable of taking into account the higher mode effects. In these advanced NSPs, the effects of some limited number of modes were included to retain the simplicity and applicability of the NSP. It is obvious that the more number of the considered modes leads to more computational efforts required and also, reduction of the considered modes increases the

[*]E-mail address of the corresponding author: hsaffari@uk.ac.ir (H. Saffari)

estimation errors. Based on these pointes, the optimized number of considered modes should be introduced to estimate the seismic demand of buildings with acceptable accuracy.

In 2002 Chopra and Goel developed the modal pushover analysis (MPA) which was based on the structural dynamics theory [2]. MPA was a multi-run method in which the number of considered modes has more influences on the required computational efforts. In MPA, first three modes were considered to estimate seismic demands of buildings. Then, some researchers used the MPA method considering up to first five modes for comparison purposes [3-5].

In 2003 Tysh Shang Jan et al. presented the upper-bound (UB) method which contained its specific lateral load pattern [6]. In that investigation, providing higher mode contributions to elastic deformation response, it was concluded that the effects of the modes higher than second one can be neglected. This result was obtained through simulating five elaborately designed buildings (2–30stories) subjected to 13 strong earthquake motions generated by the history records of the Chi-Chi Earthquake. Using first two modes, UB method underestimates the responses at lower stories and overestimates those at upper levels [7-11].

In 2009, Poursha et al. presented the consecutive modal pushover procedure (CMP) [12]. In CMP a single-stage and few multi-stage pushover analyses were performed. In the single-stage pushover analysis, an inverted triangular load pattern (TLP) for medium-rise buildings or a uniform force distribution for high-rise buildings was use. The multi-stage CMP was a consecutive non-linear static analysis using different mode load patterns until the roof reaches predetermined target displacement. In the multi-stage pushover analysis, finishing one step completely, the next step starts with the same initial structural state as the end of the previous stage. The total number of considered modes, in CMP, varied from three to five based on the selected structure fundamental mode period [13].

In 2017, Vafaee and Saffari presented the modal shear-based pushover procedure (MSP) [14]. In MSP the lateral load pattern was calculated by a weighted combination of the considered modes load patterns using modal combination factors based on modal shear portion. First three modes were introduced in MSP as considered modes for all structural models subjected to all ground motion types and intensities.

As mentioned previously, it is clearly accepted by researchers which factors such as the structural height, ground motion type and intensity have an important role in modal contribution ratio in deformation responses [15-19]. In this study, higher mode contributions to elastic deformation response are calculated for a wide range of structural models subjected to selected ground motions. These contribution ratios show the importance of the higher mode effects in seismic demand estimation of a selected structure subjected to a specific ground motion record. Then, these modal contribution ratios are calculated using MSP and on the other hand the errors made due to ignoring 2nd and 3rd modes in a wide range of structural models subjected to various ground motion records are investigated through MPA. Some examples of these wide conducted numerical studies are reported for the potential readers. These made errors in the seismic demands prediction of the buildings because of eliminating the higher modes are calculated in the comparison with NL-RHA as benchmark. The results show that a certain rule cannot be employed to eliminate or including each specific higher mode effect in seismic demands prediction of all structural models. In the other words, the importance of these contributions depends on the fundamental period of the structure and type and intensity of the ground motion used. Finally, the optimized numbers of considered modes based on the structural height and ground motion type are suggested.

2. HIGHER MODE CONTRIBUTIONS

The displacement response contribution of a higher mode compared to the fundamental mode can be expressed as Equation (1) [2]:

$$q_j = \Gamma_j D_j, \tag{1}$$

In which,

$$\Gamma_j = \frac{\Phi_j^T mI}{\Phi_j^T m\Phi_j}. \tag{2}$$

where D_j is the spectral displacement corresponding to the *j*th mode. Φ_j , *m* and *I* are the *j*th eigenvector, floor masses and the unity vector, respectively.

In order to analyze the higher mode contribution to the deformation response, 14 ground motion records including 7 far-field and 7 near-field records were chosen (among a wide number of investigated records) and presented in Tables 1-2. These ground motion records were scaled up to 1g and applied to the analytical models which are created using the open source computer software, OpenSees [20]. 2D models contain three-bay frames with four different heights of 10, 15, 20 and 30 stories. A36 steel is utilized for all considered structural models. The bays lengths are 5 m and similar stories height are equal to 3.2 m. The dead and live loads are equal to 6.63 KN/m^2 and 2.04 KN/m^2, respectively and the loading width is 5 m. The concentrated seismic mass in each floor is calculated through dead load plus 20% of the predefined live load.

Table 1: List of the used far field ground motions

No.	Record Sequence Number (RSN)	Earthquake name	Date	Magnitude	Station name	Component
1	1614	Duzce, Turkey	1999/11/12	7.14	Lamont	E
2	985	Northridge	1994/01/17	6.69	LA - Baldwin Hills	90
3	280	Trinidad, California	1980/11/08	7.2	Rio Dell Overpass, FF	270
4	265	Victoria, Mexico	1980/06/09	6.33	Cerro Prieto	45

5	501	Hollister	1986/01/26	5.45	SAGO South - Surface	295
6	187	Imperial Valley	1979/10/15	6.53	Parachute Test Site	315
7	450	Morgan Hill	1984/04/24	6.19	Corralitos	310

Special steel moment-resisting frame (SMRF) is selected as the lateral load-resisting system of the structures. The structures are located in the region with highest seismicity and on type II firm soil of the Iranian seismic code [21]. Table 3 includes the first three natural vibration

Table 2: List of the used near-field ground motions

No.	Record Sequence Number (RSN)	Earthquake name	Date	Magnitude	Station name	Component
1	253	Mammoth Lakes-07	1980/5/27	4.73	Long Valley Fire Sta	0
2	567	Kalamata Greece-02	1986/9/15	5.4	Messinia - Old Townhall	NS
3	779	Loma Prieta	1989/10/18	6.93	LGPC	0
4	828	Cape Mendocino	1992/4/25	7.01	Petrolia	90
5	901	Big Bear-01	1992/6/28	6.46	Big Bear Lake - Civic Center	90
6	1052	Northridge-01	1994/1/17	6.69	Pacoima Kagel Canyon	360
7	1599	Duzce Turkey	1999/11/12	7.14	Lamont 1058	N

periods of the frames. The strength, dimension and shear distortion of panel zones are neglected and large deformation (P-Δ) effects are considered in non-linear analyses. More information about plastic hinges and member sections is available in references [12-14].

Table 3: Characteristics of the 10, 15, 20 and 30-story buildings

No. of stories	10-Story	15-Story	20-Story	30-Story
Structural height	32	48	64	96
floors Seismic masses (KN /m)	55.48	56.57	57.12	57.63
First mode period (Sec)	1.697	2.338	3.092	3.866
Second mode period (Sec)	0.605	0.854	1.135	1.381
Third mode period (Sec)	0.347	0.493	0.67	0.798

The displacement response contributions of higher modes compared to the fundamental mode are calculated using Equation (1) for considered structural models subjected to various ground motion records. These values are shown in Figs. 1 and 2. As could be expected, an increase in the structural height leads to increase in higher modes contribution rather than fundamental mode [22-25]. For far-field set, the second mode to the first mode contribution ratio varies from 0.169 for 10-story building to 0.3659 for 20-story building. Same manner can be observed in the third mode to the fundamental mode contribution ratio where this ratio varies from 0.0448 for 10-story building to the 0.0959 for 30-story building. Also, for near-field set, the second mode to the first mode contribution ratio varies from 0.1184 for 10-story building to 0.2387 for 30-story building. The values corresponding to third mode contribution ratio to the first one varies from 0.0234 to 0.0976. It is noticeable that in some NSP presentations it is concluded that the first two modes dominate the displacement response and the third or higher modes can be ignored [6]. In such cases if the third mode effects on the structural responses are significant, the obtained results may be far from the exact responses of the NL-RHA [26-27]. Others offered using first three modes (or even more) in all cases which may cause additional and useless computational efforts especially in the case studies where the higher modes have negligible effects on the structural responses. In this investigation an effort is made to realize how many modes should be taken into account in various structures seismic demand estimation to reduce the computational time without losing so much accuracy.

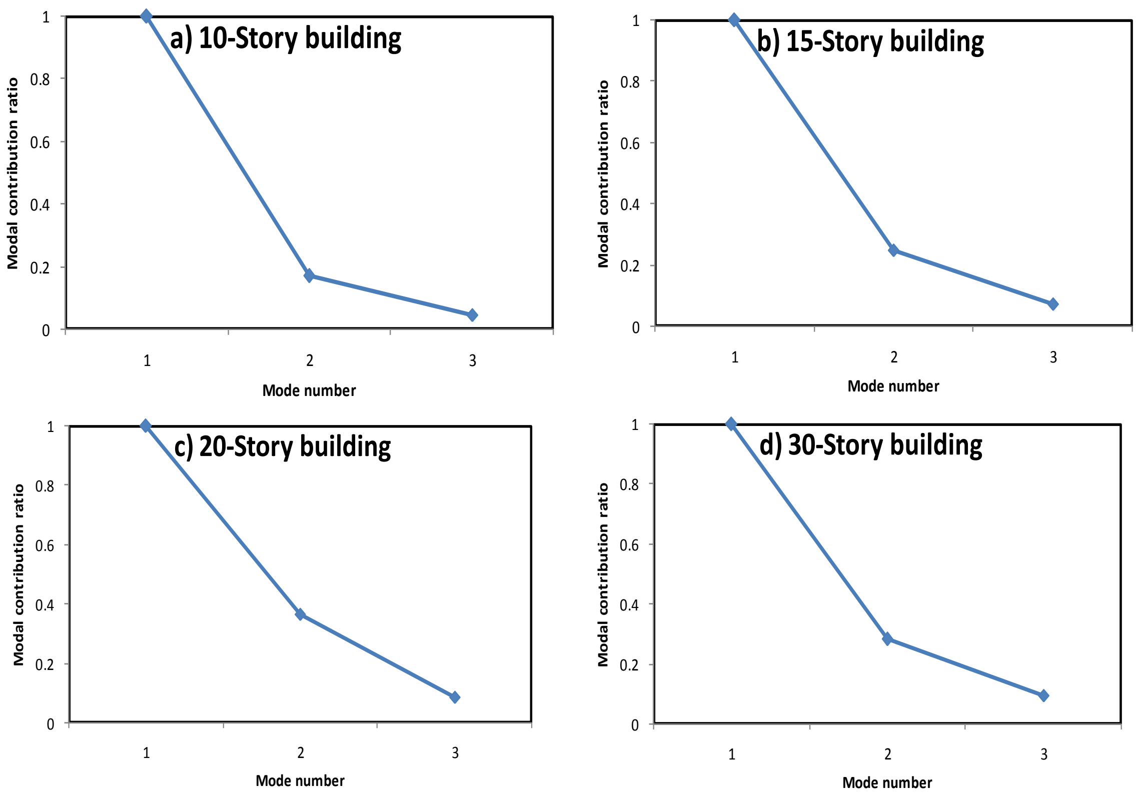


Figure 1. The displacement response contributions of the higher modes compared to the fundamental mode, (q_j/q_1); a) 10-story; b) 15-story building; c) 20-story building and d) 30-story building (Far-field records)

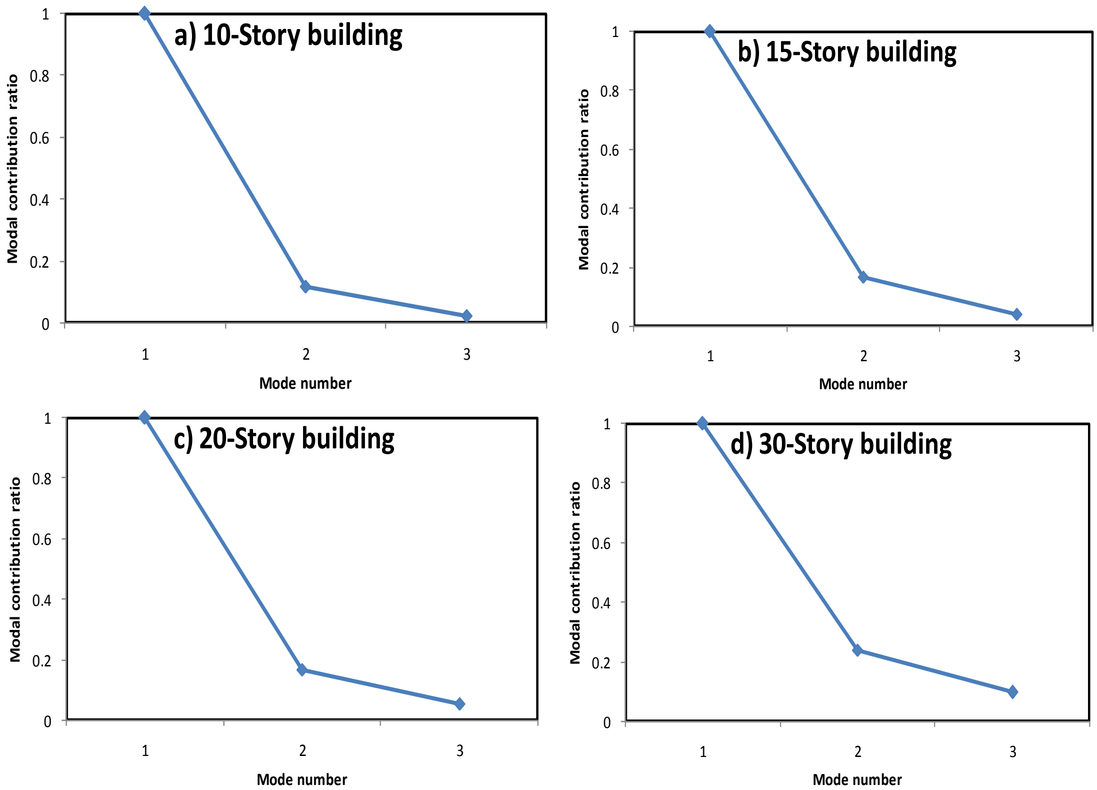


Figure 2. The displacement response contributions of the higher modes compared to the fundamental mode, (q_j/q_1); a) 10-story; b) 15-story building; c) 20-story building and d) 30-story building (Near-field records).

3. MODAL PUSHOVER ANALYSIS (MPA) AND MODAL SHEAR-BASED PUSHOVER (MSP) PROCEDURE

In this investigation to estimate the modal contribution ratios of the higher modes in seismic responses of the structures MPA and MSP procedures are employed.

3.1 Modal pushover analysis (MPA)

Chopra and Goel first developed the modal pushover analysis (MPA) in 2002 [2]. This method was based on structural dynamics theory and the conceptual simplicity and computational attractiveness were its salient features. The main steps of MPA can be summarized as follows:

(a) Calculating the natural frequencies, ω_j, and the mode-shapes, Φ_j.

(b) Developing the base shear-roof displacement (V_{bj}-u_{rj})) pushover curve for the force distribution formulated in Equation (3).

$$F_j = m\Phi_j \tag{3}$$

(c) Idealizing the pushover curve as a bilinear curve, using the procedure described in reference [2].

(d) Developing the $\frac{F_{sj}}{L_j} - D_j$ relation as mentioned in reference [2].

(e) Solving Equation (4) for the peak deformation of the first mode inelastic SDOF system with unit mass and force-deformation relation developed in step (d).

$$\ddot{D}_j + 2\zeta_j\omega_j\dot{D}_j + \frac{F_{sj}}{L_j} = \ddot{u}_g(t). \tag{4}$$

(f) Calculating the peak roof displacement using Equation (5).

$$u_{rjo} = \Gamma_j\Phi_{rj}D_j \tag{5}$$

where Φ_{rj} is the mode shape component in the roof, and D_j is calculated in step (e). It is noticeable that in this research the MPA is performed using first three modes, therefore, the steps (b) to (f) should be repeated for all of the considered modes.

(g) Computing the total response combining the peak modal responses using SRSS.

This method presents an accurate contribution ratio for each considered mode so in this study is used to compare with robust NL-RHA to optimize the total number of considered modes in NSPs.

3.2 Modal shear-based pushover (MSP) procedure

Another NSP which is used to obtain the approximate contribution ratio of the considered modes in seismic responses of the structures is the MSP. MSP was developed by Vafaee and Safarri in 2017 [14]. The main steps of the MSP are as follows:

Finding the natural frequencies, ω_j, and mode shapes, Φ_j, for the selected building and normalizing the mode shapes so that $\Phi_{rj} = 1$. Φ_{rj} would be the normalized roof lateral component of *jth* mode shape.

Computing *jth* mode force vectors, $m\Phi_j$, for sufficient number of modes and in different levels.

Determining the target displacement. The MSP target displacement can be obtained from Equation (6):

$$\delta_{t,MSP} = \Gamma_1\Phi_{r1}D_1 \tag{6}$$

Which is the peak value of the roof displacement due to the first mode. Φ_{r1} is the first mode component in the roof.

(a) Calculating the shear portion for each mode using Equation (7).

$$\eta_j = \frac{V_j}{\upsilon_j}. \tag{7}$$

where V_j is the modal shear base and υ_j can be formulated as Equation (8).

$$\upsilon_j = \sum_{i=1}^{K} m_i \left|\Phi_{ij}\right|. \tag{8}$$

Running a non-linear static analysis of the structure subjected to the lateral load pattern presented in Equation (9) to reach the target displacement obtained from step (c).

$$F_i = \sum_{j=1}^{N} \eta_j \left[m_i \Phi_{ij} \right], \tag{9}$$

(b) Performing a parallel pushover analysis using a triangular load pattern for structural models if the fundamental period is less than 2.2s, in order to avoid underestimating the responses at lower stories. Moreover, an additional pushover analysis using uniform force distribution may be conducted if the fundamental period is more than 2.2s until the control node reaches target displacement in Equation (6).

(c) Calculating the envelope of the peak responses obtained from steps (e) and (f).

Similar to MPA, this method is able to predict modal contribution ratios with acceptable accuracy and in this investigation is used to achieve the purposes.

4. NUMERICAL STUDIES

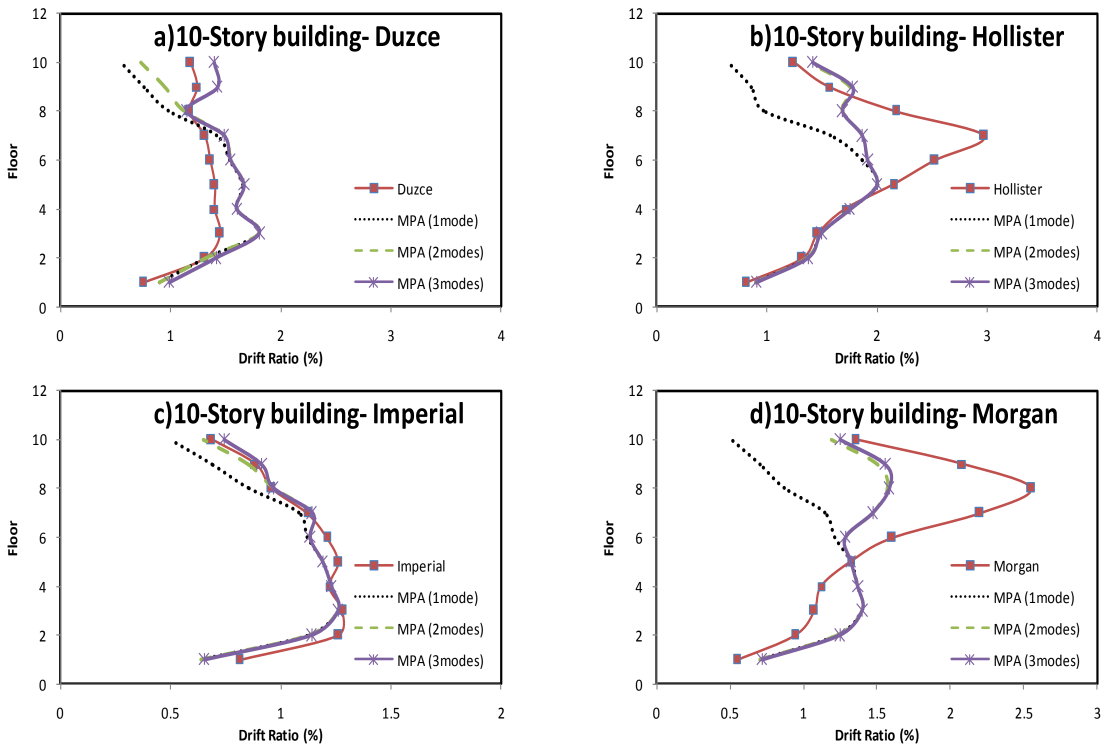
In order to investigate the contribution of the higher modes in seismic demand prediction of the structures subjected to different ground motions, structural models of 2D buildings are simulated in OpenSees computer software. As mentioned before, these structural models are subjected to different ground motion records and analyzed using MPA and also NL-RHA as benchmark. MPA is performed using first three modes, first two modes and first mode and the obtained results are compared with those of NL-RHA to realize the importance of each mode in seismic demands prediction. Also the contribution ratio of the higher modes to the fundamental mode is provided using MSP. Each NSP error in estimating drift ratios is calculated through Equation (10).

$$Error_{\Delta} = 100 \frac{\Delta_{i\ NL\ RHA} - \Delta_{i\ NSP}}{\Delta_{i\ NL\ RHA}} \tag{10}$$

where $\Delta_{i\ NL\ RHA}$ is the peak inter-story drift at ith level obtained from the NL-RHA and $\Delta_{i\ NSP}$ is the corresponding inter-story drift of the NSP.

Fig. 3 shows the inter-story drift ratios obtained from MPA using different number of modes in addition to the NL-RHA results for 10-story model subjected to some selected far-field ground motion records (the reported numerical studies in this section are examples of wide numerical studies investigated). As can be seen from this figure, in such structural heights (fundamental periods) and subjected to far-field ground motions, in general, the first two modes dominate the responses and the third mode has no meaningful effect on the seismic demands. So, in different NSPs, in such structural fundamental period and subjected to far-field ground motion the third mode effects can be ignored to reduce the computational efforts without losing so much accuracy.

Table 4 includes the average error of MPA procedure (considering different number of modes) obtained using Equation (10) which explains the mentioned point more clearly.



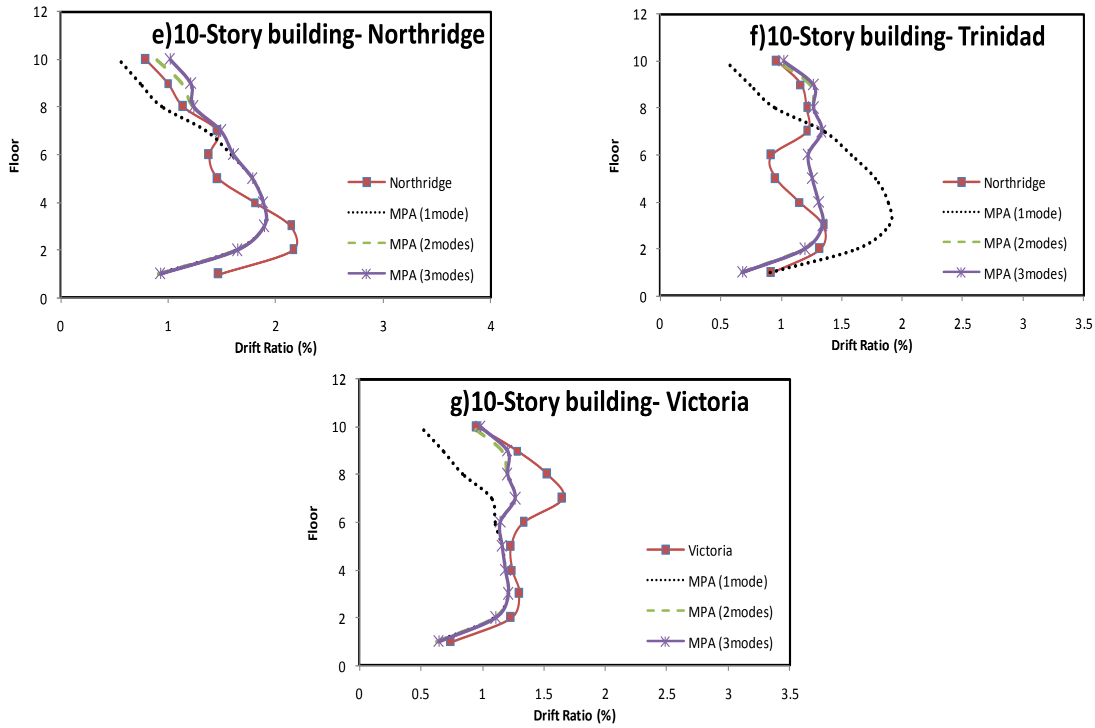


Figure 3. Story drift ratios obtained from MPA and NL-RHA for the 10-story building subjected to far-field ground motions. (a) Duzce; (b) Hollister; (c) Imperial Valley; (d) Morgan Hill; (e) Northridge; (f) Trinidad and (g) Victoria

Table 4: Average error (%) in predicting story drift ratios of 10-story building subjected to far-field ground motions using MPA and with different number of modes

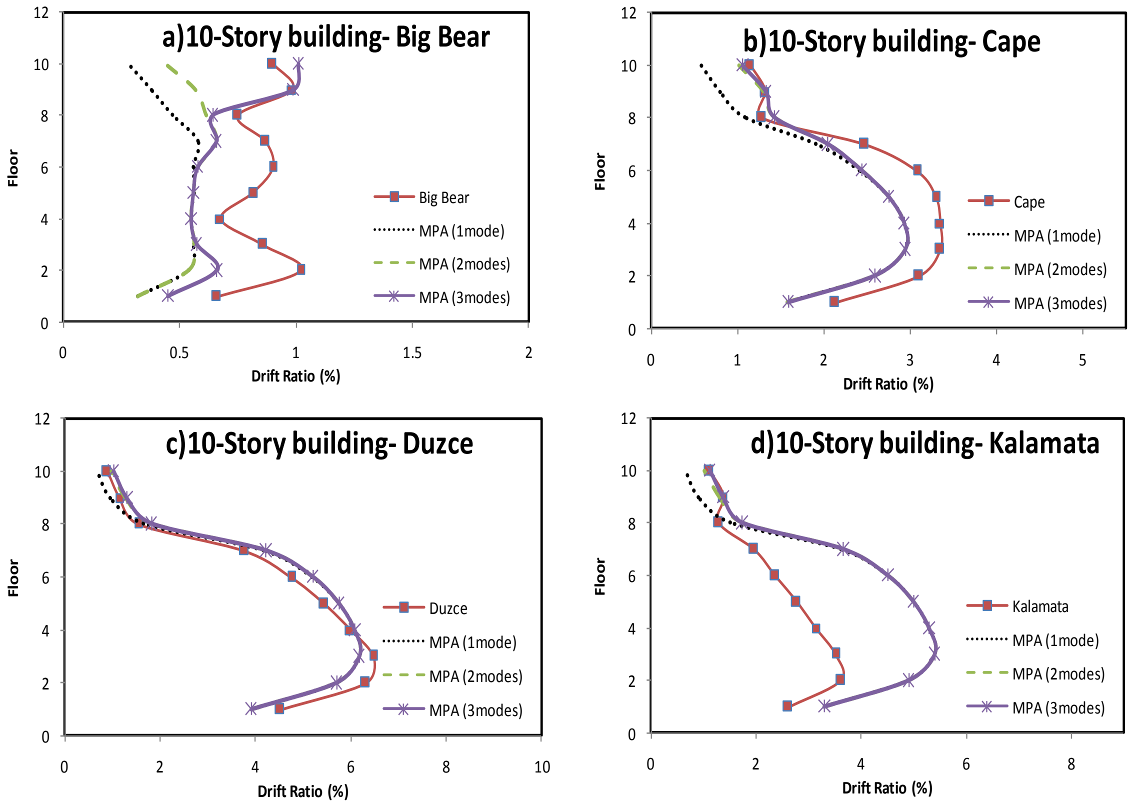
	Number of used modes in MPA		
Ground motion	1 mode	2 modes	3modes
Duzce	20.8	17.3	15.9
Hollister	24.8	13.5	14
Imperial Valley	11	5.7	5.8
Morgan Hill	37.9	24.4	24.11
Northridge	19.7	15.27	17.65
Trinidad	23.5	13.83	14.45
Victoria	23.4	11.3	10.8
Average	23	14.47	14.67

According to the errors reported in Table 4, using first two modes in the considered NSP is required since these modes have outstanding portions in the structural responses. Same point can be realized using other employed NSP (MSP). Table 5 shows the modal contribution factors obtained for first three modes in seismic demand of the 10-story building using MSP. The results show that in this case the third mode effects can be ignored to reduce the computational efforts.

Table 5: Modal contribution factors based on MSP for first three modes (10-story building subjected to far-field records)

	Modal contribution factor based on MSP		
Ground motion	1st mode	2nd mode	3rd mode
Duzce	28.9	7.1	13.9
Hollister	33.07	19.67	3.62
Imperial Valley	18.19	6.34	4.2
Morgan Hill	19.84	16.88	5.21
Northridge	25.63	10.66	5.59
Trinidad	19.02	12.82	3.61
Victoria	18.19	11.67	3.9
Average	23.22	10.73	5.71
Normalized Mean	1	0.46	0.24

Fig. 4. Shows the story drift ratios obtained from the MPA using different number of modes and NL-RHA for 10–story building subjected to near-field records.



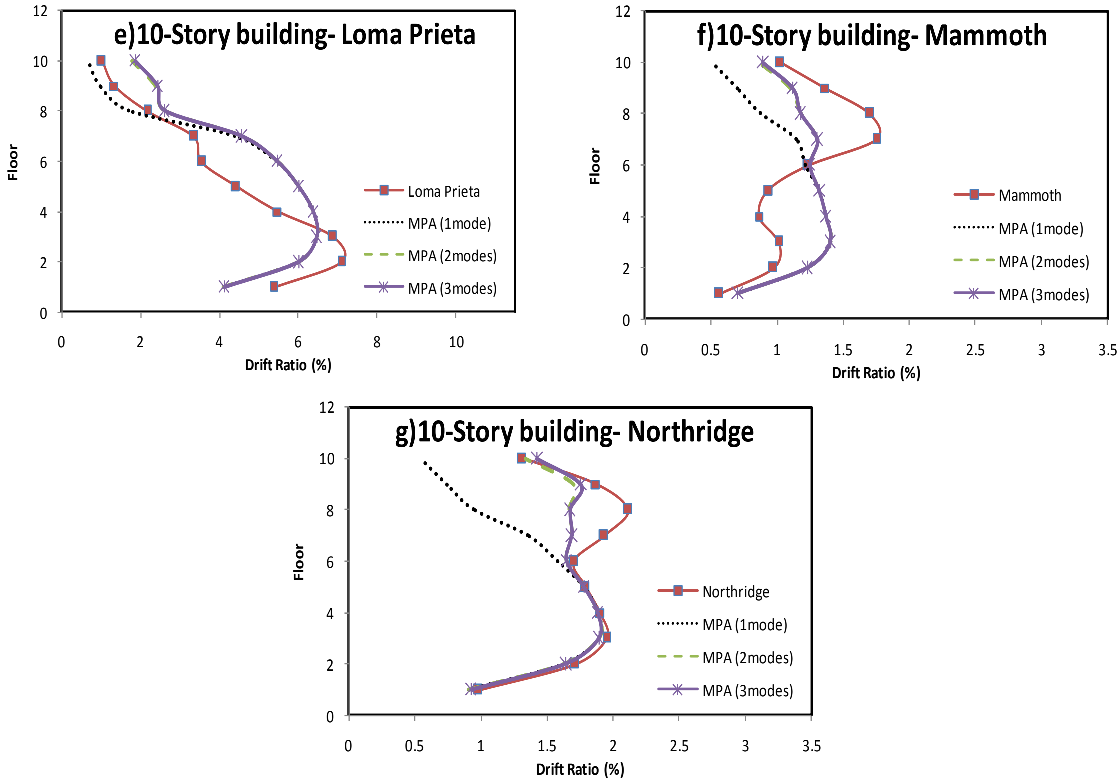


Figure 4. Story drift ratios obtained from MPA and NL-RHA for the 10-story building subjected to near-field ground motions. (a) Big Bear; (b) Cape Mendocino; (c) Duzce; (d) Kalamata; (e) Loma Prieta; (f) Mammoth and (g) Northridge

Also Table 6 includes the mean error (%) obtained in drift ratio prediction of 10-story building subjected to different near-field ground motions. As outlined before, the MPA is conducted using different number of modes to investigate each mode importance in obtained results.

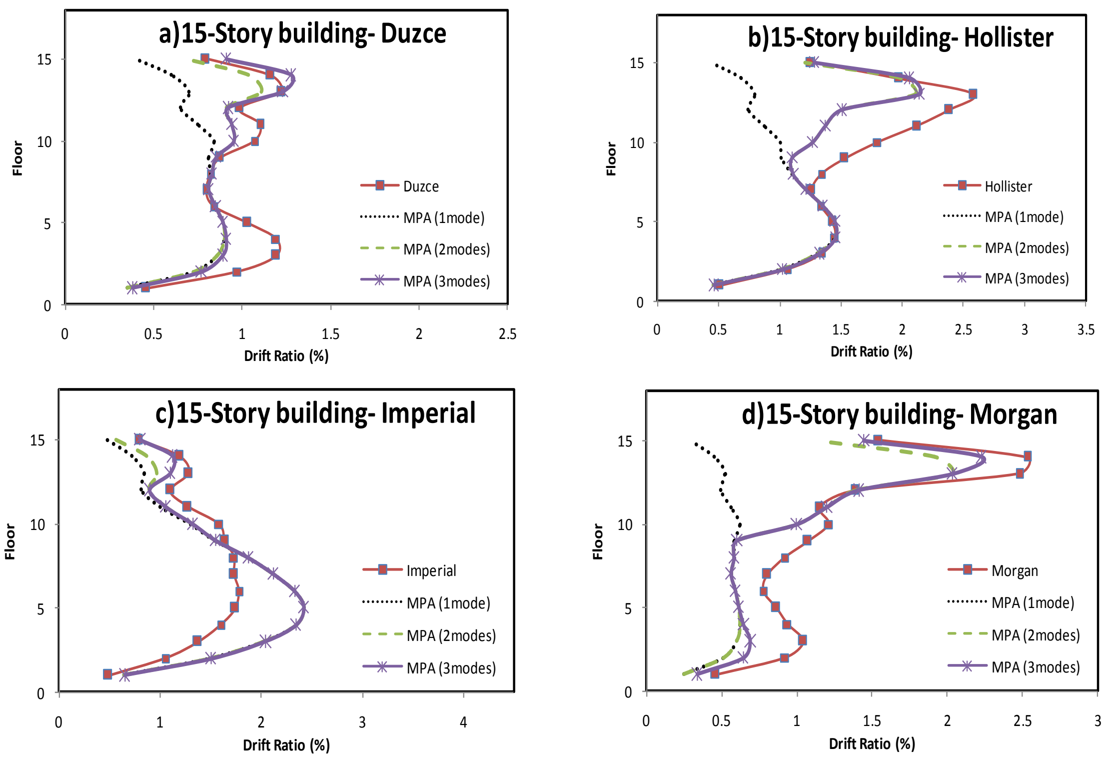
Table 6: Average error (%) in predicting story drift ratios of 10-story building subjected to near-field ground motions using MPA

	Number of used modes in MPA		
Ground motion	1 mode	2 modes	3modes
Big Bear	42.1	35.4	23.7
Cape Mendocino	23.2	14.6	13.6
Duzce	10.9	9.8	10.0
Kalamata	53.9	46.2	47.1
Loma Prieta	37.4	36.4	26.4
Mammoth	37.4	28.2	27.5
Northridge	22.8	6.4	6.5
Average	27.18	24.02	22.11

Table 7 contains the modal contribution factors based on MSP which show the importance of the considered mode in the seismic demand prediction. According to this table, in the near-field records, 3rd mode has more influence on the responses rather than far-field records (compare the portion of the normalized mean for 2nd and 3rd modes in Table 7) although for the 10-story building still 3rd mode effect can be ignored.

Table 7: Modal contribution factors based on MSP for first three modes (10-story building subjected to near-field records)

	Modal contribution factor based on MSP		
Ground motion	1st mode	2nd mode	3rd mode
Big Bear	9.09	5.33	13.43
Cape Mendocino	37.2	25.1	7.1
Duzce	77.73	9.13	8.64
Kalamata	67.8	11.8	9.06
Loma Prieta	81.87	29.83	7.67
Mammoth	14.88	10.5	6.6
Northridge	25.63	21.83	8.5
Average	44.88	16.21	8.71
Normalized Mean	1	0.36	0.194



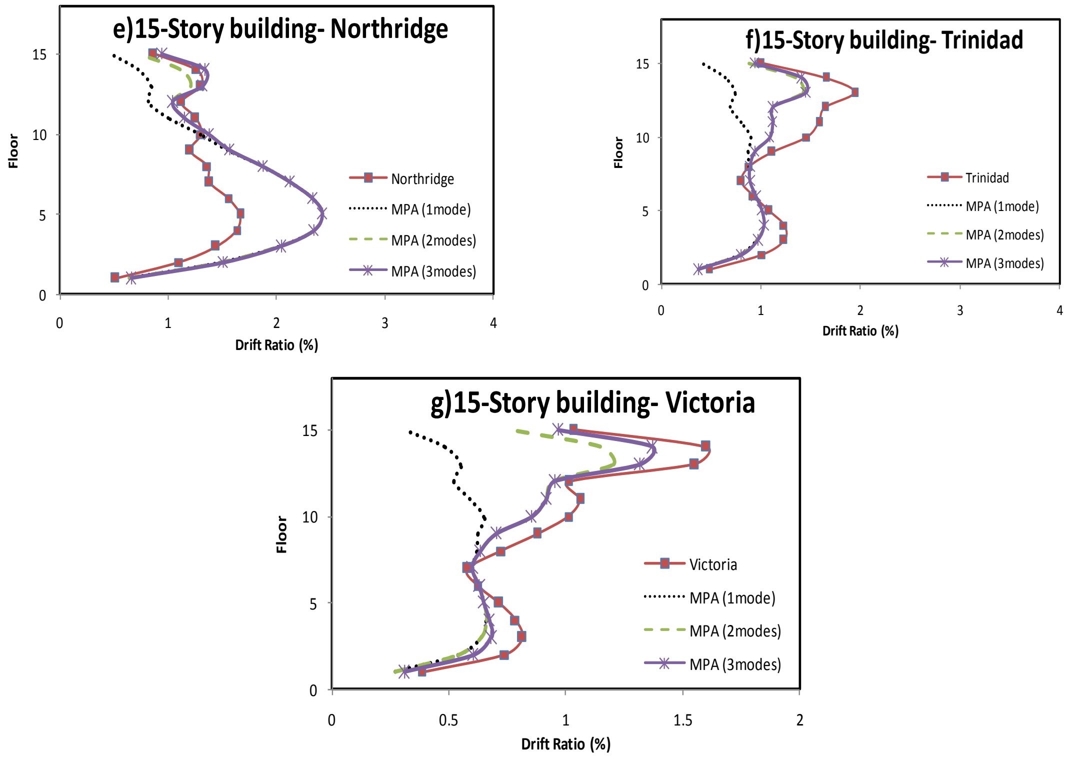


Figure 5. Story drift ratios obtained from MPA and NL-RHA for the 15-story building subjected to far-field ground motions. (a) Duzce; (b) Hollister; (c) Imperial Valley; (d) Morgan Hill; (e) Northridge; (f) Trinidad and (g) Victoria

Fig. 5. shows the story drift ratios obtained from MPA and also NL-RHA for 15-story building subjected to far-field ground motion records. According to this figure, it can be clearly understood that still in this fundamental period the third mode effects can be neglictable.

Table 8: Average error (%) in predicting story drift ratios of 15-story building subjected to far-field ground motions using MPA and with different number of modes

	Number of used modes in MPA		
Ground motion	1 mode	2 modes	3modes
Duzce	23.5	12.5	10.9
Hollister	29.9	13	12.74
Imperial Valley	30.1	27	23.5
Morgan Hill	49.2	28.1	23
Northridge	35.4	27.9	27.1
Trinidad	30.2	17.6	16.8
Victoria	32.1	16.7	12.3
Average	32.91	20.4	18.04

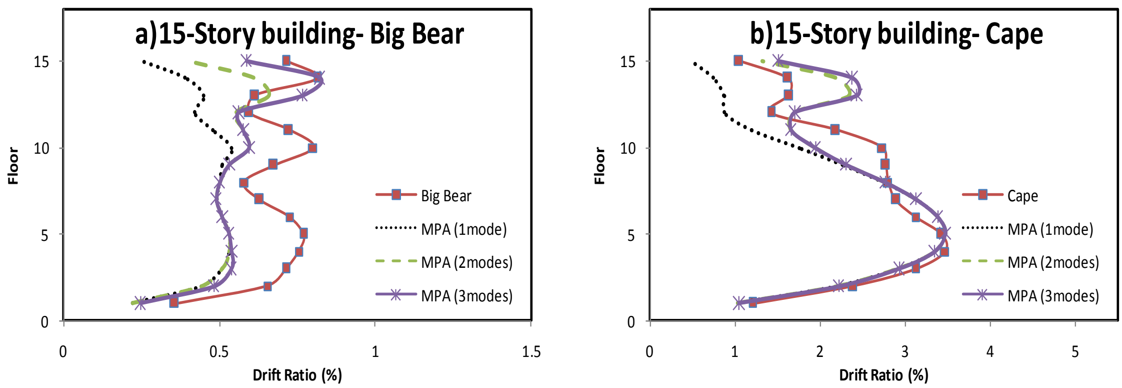
Table 8 includes the average errors obtained by MPA in predicting drift ratios of the 15-story building subjected to far-field ground motions. Noting to the values reported in this table, it is clear that an increase in the structural height leads to higher mode effects increment but in the case of 15-story building subjected to far-field ground motion another time the third mode effect can be neglected.

Using MSP method to investigate the 2nd and 3rd modes contributions leads to same findings. Table 9 consists of the modal contribution factors obtained for the first three modes of the 15-story building subjected to far-field ground motion records.

Table 9: Modal contribution factors based on MSP for first three modes (15-story building subjected to far-field records)

	Modal contribution factor based on MSP		
Ground motion	1st mode	2nd mode	3rd mode
Duzce	11	7.3	5.56
Hollister	15.28	16.72	4.03
Imperial Valley	22.07	4.07	5.33
Morgan Hill	7.64	16.7	8.58
Northridge	24.62	7.44	5.46
Trinidad	11.88	10.25	3.06
Victoria	8.49	8.99	5.42
Average	14.42	10.21	5.34
Normalized Mean	1	0.7	0.37

Fig. 6 shows the story drift ratios of the 15-story building subjected to near-field records. According to this figure the effects of the 3rd mode are increasing in the structure subjected to near-field records rather than far-field ones.



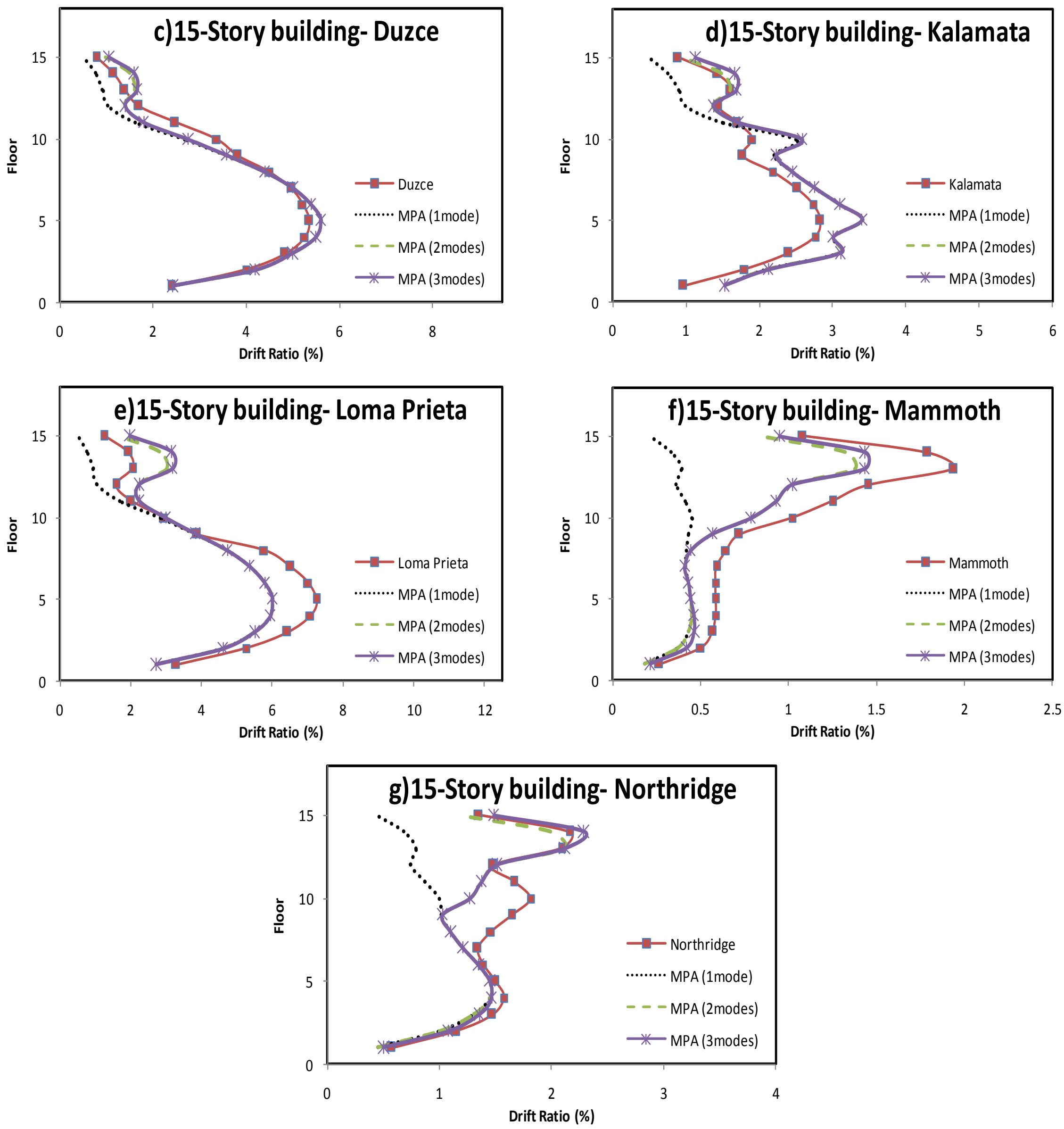


Figure 6. Story drift ratios obtained from MPA and NL-RHA for the 15-story building subjected to near-field ground motions. a) Big Bear; b) Cape Mendocino; c) Duzce; d) Kalamata; e) Loma Prieta; f)Mammoth and g) Northridge.

Table 10 includes the mean error (%) obtained in drift ratios prediction of 15-story building subjected to different near-field ground motions. According to this table, the effects of the 3rd mode consideration in error reduction increases in this case rather than 10-story building subjected to near-field and also 15-story building subjected to far-field ground motion records.

Table 10: Average error (%) in predicting story drift ratios of 15-story building subjected to near-field ground motions using MPA

	Number of used modes in MPA		
Ground motion	1 mode	2 modes	3 modes
Big Bear	32.5	25	20.5
Cape Mendocino	22.98	16.4	17.1
Duzce	15.4	10.9	10.95
Kalamata	26.8	16.7	17.2
Loma Prieta	24.2	20.6	21.11
Mammoth	46.7	28.3	22
Northridge	31.5	14.45	10.8
Average	28.58	18.9	16.95

Table 11 includes the contribution factor for each mode and for the 15-story building subjected to near-field ground motion records obtained from MSP.

Table 11: Modal contribution factors based on MSP for first three modes (15-story building subjected to near-field records)

	Modal contribution factor based on MSP		
Ground motion	1st mode	2nd mode	3rd mode
Big Bear	6.79	4.2	3.6
Cape Mendocino	30.5	18.2	6.95
Duzce	49.25	11.24	4.36
Kalamata	45.84	11.52	5.7
Loma Prieta	52.65	26.13	11.36
Mammoth	5.94	11.24	3.4
Northridge	15.28	16.86	8.77
Average	29.46	14.19	6.3
Normalized Mean	1	0.48	0.21

Based on Fig. 6 and Tables 10 and 11 the third mode effects for the 15-story building subjected to near-field ground motion can be ignored to reduce the NSP computational efforts.

Fig. 7 shows the story drift ratios obtained from the MPA and NL-RHA for the 20-story building subjected to far-field ground motion records.

The errors made by MPA using different number of modes are included in Table 12. These values are obtained for 20-story building subjected to far-field ground motion records.

The contribution of different modes in the responses of the 20-story building subjected to far-field ground motion can be calculated using MSP method. These values are provided in Table 13.

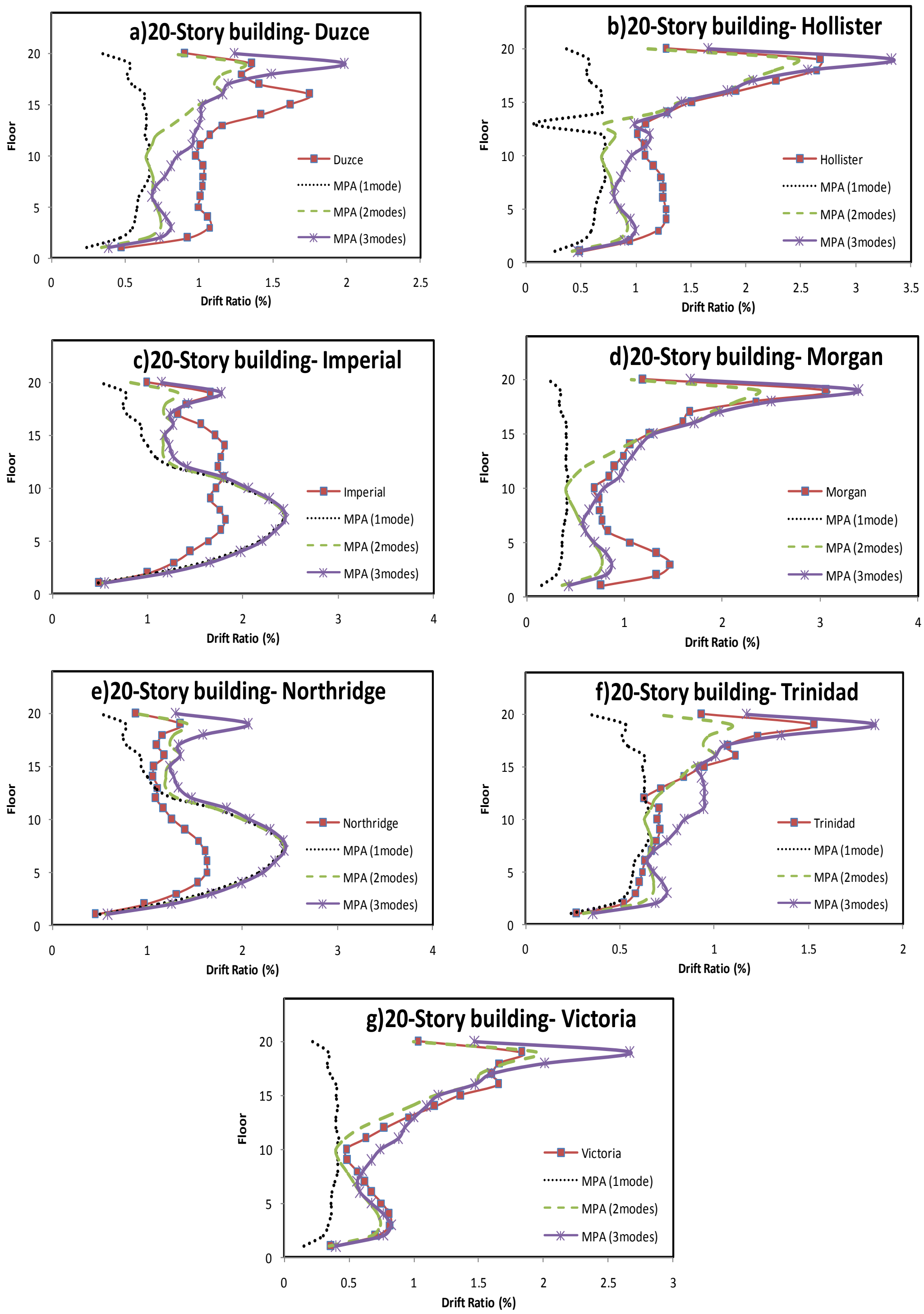


Figure 7. Story drift ratios obtained from MPA and NL-RHA for the 20-story building subjected to far-field ground motions. a) Duzce; b) Hollister; c) Imperial Valley; d) Morgan Hill; e) Northridge; f) Trinidad and g) Victoria

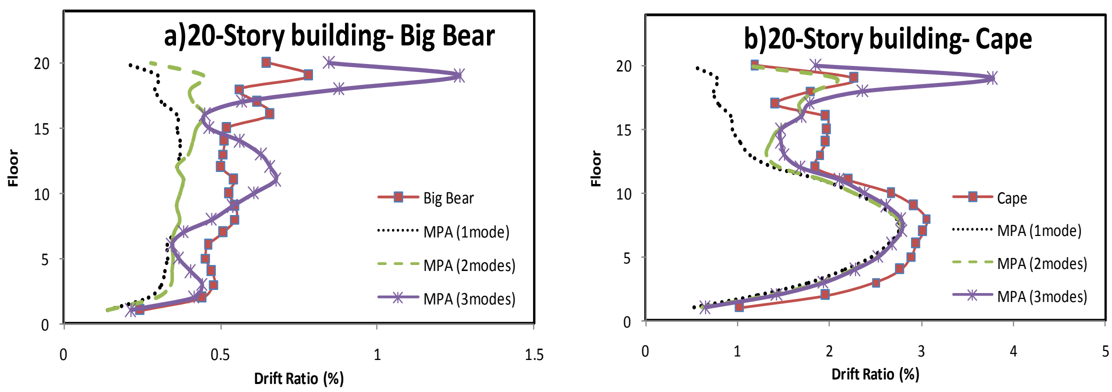
Table 12: Average error (%) in predicting story drift ratios of 20-story building subjected to far-field ground motions using MPA

	Number of used modes in MPA		
Ground motion	1 mode	2 modes	3 modes
Duzce	48.1	28	24.2
Hollister	54.02	22	15.3
Imperial Valley	32.3	24.5	22.7
Morgan Hill	65.6	28.1	20.7
Northridge	37.8	27.7	29.7
Trinidad	22.13	10.7	16.2
Victoria	54.5	12	16.2
Average	44.92	21.85	20.71

Table 13: Modal contribution factors based on MSP for first three modes (20-story building subjected to far-field records)

	Modal contribution factor based on MSP		
Ground motion	1st mode	2nd mode	3rd mode
Duzce	8.66	7.59	2.67
Hollister	6.93	14.86	4.91
Imperial Valley	15.59	6.62	2
Morgan Hill	3.46	14.37	5.56
Northridge	16.46	7.43	2.76
Trinidad	6.06	5.97	3.02
Victoria	3.46	11.79	3.5
Average	8.66	9.8	3.49
Normalized Mean	1	1.13	0.4

The effects of the higher modes especially for 2^{nd} mode increases with the structural height and subjected to far-field ground motion records. Shown in Fig. 8 are the story drift ratios obtained by MPA (considering different number of modes) for the 20-story building subjected to near-field ground motion records.



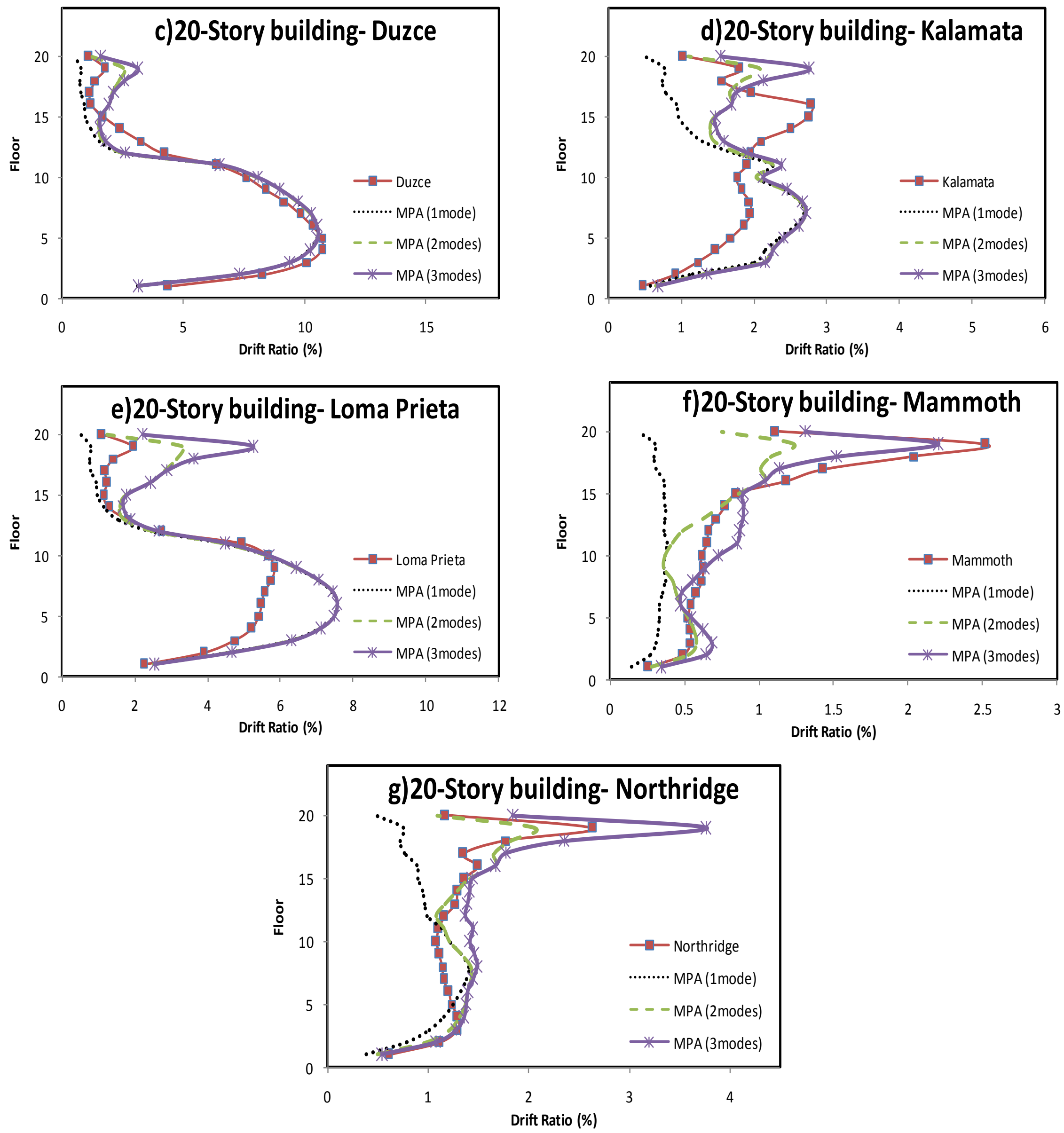


Figure 8. Story drift ratios obtained from MPA and NL-RHA for the 20-story building subjected to near-field ground motions. a) Big Bear; b) Cape Mendocino; c) Duzce; d) Kalamata; e) Loma Prieta; f)Mammoth and g) Northridge

Table 14 includes the average errors of MPA in predicting drift ratios of 20-story building subjected to near-field ground motion records.

According to Table 14, in general, taking into account the third mode effects reduces the error in seismic demand prediction by 3.21% which is 23.6% of the second mode. In another words, the third mode effects in the high-rise structures subjected to near-field ground motion should be considered. It is noticeable that these case studies are only some examples and results from wide numerical studies prove the effect of the structural height and type of ground motion record (especially in the case of near-field ground motions) on the higher modes contribution ratios. Table 15 includes the modal contribution factors based on MSP for first three modes of the 20-story building subjected to near-field ground motions which approves the mentioned point.

Table 14: Average error (%) in predicting story drift ratios of 20-story building subjected to near-field ground motions using MPA.

	Number of used modes in MPA		
Ground motion	1 mode	2 modes	3 modes
Big Bear	37.5	30.9	21.4
Cape Mendocino	33.4	17.7	20.1
Duzce	28.2	23.9	23.8
Kalamata	42	33.02	35.5
Loma Prieta	51.2	39.2	26
Mammoth	52.9	21.4	13.9
Northridge	27.9	11.8	14.7
Average	39.01	25.41	22.2

Table 15: Modal contribution factors based on MSP for first three modes (20-story building subjected to near-field records)

	Modal contribution factor based on MSP		
Ground motion	1st mode	2nd mode	3^{rd} mode
Big Bear	3.46	2.09	1.92
Cape Mendocino	17.33	13.24	8.77
Duzce	59.79	15.5	3.95
Kalamata	22.53	11.63	3.5
Loma Prieta	49.39	20.67	11.62
Mammoth	3.46	7.43	4
Northridge	11.26	12.27	7.36
Average	23.88	11.83	5.87
Normalized Mean	1	0.49	0.25

As the last structural model, 30-story building is analyzed subjected to both far and near-field ground motions. Figs. 9 and 10 show the story drift ratios of the 30-story building subjected to far and near-field records, respectively. These values are obtained by MPA and NL-RHA.

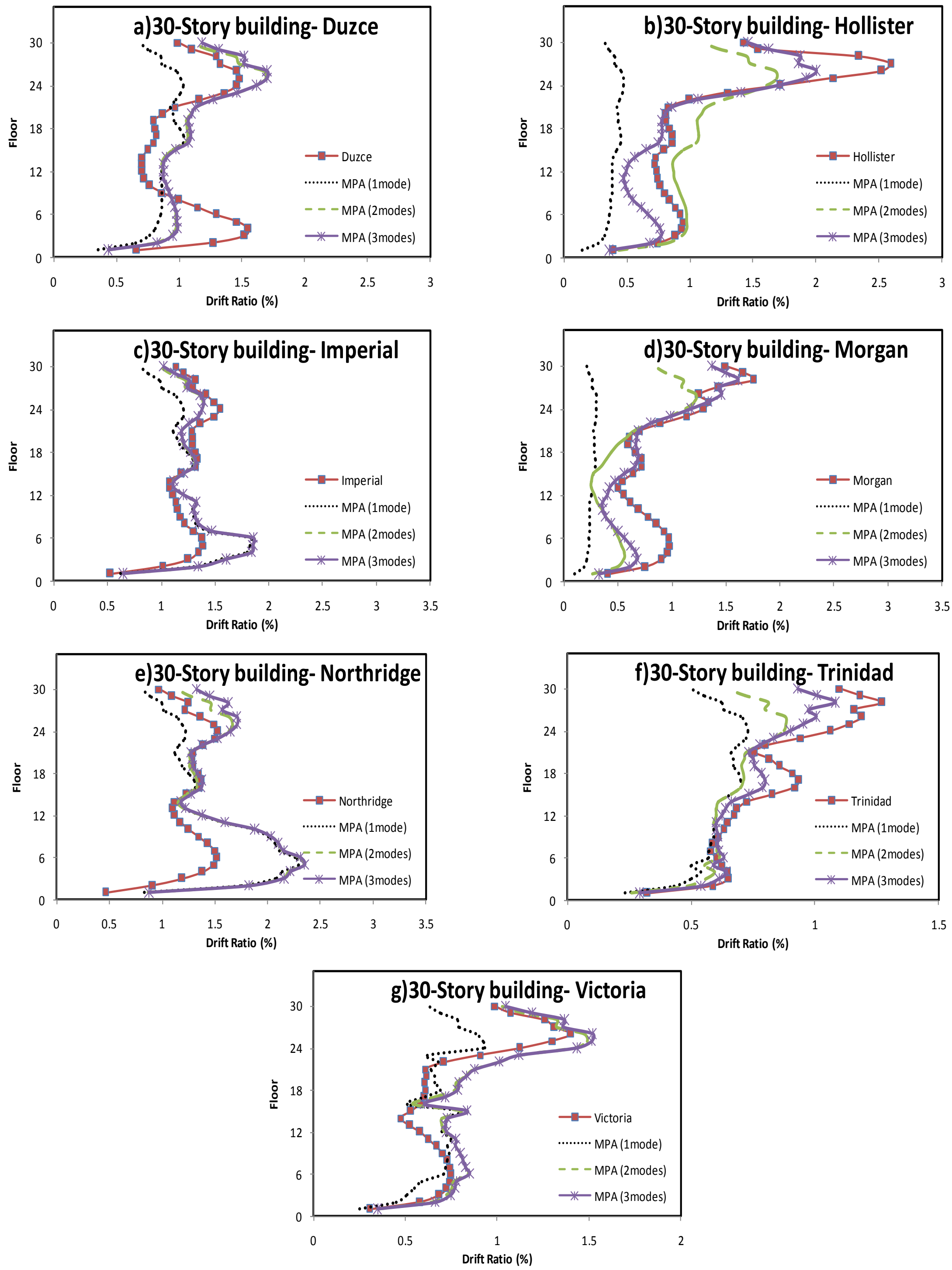


Figure 9. Story drift ratios obtained from MPA and NL-RHA for the 30-story building subjected to far-field ground motions. (a) Duzce; (b) Hollister; (c)Imperial Valley; (d) Morgan Hill; (e) Northridge; (f) Trinidad and (g) Victoria

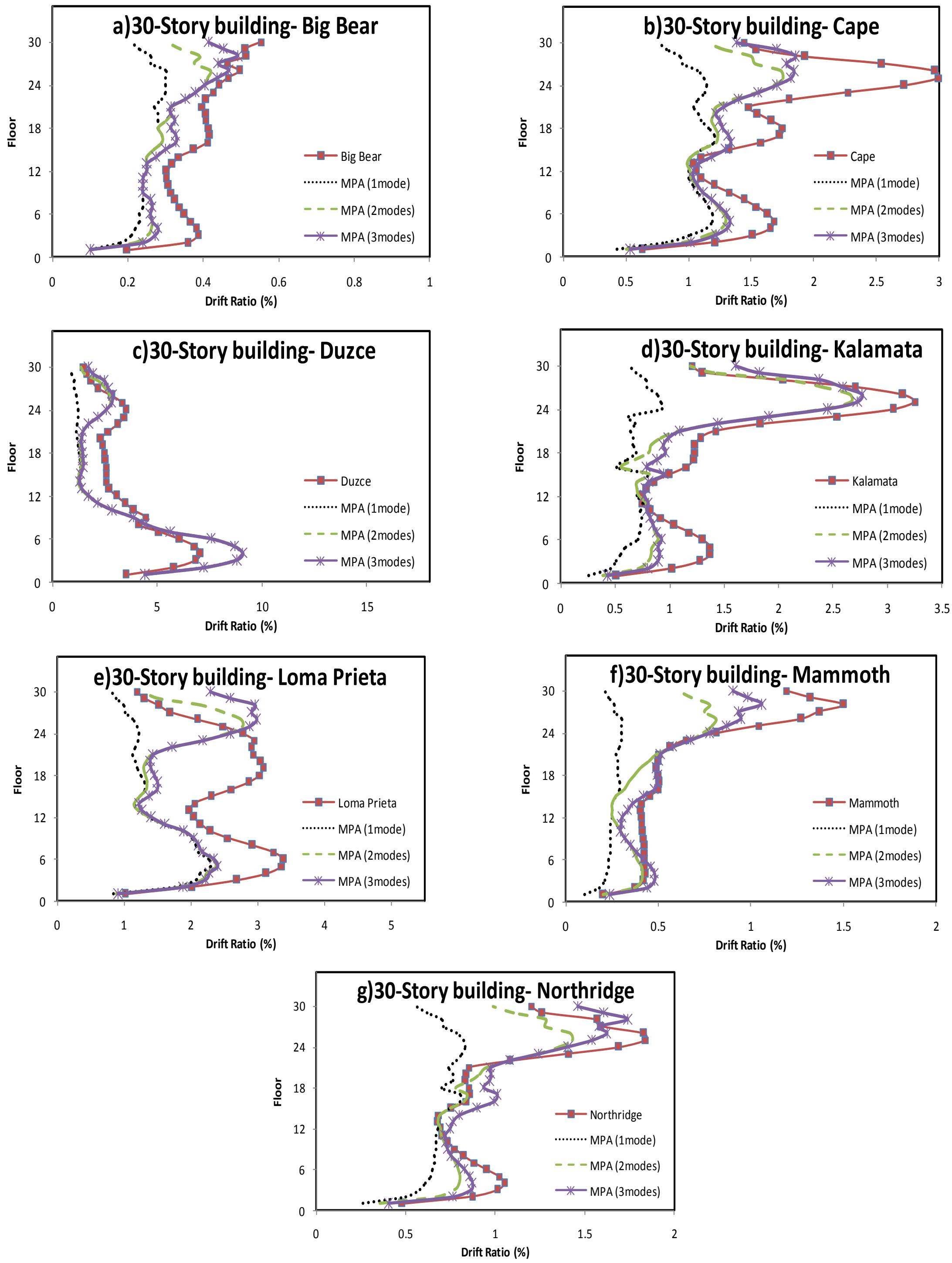


Figure 10. Story drift ratios obtained from MPA and NL-RHA for the 30-story building subjected to near-field ground motions. (a) Big Bear; (b) Cape Mendocino; (c) Duzce; (d) Kalamata; (e) Loma Prieta; (f) Mammoth and (g) Northridge

For more detail, the mean error of the MPA in estimating seismic demands of the 30-story building subjected to far and near-field ground motion records are provided in Tables 16 and 17, respectively.

Table 16: Average error (%) in predicting story drift ratios of 30-story building subjected to far-field ground motions using MPA

	Number of used modes in MPA		
Ground motion	1 mode	2 modes	3modes
Duzce	27.3	20.4	23.88
Hollister	59.74	25.68	18.07
Imperial Valley	16.49	12.53	13.8
Morgan Hill	68.89	33.2	20.66
Northridge	29.82	27.42	29.1
Trinidad	22.57	15.15	10.2
Victoria	20.9	18.8	21.8
Average	35.1	21.88	19.64

Table 17: Average error (%) in predicting story drift ratios of 30-story building subjected to near-field ground motions using MPA

	Number of used modes in MPA		
Ground motion	1 mode	2 modes	3modes
Big Bear	34.3	26	18.5
Cape Mendocino	32.3	23.2	16.1
Duzce	41.6	31	29.1
Kalamata	45.3	22.9	17.4
Loma Prieta	40.1	35.4	37.5
Mammoth	52.1	24.9	12.8
Northridge	27.5	11.6	11.1
Average	39.02	25	20.3

Also, Tables 18 and 19 include the modal contribution factors obtained from MSP for 30-story building subjected to far and near-field ground motion records, respectively. According to this Tables, in the case of the 30-story building subjected to near-field ground motion records, 3nd mode contribution factor has more development rather than same structure subjected to other ground motion investigated type.

Table 18: Modal contribution factors based on MSP for first three modes (30-story building subjected to far-field records)

	Modal contribution factor based on MSP		
Ground motion	1st mode	2nd mode	3rd mode
Duzce	8.66	8.4	1.93
Hollister	4.3	10.8	5.2
Imperial Valley	13.86	4.68	1.31

Morgan Hill	2.59	7.43	4.82
Northridge	16.46	7.1	3.2
Trinidad	6.06	3.39	2.76
Victoria	4.33	6.78	2.28
Average	8.03	6.94	3.07
Normalized Mean	1	0.86	0.38

Table 19: Modal contribution factors based on MSP for first three modes (30-story building subjected to near-field records)

	Modal contribution factor based on MSP		
Ground motion	1st mode	2nd mode	3rd mode
Big Bear	2.7	2.11	2.26
Cape Mendocino	11.7	10.39	9.83
Duzce	38.7	18.28	6.72
Kalamata	8.1	18.2	7.03
Loma Prieta	32.4	20.4	14.3
Mammoth	1.8	5.77	5.53
Northridge	7.2	8.08	7.9
Average	14.65	11.89	7.65
Normalized Mean	1	0.81	0.52

5. DISCUSSION OF THE RESULTS

The reported numerical studies were examples of wide structural models subjected to ground motion records investigated. According to these wide numerical studies it is found that in the case of the structural models with the fundamental period under 2.2s and subjected to both far-field ground motion records, the second mode effects should be considered and the effects of the modes higher than 2nd mode can be ignored to reduce the computational time. Figs. 3-6 and Tables 4-11 approve this fact. On the other hand and according to the Figs. 7-8 and Tables 12-15, it can be concluded that for the structural models subjected to far-field ground motions, the structural height increment has more influence on the 2nd mode contribution rather than 3rd or higher ones. Therefore, considering first two modes in the analysis of the structural models with the fundamental period over 2.2s subjected to far-field ground motion records seems rational.

Finally, according to Figs. 9-10 and Tables 16-19, it can be realized that for the structural models with fundamental period over 2.2s and subjected to near-field ground motion records, an increase in the structural height has more effects on the 3rd mode contribution factor rather than 2nd one. In brief, in the structural models with the fundamental period over 2.2s, to estimate the seismic demands of the structure subjected to near-field ground motion records first three modes should be considered.

6. CONCLUSION

In this study, an effort was made to determine the total number of required modes to estimate the seismic demands of buildings. Employing less number of modes than the optimize number leads to an inaccurate prediction while considering more numbers increases the computational efforts and reduces the NSP (especially multi-run NSPs) attractiveness. To offer optimized number of required modes to predict seismic demands of buildings, the MPA and MSP were employed. MPA was conducted using different number of modes and its results were compared with those of NL-RHA as benchmark. The MPA errors in seismic demand prediction using a specific number of considered modes decided the importance of the neglected modes. On the other hand, MSP presents its specific modal contribution factor which can determine the importance of each mode in the seismic demand prediction of the structures subjected to ground motion records. Among all studied structures, results of four structural models with different heights of 10, 15, 20 and 30 stories subjected to two sets of 7 far and near-field ground motion records were reported. These structural models were simulated using OpenSees computer software. Results of the numerical studies show that in the case of the structural models subjected to far-field ground motion records considering first two modes are suitable to reduce the computational efforts without losing so much accuracy. Also, same number of considered modes seems to be sufficient for the structural models with the fundamental period under 2.2s subjected to near-field ground motions. Although first three modes are required for an accurate seismic demand prediction of the structures with fundamental period over 2.2s and subjected to near-field ground motion.

REFERENCES

1. López-Menjivar MA. A review of existing pushover methods for 2-D reinforced concrete building. *Ph.D Dissertation*, Rose school, Universitá degli Studi di Pavia, Pavia, 2004.
2. Chopra AK, Goel RK. A modal pushover analysis procedure for estimating seismic demands for buildings, *Earthquake Engineering and Structural Dynamics*, **31**(2002) 561-82.
3. Chopra AK, Goel RK, Chintanapakdee C. Evaluation of a modified MPA procedure assuming higher modes as elastic to estimate seismic demands, *Earthquake Spectra*, **20**(2004) 757-78.
4. Sasaki KK, Freeman SA, Paret TF. Multi-mode pushover procedure (MMP) - a method to identify the effects of higher modes in a pushover analysis, *Proceedings of the 6th U.S. National Conference on Earthquake Engineering*, Seattle, Washington, 1998.
5. Moghadam AS. A pushover procedure for tall buildings, In: *Proceedings of the 12th European Conference on Earthquake Engineering*, London (United Kingdom): Elsevier Science Ltd; 2002.
6. Jan TS, Liu MW, Kao YC. An upper-bound pushover analysis procedure for estimating the seismic demands of high-rise buildings, *Engineering Structures*, **26**(2004) 117-28.

7. Rofooei FR, Attari NK, Rasekh A, Shodja AH. Adaptive pushover analysis, *Asian Journal of Civil Engineering*, **8**(2007) 343-58.
8. Kadid A, Boumrkik A. Pushover analysis of reinforced concrete frame structures, *Asian Journal of Civil Engineering*, **9**(2008) 75-83.
9. Mahdi T, Soltan Gharaie V. Plan irregular RC frames: comparison of pushover with non-linear dynamic analysis, *Asian Journal of Civil Engineering*, **12(**2011) 679-90.
10. Antoniou S, Pinho R. Advantages and limitations of adaptive and non-adaptive force-based pushover procedures, *Journal of Earthquake Engineering*, **8**(2004) 497–522.
11. Antonio S, Pinho R. Development and verification of a displacement-based adaptive pushover procedure, *Journal of Earthquake Engineering*, **8(**2004) 643-61.
12. Poursha M, Khoshnoudian F, Moghadam AS. A consecutive modal pushover procedure for estimating the seismic demands of tall buildings, *Engineering Structures*, **31**(2009) 591-9.
13. Poursha M, Khoshnoudian F, Moghadam AS. A consecutive modal pushover procedure for non-linear static analysis of one-way unsymmetric-plan tall building structures, *Engineering Structures*, **33**(2011) 2417-34.
14. Vafaee MH, Saffari H. A modal shear-based pushover procedure for estimating the seismic demands of tall building structures, *Soil Dynamics and Earthquake Engineering*, **92**(2017) 95-108.
15. Fajfar P, Gaspersic P. The N2 method for the seismic damage analysis of RC buildings, *Earthquake Engineering and Structural Dynamic*, **25**(1996) 31-46.
16. Kreslin M, Fajfar P. The extended N2 method taking into account higher mode effects in elevation, *Earthquake Engineering and Structural Dynamics*, **40**(2011) 1571-89.
17. Kreslin M, Fajfar P. The extended N2 method considering higher mode effects in both plan and elevation, *Bulletin of Earthquake Engineering*, **10(**2012) 695-715.
18. Tarbali K, Shakeri K. Story shear and torsional moment-based pushover procedure for asymmetric-plan buildings using an adaptive capacity spectrum method, Engineering *Structures*, **79**(2014) 32-44.
19. Gupta A, Krawinkler H. Estimation of seismic drift demands for frame structures, *Earthquake Engineering and Structural Dynamics*, **29(**2000) 1287-1305.
20. PEER. Open system for earthquake engineering simulation: opensees. Berkeley: Pacific Earthquake Engineering Research Center (PEER), University of California; 2016 [URL: http://opensees.berkeley.edu].
21. Standard No.2800-05. *Iranian Code of Practice for Seismic Resistant Design of Buildings*, 3rd edition, Building and Housing Research Centre, Iran, 2005.
22. Abbasnia R, Davoudi AT, Maddah MM. An adaptive pushover procedure based on effective modal mass combination rule, *Engineering Structures*, **52**(2013) 654-66.
23. Kalkan E, Kunnath SK. Adaptive modal combination procedure for non-linear static analysis of building structures, *ASCE Journal of Structural Engineering*, **132**(2006) 1721-31.
24. Shakeri K, Shayanfar MA, Kabeyasawa T. A story shear-based adaptive pushover procedure for estimating seismic demands of buildings, *Engineering Structures*, **32(**2010) 174-83.
25. Tabatabaei R, Saffari H. Evaluation of the torsional response of multistory buildings

using equivalent static eccentricity, *ASCE Journal of Structural Engineering*, **137(**2011) 862-8.

26. Tabatabaei R, Saffari H. Energy-based approach to estimate seismic demands for asymmetric buildings, *Journal of Earthquake and Tsunami*, **4**(2010) 215-30.
27. Tabatabaei R, Saffari H. Demonstration of torsional behaviour using vibration-based single-storey model with double eccentricities, *KSCE Journal of Civil Engineering*, **14**(2010) 557-63.