Higher Mode Effects on Seismic Behavior of MDOF Steel Moment Resisting Frames

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ABSTRACT: *In this paper, the effects of higher modes on seismic response of multi degree of freedom (MDOF) steel moment-resisting frames (SMRF) are investigated. Modification factors to the response of first mode SDOF system are presented in order to estimate seismic MDOF system demands. The study is based on spectral analysis and linear and nonlinear dynamic time history analysis of 4, 10, 15, 20 and 25 storey SMRFs under Elcentro, Tabas, Naghan and Manjil earthquake loading. A modification factor* α_{disp}^{el} *is defined in order to estimate roof elastic displacement demands of an MDOF frame from first mode elastic displacement spectra. Base shear modification factor* $\alpha_{H.M}^{V}$ *(to compute MDOF strength reduction factors), maximum story drift demand modification factor* $\alpha_{H.M}^{d}$*, and maximum story dynamic ductility demand modification factor* $\alpha_{H.M}^{\mu}$ *are defined and presented for SDOF system responses in order to estimate the main MDOF system nonlinear seismic responses, including higher mode effects.*

Keywords: Seismic response; Demand; Higher mode effects; Dynamic analysis; SMRF

1. Introduction

Different responses of *MDOF* frames under seismic motions are influenced by higher mode effects and thus the overall response of the structure will be usually significantly different from the first mode response. The amount of this effect depends on various parameters such as response type, earthquake specifications, structural configurations and level of ductility. Higher mode effects are clearly more important for high rise structures and thus eliminating higher modes may lead to incorrect results. The sensitivity of different structural responses to higher mode effects is also different.

Several studies on strength reduction factors, have been conducted in *SDOF* systems, the most important one is presented by Miranda and Bertero [1] however only few researchers have studied the *MDOF* effects on strength reduction factors. The relationship between *MDOF* and *SDOF* systems was first studied by Veletsos and Vann [2]. The objective of their study was to identify the significant parameters in the response of *MDOF* elastoplastic systems. The relationship between the response of these systems with the equivalent linear ones was also studied. Nassar and Krawinkler [3] studied three types of simplified *MDOF* models to estimate the modifications required to the inelastic strength demands, obtained from bilinear *SDOF* systems in order to limit the story ductility demand in the first story of *MDOF* systems to a predetermined value. The three types of *MDOF* models were composed of two-dimensional regular frames named “beam-hinge”, “column-hinge” and “weak-story” models.

Humar and Rahgozar [4] studied a ten-story shear frame with a uniform distribution of mass and story heights. In the study, it was shown that for high levels of ductility, the displacement ductility demand in many stories of *MDOF* frame can be much higher than the equivalent *SDOF* system. They also concluded that the critical story in most of *MDOF* systems is the lowest; however, the upper stories can also exhibit larger ductility demands due to the participation of higher modes. Krawinkler and Seneviratna [5] studied the modifications to *SDOF* system responses in order to estimate seismic demands of *MDOF* frames from elastic and inelastic spectra. They considered two types of lateral load resisting systems of moment-resisting frames and isolated structural walls. This study concluded that except for short period frames, the maximum story ductility demand for *MDOF* models was higher than the target ductility ratio of the first mode *SDOF* system. This amplification increases with increasing periods, which indicates the importance of higher mode effects.

Gupta [6] studied the behavior of moment frames under different levels of seismic hazard. They considered 3, 9 and 20 story frames and evaluated higher mode effects on maximum story drift demand. The emphasis of their study was on quantification of global and local deformation demands for various hazard levels. It was concluded that for long periods, as higher mode effects become more important, the distribution of drift demands in the height of the frame would be no more uniform and the difference between global and story drift demands increase with period. Santa-Ana and Miranda [7] studied strength reduction factor of *MDOF* systems by defining modification factors to *SDOF* systems. They also investigated soil condition effects on these factors. Their study concluded that the modification factors increase for long periods and high levels of target ductility. This implies the importance of higher modes in strength (base shear) response of *MDOF* frames. Daneshjoo and Gerami [8-9] studied the reasons contributing in overstrength of highrise *SMRFs* and higher mode effects importance on seismic behavior. They concluded that higher mode effects in seismic evaluation of *MDOF* frames result in the amplification of ductility demand and thus reduction of behavior factor. Therefore neglecting these effects, specially in the case of tall buildings would lead to unconservative results.

The main objective of this paper is to present modification factors to the response of first mode *SDOF* system in order to estimate seismic *MDOF* system demands. In this context, seismic response of five steel moment resisting frames models under four different earthquakes are studied using spectrum analysis, linear and nonlinear dynamic time history analysis and *DRAIN-2DX* software [20]. The influences of period and ductility level on higher mode effects are also investigated.

2. Steel Moment Resisting Frame Models

Two dimensional 4, 10, 15, 20 and 25 storey steel moment resisting frames with three bays have been designed according to Iranian 519 loading code and Iranian 2800 code for seismic resistant design of buildings and are used in this study. The configurations of the frames together with their design results are shown in Figure (1a). The inter-storey height and span length of the frames are all constant and equal to 4*m* and 5*m*, respectively. Storey masses are calculated using dead load plus 20% of live load. High seismic relative hazard for site region with design base acceleration A=0.35*g*, beds of gravel and sand with weak cementation for site soil classifications, median importance factor (such as residual building frames) for the frames, and a behavior factor of 6 have been assumed in the designs. In mathematical modeling strain hardening ratio of 3% and damping ratio of 5% of critical one have been assumed. The criteria for the formation of plastic hinge and the elements behavior, was an interaction of Moment-Axial force (*M-P*) curve. The inter-storey drift angle capacity at the serviceability Limit State has been assumed equal to 0.006*rad*. The stiffness requirement has governed the design, as is usually the case for steel

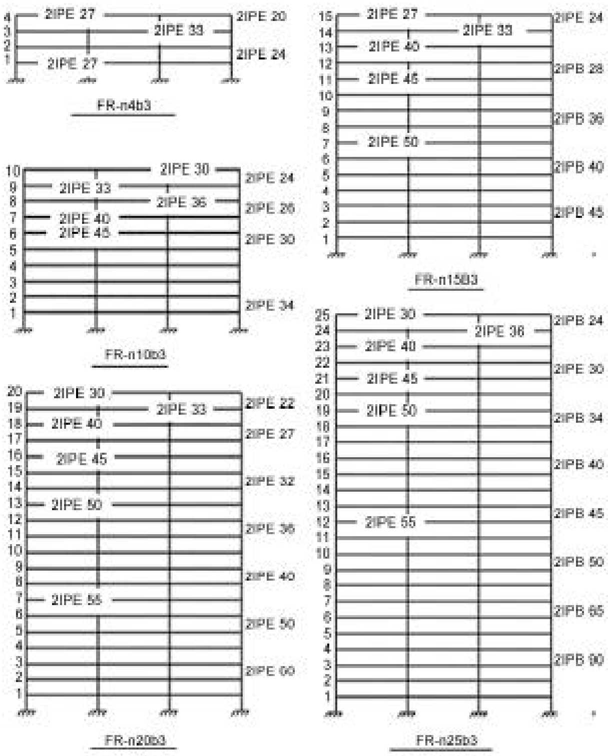

Figure 1a. Steel Moment Resisting Frame Models.

structures. The beam-to-column joints were assumed to be full-strength and rigid in the design procedure. Rigid and full strength connections are characterized by moment-rotation relationships with strength degradations. Nonlinear dynamic time history analyses have been performed by using *DRAIN*-2*DX* software, where the proposed hysteretic models have been implemented.

3. The Seismic Input Characteristics

Four ground acceleration time-histories (Tabas, Naghan, Manjil and Elcentro earthquakes) have been selected for performing numerical analysis. Tabas earthquake has a peak ground acceleration (*PGA*) of about 0.93*g* and strong motion duration of about 25 seconds. Its predominant period is 0.769 seconds. Naghan earthquake has been recorded for 20.98 seconds and has a *PGA* of about 0.72*g* and predominant period of 0.764 seconds. The duration of Manjil record is 53.52 seconds. The *PGA* and predominant period of this earthquake are 0.5*g* and 0.556 seconds respectively. And finally Elcentro earthquake has a strong motion duration of about 12.1 seconds. Its *PGA* and predominant period are 0.32*g* and 0.555 seconds, respectively. Predominant periods of the ground motions are calculated from predominant frequency content of the same ground motions, which is quantified by plotting Fourier Amplitude Spectrum (*FAS*) and Power Spectrum Density (*PSD*), using Finite Fourier Transform (*FFT*). Figures (1b) and (1c) show the acceleration time history of these earthquake components and corresponding spectrums together with appropriate Iranian 2800 design spectrum.

4. Method of Estimating Inelastic Demands

Few researchers have investigated the methods of estimating *MDOF* inelastic seismic demands. Their efforts can be categorized into following three main groups:

❖) Methods based on equivalent linear structures. Demands of an inelastic *MDOF* system are estimated from an elastic analysis of an equivalent *MDOF* system called "substitute structure" [10]. In order to gain such a linear structure, stiffness of potential inelastic elements of the original structure is reduced and their effective damping is increased. Empirical relations are presented to compute these equivalent properties.

❖ Methods based on equivalent *SDOF* systems.

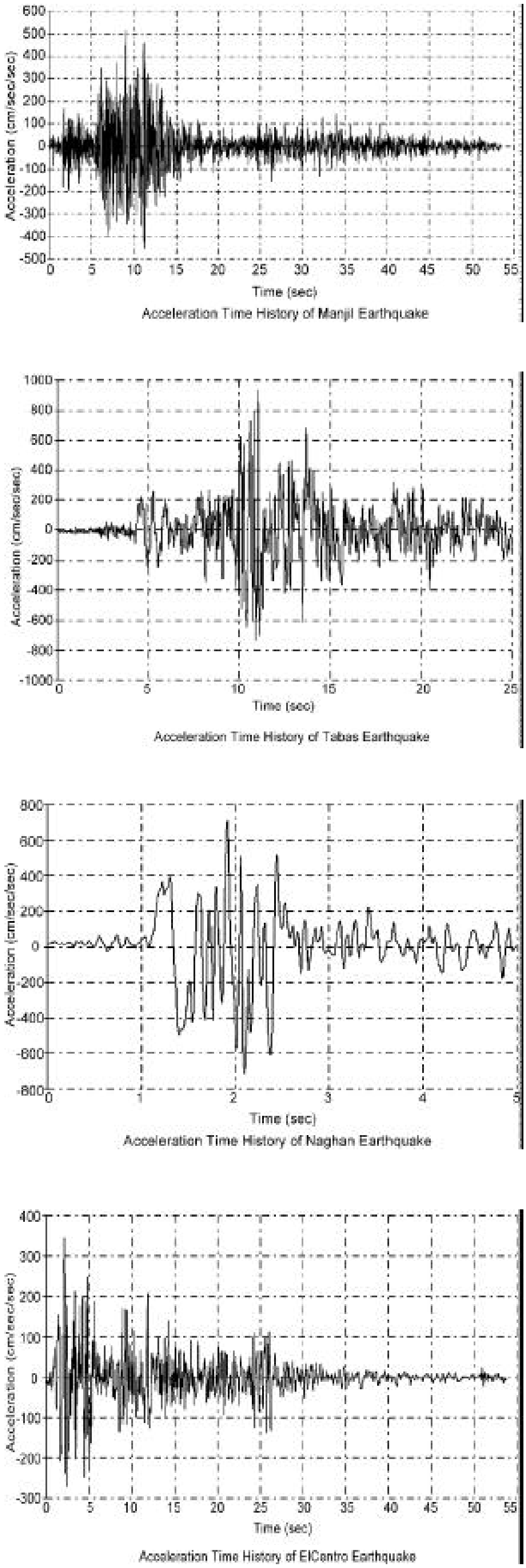

Figure 1b. Acceleration time histories of earthquake components.

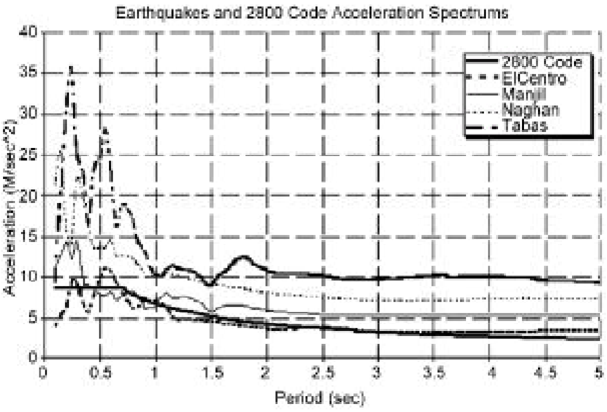

Figure 1c. Acceleration spectrum of the related earthquake and design spectrum of Iran seismic code (2800).

The response of *MDOF* system is controlled by a single mode and the shape of this mode remains constant throughout the time history. Although both assumptions are not always correct, some studies conducted by several researchers [11, 12, 13, 14, 15] have indicated that they may lead to rather good predictions of maximum seismic response of many *MDOF* systems.

❖ Methods based on using inelastic response spectral, with elastic modal combination methods (i.e. *SRSS* and *CQC*) to compute the seismic demands of inelastic *MDOF* systems [16, 17]. Although this method has no theoretical justification, it is expected to approximate the overall inelastic behavior of *MDOF* systems. The studies carried by some researchers [18, 19] have shown that the results of this method may need to be modified to take into account the local concentration of inelastic effects and special effects due to near source motions.

In this paper, the quantification of seismic demands for an *MDOF* system is conducted through a comparative evaluation of inelastic dynamic response of *MDOF* frames and their equivalent *SDOF* systems and presenting modification factors to the response of *SDOF* systems. Thus for each of the *MDOF* frames, an equivalent *SDOF* system is defined. The properties of these equivalent *SDOF* systems are set such that the weight of the *SDOF* system is the same as the total weight of the original *MDOF* frame and the period of vibration and damping ratio of *SDOF* system are the same as the fundamental mode properties of the *MDOF* frame. The main reason of difference between the response of an inelastic *MDOF* frame and its equivalent *SDOF* system is the contribution of higher modes in the response of *MDOF* system. However, other structural characteristics such as the global mode of deformation, distribution of strength and stiffness over the height of the structure, structural system redundancy, mode of failure at both element and global levels and finally the torsional affects can also affect the difference of responses between *MDOF* systems and their equivalent *SDOF* ones.

5. Higher Mode Effects in Elastic Analysis

The maximum effect of each mode is determined by considering the period of vibration of various modes of the frames and making use of the design response spectrum. Then these maximum effects are combined using square root of sum of squares (*SRSS*) method to obtain the required response in the frames. In each one of the perpendicular directions at least the first three modes of vibration, or all the modes of vibration with a period of more than 0.4 seconds, or all first *N* modes that sum of their modal mass participation factors is more than 90 percent. The greater one is taken into consideration. Modal properties of the frames are shown in Table (1).

It can be observed that normalized first mode modal masses (represented by $W1^*/W$ in percent) decrease with increasing number of stories (period) which indicates the importance of higher mode effects in highrise frames. For the same reason, the number of modes required for analysis, increases with number of stories or the fundamental periods.

Various linear seismic responses of a frame *R* are

Table 1. Designed MDOF Frame Modal Properties.

Frame Type	N4b3	N10b3	N15b3	N20b3	N25b3
T_1(Sec)	1.24	1.95	2.51	3.12	3.70
T_2(Sec)	0.436	0.74	1.00	1.22	1.43
T_3(Sec)	0.264	0.43	0.59	0.76	0.86
T_4(Sec)	0.176	0.30	0.41	0.53	0.60
T_5(Sec)	------	0.23	0.32	0.40	0.45
PF_1	1.305	1.397	1.484	1.533	1.556
PF_2	-0.489	-0.587	-0.729	-0.867	-0.880
PF_3	0.289	0.309	0.382	0.513	0.504
PF_4	-0.105	0.212	0.285	0.318	0.312
PF_5	------	-0.180	-0.181	-0.212	-0.278
W_1^*/W(%)	79.94	75.99	70.98	67.15	66.28
W_2^*/W(%)	13.65	12.41	14.43	14.58	15.28
W_3^*/W(%)	3.85	4.55	5.02	6.01	5.93
W_4^*/W(%)	2.56	2.62	2.71	3.55	3.11
W_5^*/W(%)	-------	1.22	1.59	1.84	1.81
Number of Modes Required for Analysis	3	3	4	5	5

influenced by higher mode effects differently. In this paper, higher mode effects on roof shear V_{roof}, base shear V_{base} and roof displacement U_{roof} are investigated. The higher model Eq. (1) is considered as a criteria to evaluate the error caused by eliminating modes higher than one.

$$\alpha_R^{el} = \frac{R_N - R_1}{R_N} \times 100 \tag{1}$$

α_R^{el} is the percentage of higher mode effect in response R of an N story frame. R_1 and R_N are the linear spectral response R of the frame (i.e. V_{roof}, V_{base} and U_{roof}) considering 1 and N modes of vibrations, respectively.

For each of the frames, linear seismic spectral responses i.e. V_{roof}, V_{base} and U_{roof} are calculated once using all the N required modes of vibrations and another time using only the first mode of vibration. The percentage of higher mode effect in each response for each of the frames is then calculated using Eq. (1). Figure (2) shows how the higher mode effect factor α_R^{el} varies with the first period T_1 of each frame for different spectral responses.

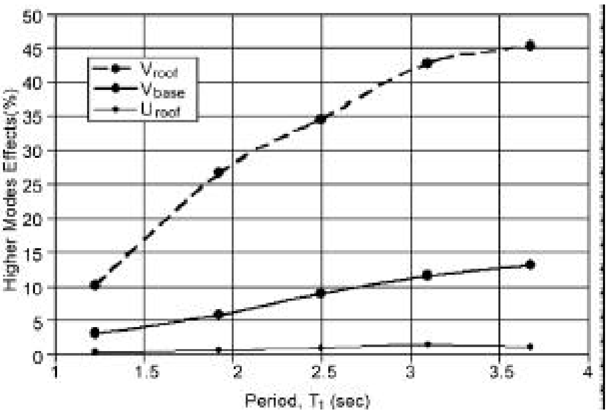

Figure 2. Higher mode effects on roof shear, base shear and roof displacement of frames (%), linear spectrum analyses.

It can be seen that the percentage of higher mode effects in different responses of the frames increases with increasing period which indicates the importance of higher modes in high rise frames. On the other hand for a certain frame, roof shear is affected by higher modes more than the other two responses and roof displacement takes the least affect (i.e. $\alpha_{V_{roof}}^{el} > \alpha_{V_{base}}^{el} > \alpha_{U_{roof}}^{el}$). For example about half of the overall roof shear response in the frame *n*25b3 (45.3%) is allocated to higher modes while this percentage for base shear and roof displacement responses decreases to 13.06% and 1.16%, respectively.

The above results were only presented for 3 bay frames. Higher mode effects modification factors are also calculated for 20 storey frames with 1, 2, 3 and 5 bays in order to investigate the effects of number of bays. The higher mode effect modification factor is computed for each response of these frames (*n*20-b1, *n*20-b2, *n*20-b3 and *n*20-b5). The results are shown in Figure (3).

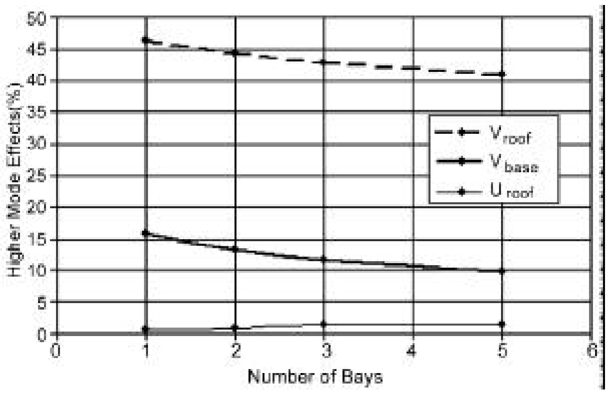

Figure 3. Influence of number of bays in higher mode effects on roof shear, base shear and roof displacement of 20-story frames.

It is observed that the trend of higher mode effects on different responses holds true for all number of bays. Higher mode effects in responses of roof shear and base shear is reduced with increasing number of bays. An opposite trend was concluded for roof displacement response.

Elastic first mode spectral displacement can be used to estimate the roof elastic displacement demands of *MDOF* frames using the elastic displacement demand modification factor α_{disp}^{el} as defined by Eq. (2)

$$\alpha_{disp}^{el} = \frac{\delta_t^{el}}{\delta_{SDOF}^{el}} \tag{2}$$

Where δ_t^{el} is the maximum roof displacement demand of an elastic *MDOF* frame under a particular earthquake calculated by linear dynamic time history analysis. And α_{disp}^{el} is the elastic first mode displacement obtained from response spectrum of the same earthquake. Thus the maximum roof displacement of an elastic *MDOF* frame is related to the elastic first mode spectral displacement. Variation of α_{disp}^{el} computed for each of the five frames under the different four earthquakes, together with variation of the first mode participation factors (PF_1 s) of the frames are shown in Figure (4).

It can be seen that the mean values of α^{el}_{disp} amplification factors for different records are in good agreement with PF_1 factors. On the other hand, α^{el}_{disp} factors increase with increasing fundamental period, and their variation is similar to PF_1 factors. This means that maximum elastic roof displacement demand of an *MDOF* frame can be estimated by the product of elastic first mode spectral displacement by first mode participation factor. PF_1 factors are actually applied to account for higher mode effects. The compatibility of PF_1 and $\alpha^{d,el}_{H.M}$ factors was also concluded in other studies [21-22].

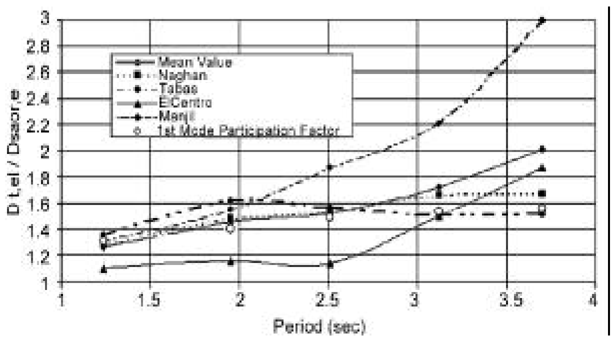

Figure 4. Elastic normalized roof displacement demands-frame structures.

The important note in this process is to evaluate fundamental period of the structures. Design codes usually underestimate the period of *SMRFs* and consequently elastic spectral displacements (*Sd*) are underestimated too. Thus, it is strongly recommended to compute fundamental period of the structures through eigen value analysis in order to get relatively justified estimations of maximum roof displacement demands in elastic *MDOF* frames.

6. Higher Mode Effects on Strength Reduction Factors of MDOF Frames

Linear analyses are unable to predict the nonlinear behavior of the structures under strong earthquake excitations. A rational design concept should compare the evaluated ductility reserves of the structure with ductility demands evaluated for appropriate ground motion by nonlinear time history analysis. Seismic codes allow the structures to behave inelastically when subjected to strong earthquake ground motions. Nonlinear behavior of the structures in inelastic range results in the reduction of effective lateral forces. This reduction in design forces is applied through strength reduction factors $R\mu$. In this paper, at first, nonlinear effects of *SDOF* systems are investigated using R_μ factors and then a modification factor $\alpha^V_{H.M}$ is defined to account for higher mode effects in strength reduction factor of *MDOF* frames.

SDOF strength reduction factors R_μ that take into account the nonlinear behavior of these systems are defined by Eq. (3)

$$R_\mu = \frac{V^{el}_{SDOF}}{V^{\mu}_{SDOF}} \tag{3}$$

Where V^{el}_{SDOF} is the elastic strength demand of *SDOF* system and V^{μ}_{SDOF} is the minimum strength demand required to keep displacement ductility demand of *SDOF* system less than a predetermined value of target ductility μ. Figure (5a) illustrates how Rμ varies in different frames with the period of first mode of vibrations of the frames under different earthquake loading and for different values of μ. Figure (5b) shows the variation of the mean values.

The results indicate that R_μ factors increase with the increase in first natural period of vibration T_1 and with increase in level of ductility μ. The greater R_μ factors for large ductility values are due to the fact that these factors account for inelasticity in *SDOF* systems. Thus, they must increase in high levels of ductility to cause more reductions in design forces.

Due to the participation of higher modes, R_μ factors as defined by Eq. (3) can not be used as *MDOF* strength reduction factors. In order to account for higher modes effect, $\alpha^V_{H.M}$ modification factor is defined by Eq. (4)

$$\alpha^V_{H.M} = \frac{V^{\mu}_{MDOF}}{V^{\mu}_{SDOF}} \tag{4}$$

Where V^{μ}_{MDOF} and V^{μ}_{SDOF} are the minimum lateral strengths required to limit the ductility ratio of *MDOF* and *SDOF* systems to target values.

The strength demand of an *SDOF* system with ductility μ, is multiplied by the modification factor $\alpha^V_{H.M}$ to get the lateral strength demand of the original *MDOF* frame with the same level of ductility μ. On the other hand, $1/\alpha^V_{H.M}$ represents a modification factor to *SDOF* strength reduction factors R_μ, to be applied to original *MDOF* frames. Thus the introduced modification factors must be applied to R_μ, *Y* and μ factors, which are drawn from analytical results, in order to account for higher mode effects and not to the presently used reduction factors in codes of practices.

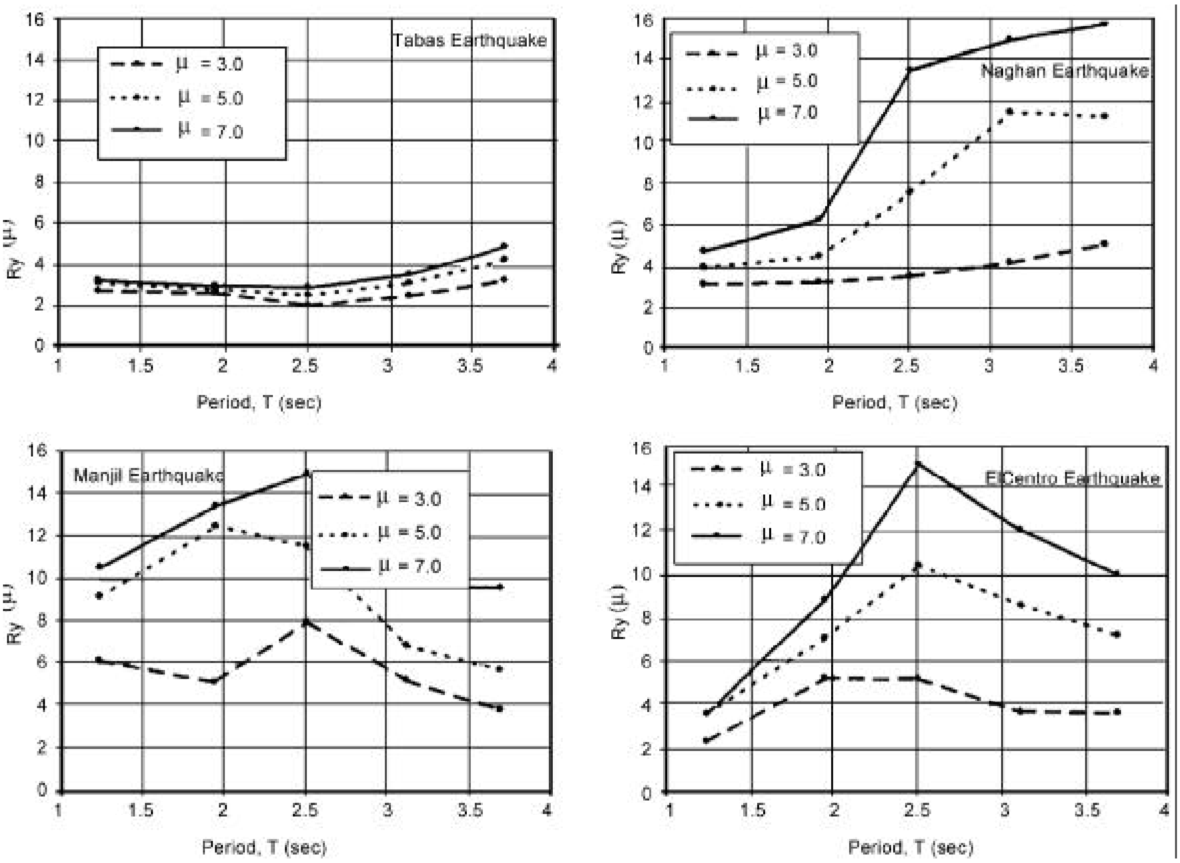

Figure 5a. SDOF strength reduction factors.

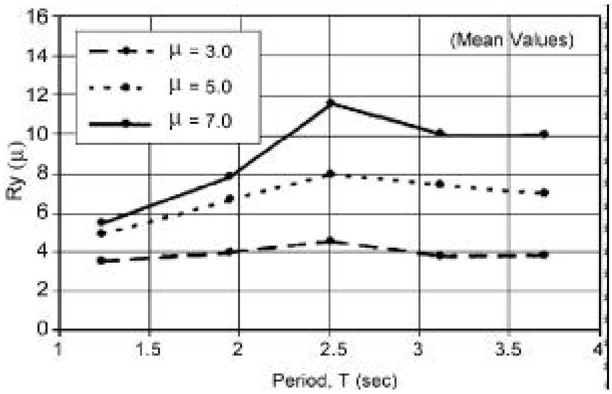

Figure 5b. SDOF mean strength reduction factors.

In this study, $\alpha^{V}_{H.M}$ modification factors for each of the five frames are computed under the four different earthquakes and with three different target ductility values of 3, 5 and 7. Figure (6a) illustrates how $\alpha^{V}_{H.M}$ modification factors varies with the first natural period of each frame T_1 for different ductility μ. Figure (6b) shows the variation of the mean values.

It can be observed that $\alpha^{V}_{H.M}$ factors always increase with increase in period T_1, indicating the importance of higher modes in strength demands of *MDOF* frames. They are also usually incremental with level of ductility. These factors are higher than unity in all cases and for *n*25b3 frame, values as large as 4 have also been observed under certain records.

Estimation of interstory and global drift demands is of great significance in seismic design of *SMRFs* because their excess from allowable limits would cause great damage in both structural and nonstructural components. The distribution of drift demands in frames' height and the relationship between maximum story drift and global drift demands are investigated. The frames with three different levels of structural yield strength μ_{SDOF} of 3, 5 and 7 are subjected to the four different earthquakes. Nonlinear dynamic time history analysis are conducted and interstory drift angles (i.e. storey drift over storey heigth) and global drift angles (Roof drift over total heigth of frame) are calculated. The corresponding results for the 20-story frame are shown in Figures (7a) and (7b).

The distribution of drift demands in the structures, responding predominantly in their first mode, is rather uniform over their height. As can be seen from Figures (7a) and (7b), the distribution of story drift demands over the height of the 20-story frame is

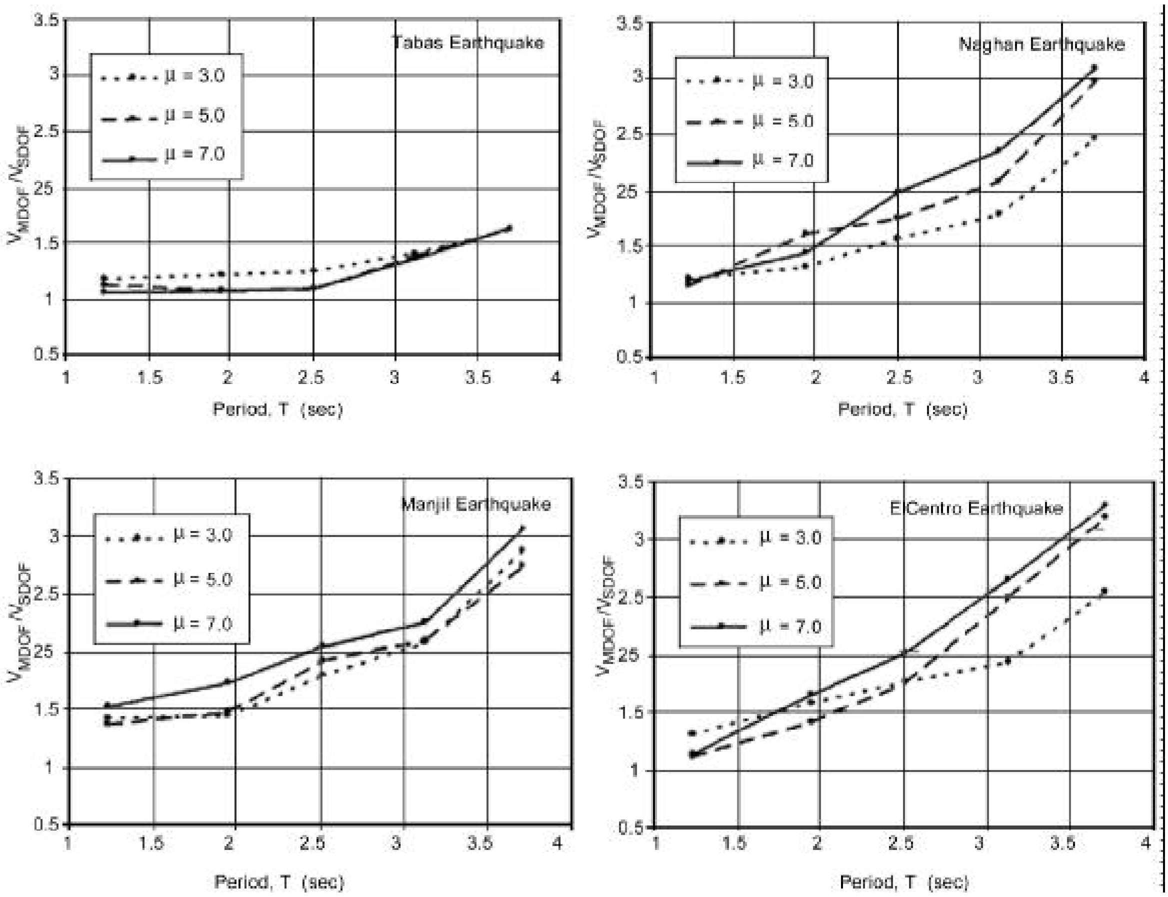

Figure 6a. MDOF modification factor for base shear (strength) demands.

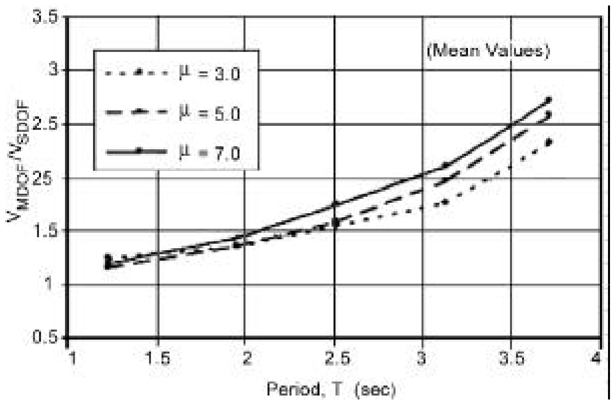

Figure 6b. Mean MDOF modification factor for base shear (strength) demands.

not uniform, specially in higher stories that shows a sudden amplification. Sudden amplification of story drift in lower stories of a structure is due to $P-D$ effects, while the occurrence of such an amplification in top stories is attributed to higher mode effects. Maximum story drift angle, has been observed larger than global drift angle under all earthquakes and for all values of *SDOF* ductility, in 20-story frame, see Figures (7a) and (7b). The same result is observed in all the other frames.

7. Higher MODF Effects on Story Drift and Ductility Demands of MDOF Frames

Yield story drift $\delta_{y,i}$ is computed using pushover analysis of story *i* such that all the nodes beneath the considered story are fixed by hinge supports and a lateral load is applied to the story roof incrementally. The consequent story drift corresponding to the formation of the first plastic hinge in the story is then yield story drift ($\tilde{\delta}_{y,i}$ dynamic story ductility of the frames under different earthquake records were computed for μ_{SDOF} values of 3, 5 and 7 using Eq. (5))

$$\mu_{s,i} = \frac{max\left\{\delta^{+}_{s,max}, \left|\delta^{-}_{s,max}\right|\right\}}{\delta_{y,i}} \tag{5}$$

Where $\mu_{s,i}$ is dynamic ductility ratio of story *i* and $\delta^{+}_{s,\max}$, $\delta^{-}_{s,\max}$ and $\delta_{y,i}$ are the maximum positive, the maximum negative and the yield story drifts, respectively.

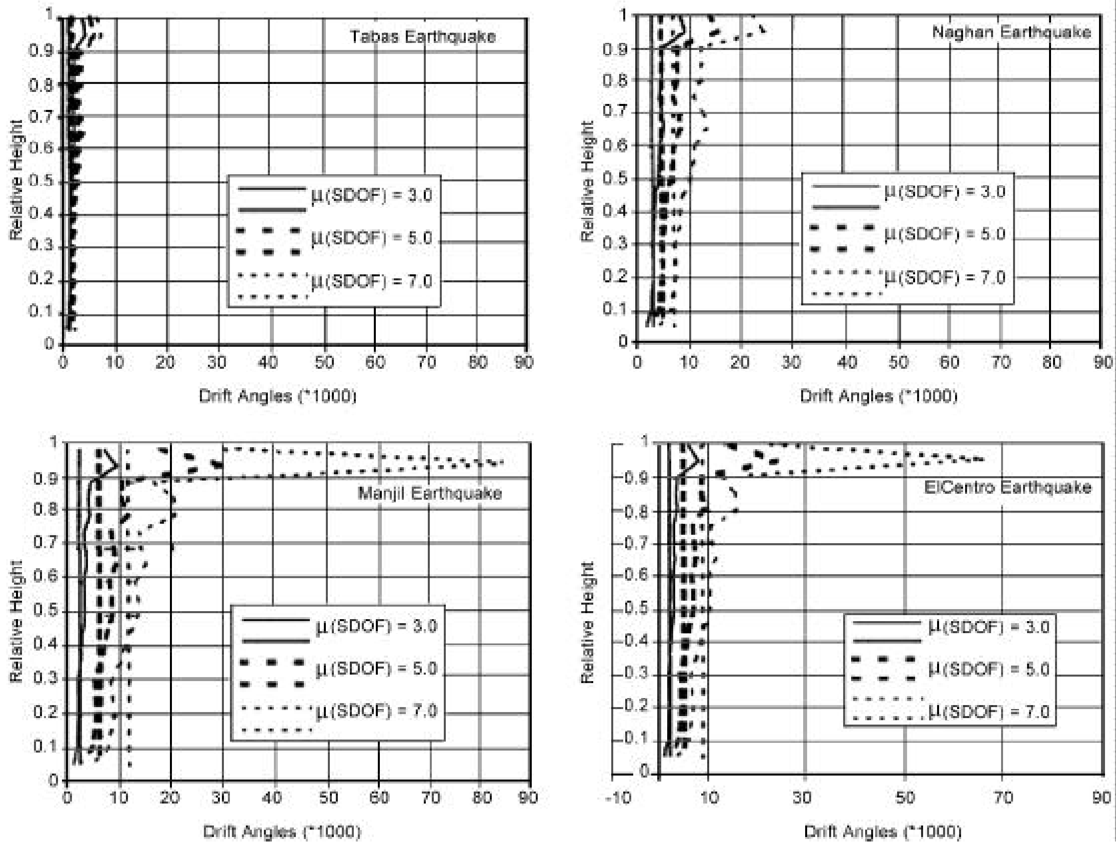

Figure 7a. Inter story and global drift demands of 20-story frame.

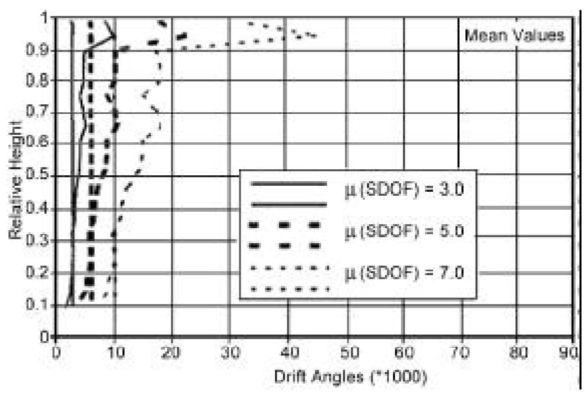

Figure 7b. Inter story and global drift demands of 20-story frame (mean values).

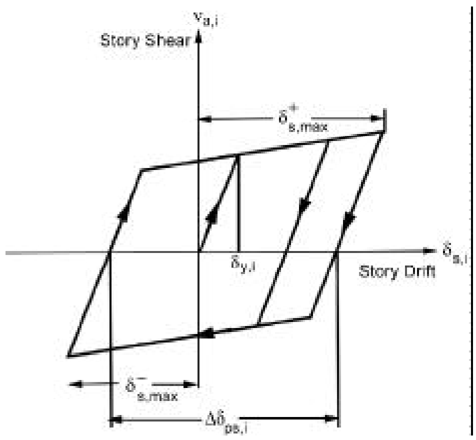

Figure 8. Story shear vs. story drift response.

These parameters are illustrated in Figure (8), schematically. In this study, the ductility of *MDOF* frames is defined as story ductility which was defined by Eq. (5). Yield story drift $(\delta_{y,i})$ is computed from pushover analysis of story i such that all the nodes beneath the considered story are fixed by hinge supports and a lateral load is applied to the story roof, incrementally. The consequent story drift corresponding to the formation of first plastic hinge in the story is then yield story drift $(\delta_{y,i})$.

Figure (9a) shows the distribution of story dynamic ductility demands over the height of 20-story frame under different earthquakes. Figure (9b) shows the variation of the mean values.

As can be seen there is a sudden amplification in dynamic ductility demands of higher stories in 20-story frame that can be ascribed to higher mode effects. The same trend was observed for story drift demands. Distribution of story drift and its variation trend in the height of a structure is generally closely

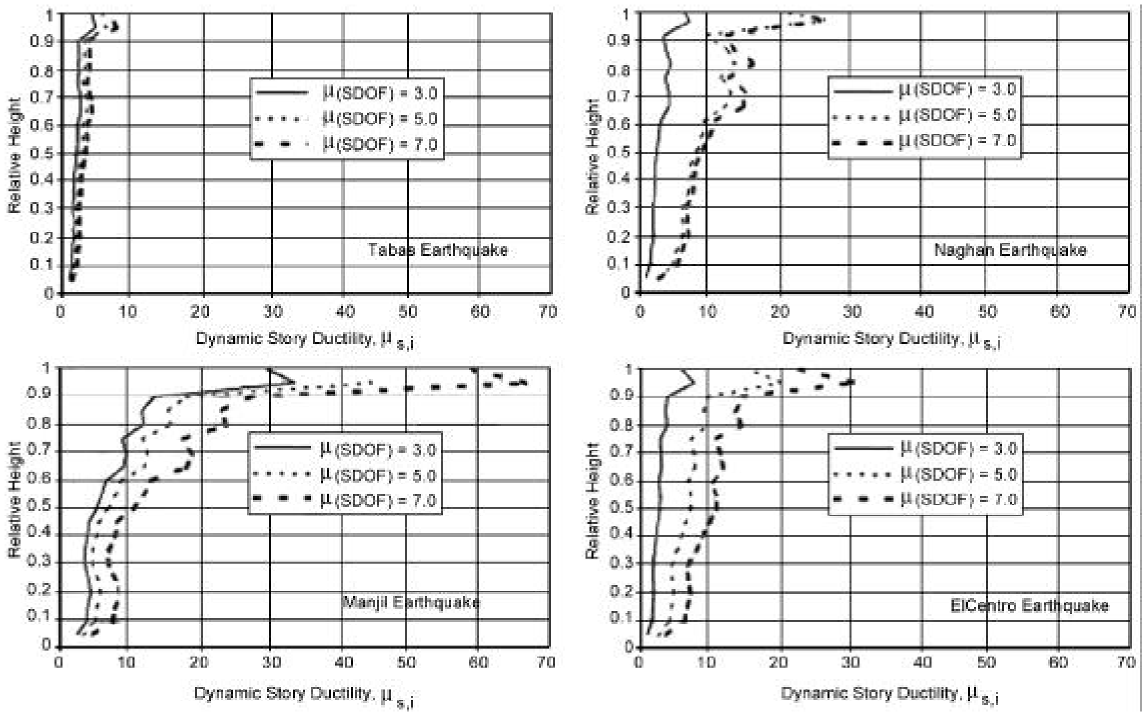

Figure 9a. Story dynamic ductility ratios of 20-story frame.

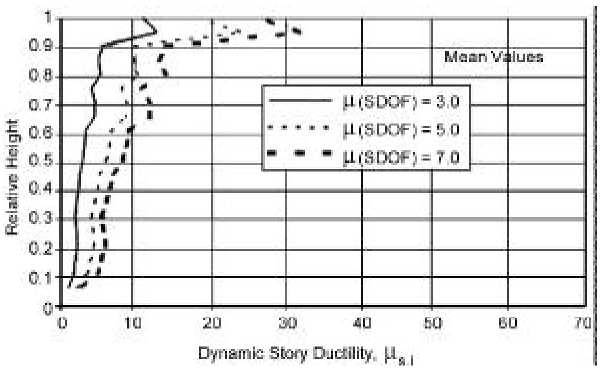

Figure 9b. Story dynamic ductility ratios of 20-story frame (mean values).

related to the story ductility demands of the same structure.

The difference between story and roof drift angles can be a parameter for evaluation of higher mode effects on maximum story drift demand. If a structure is not affected by higher modes and its behavior is controlled by one mode in linear state, the story and roof drift angles are expected to be equal according to the following equation

$$\frac{\delta_t}{h_t} = \frac{\delta_i}{h_i} \tag{6}$$

It was observed from Figure (7) that the distribution of story drift demands over the height is not uniform, specially in higher stories that shows a sudden amplification. Sudden amplification of story drift in lower stories of a structure is mostly due to $P-D$ effects while the occurrence of such an amplification in top stories is mostly attributed to higher mode effects. Therefore in reality Eq. (6) is just valid in idealized situation. This equation doesn't hold true in reality, even in the linear range and for a structure vibrating in a single mode and as was mentioned before it is just valid in idealized situation. The differences between roof drift and story drift angle cannot be attributed only to higher mode effects, but it can be said that higher modes have a direct effect in this regard. The $\alpha^d_{H.M}$ factor is defined by Eq. (7) in order to evaluate higher mode effects on maximum story drift demand

$$\alpha^d_{H.M} = \frac{\delta_{s,\max} / h_i}{\delta_t / h_t} \tag{7}$$

$\alpha^d_{H.M}$ factors were computed under different records for each value of μ_{SDOF} (3, 5 and 7). The results are illustrated against T and μ_{SDOF} in Figure (10a), separately. Figure (10b) shows the variation of the mean values.

It is observed that $\alpha^d_{H.M}$ factors increase with increasing period and level of *SDOF* ductility, indicating the importance of higher mode effects. The ratio of average interstory drifts to roof drift angles is usually greater than unity. The reason is that maximum story drifts of a frame under any earthquake

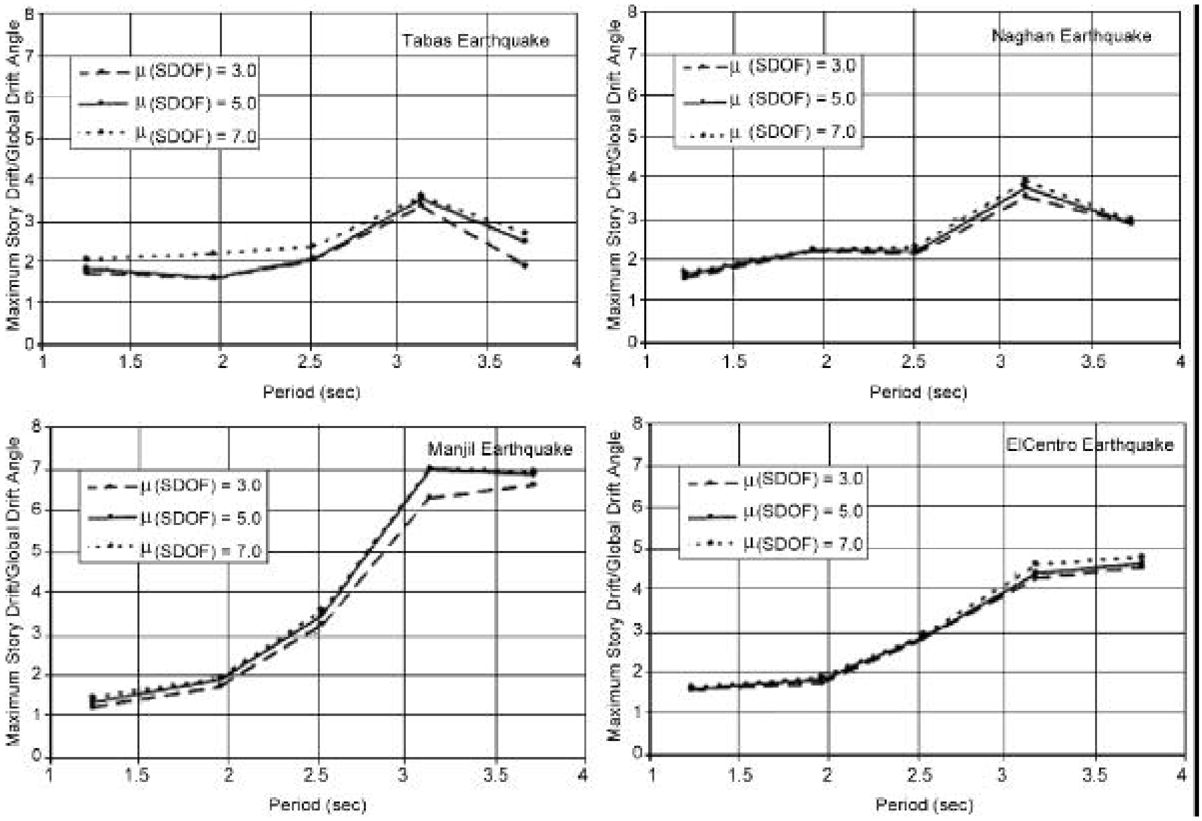

Figure 10a. Higher mode effects on maximum story drift angle demands.

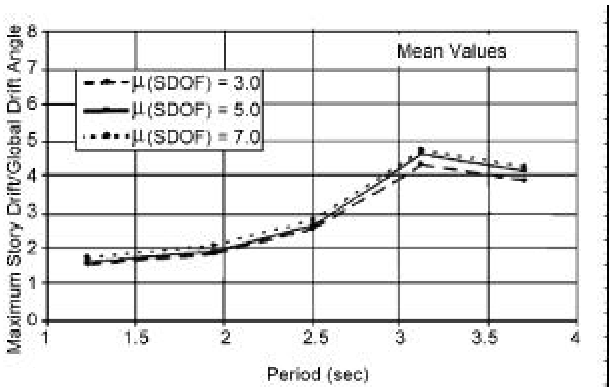

Figure 10b. Higher mode effects on maximum story drift angle demands (mean values).

do not occur simultaneously and sum of maximum story displacements is always larger than roof displacement under a certain earthquake. Thus in order to estimate maximum story drift of a frame by pushover analysis, target displacement is required to be taken larger than roof displacement under design earthquake. This case is intensified for significant contribution of higher modes. In other words, maximum story drift demand is underestimated by Pushover analysis.

Due to the close relationship between story drift and ductility demands, higher mode effects on maximum story dynamic ductility are almost similar to those for maximum story drift demands. The following factor is defined to evaluate these effects

$$\alpha^{\mu}_{H.M} = \frac{\mu_{s,max}}{\mu_{SDOF}} \quad (8)$$

Where $\mu_{s,max}$ is the maximum story dynamic ductility ratio in *MDOF* frame and μ_{SDOF} is the equivalent *SDOF* ductility ratio. Maximum story ductility of an *MDOF* frame can then be related to *SDOF* ductility through this factor which refers to higher mode effects on maximum story dynamic ductility ratio in an *MDOF* frame.

$\alpha^{\mu}_{H.M}$ factors were computed under different earthquakes and for μ_{SDOF} values of 3, 5 and 7. The corresponding results are shown in Figure (11a). Figure (11b) shows the variation of the mean values.

It can be seen that the amplification of maximum story ductility demand in an *MDOF* frame, relative to equivalent *SDOF* ductility (represented by $\alpha^{\mu}_{H.M}$), mostly increases with increasing period and *SDOF* ductility. This indicates the importance of higher mode effect on maximum story ductility demand in high rise frames and higher *SDOF* ductility levels.

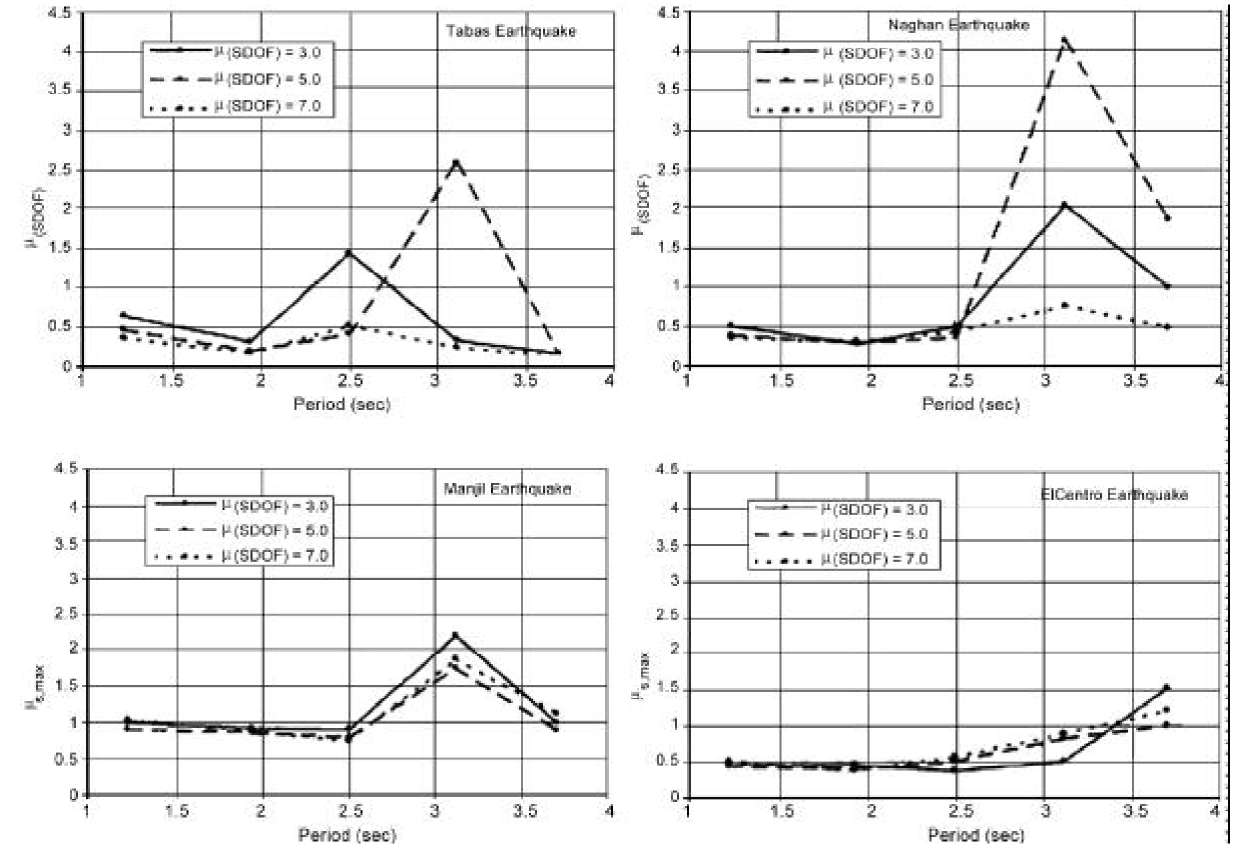

Figure 11a. Higher mode effects on maximum story ductility demands.

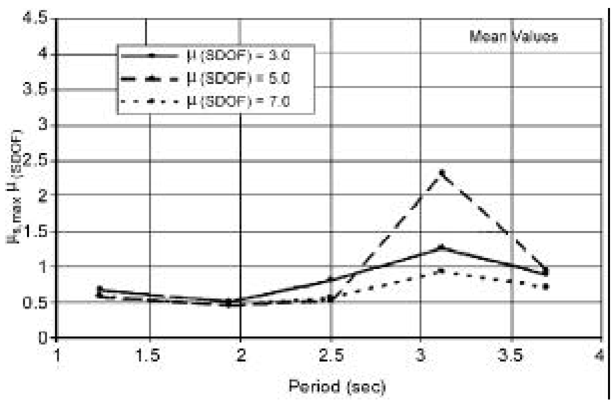

Figure 11b. Higher mode effects on maximum story ductility demands (mean values).

8. Conclusions

The purpose of this study was to investigate higher mode effects on different responses of *MDOF* steel moment-resisting frames under seismic motions. In this regard, some modification factors were defined to estimate seismic demands of *MDOF* frames from equivalent SDOF systems. The following conclusions are drawn from different parts of this study:

A) Higher mode effects in elastic analysis:

- The percentage of higher modes' participation in all responses of *MDOF* frames increases with number of stories (Fundamental period).
- Among different responses of an *MDOF* frame, roof shear is the most influenced by higher modes and base shear response is in the next order. Roof displacement is not that much affected by higher modes. Force responses are generally more dependent on higher mode affects rather than deformation responses.
- The percentage of higher mode effects in force responses decrease with a rise in the number of bays, while the opposite trend was observed for deformation responses.
- The ratio of roof elastic displacement of an *MDOF* frame to elastic first mode spectral displacement, defined as $\alpha_{H.M}^{d,el}$ can be approximated by PF_1 factors. These factors always increase with an increase in period.

B) Strength reduction factors of *MDOF* frames:

- R_μ factor, which accounts for inelasticity in *SDOF* systems, always increases with increasing target ductility and mostly with structural period.
- Strength reduction factors of *MDOF* frames,

can be computed by multiplying R_μ by $1/\alpha^{V}_{H.M.}$ modification factor which takes the higher mode effects into account.

- Base shear higher modes modification factors always increase with increase in fundamental period of frames and mostly increase with increase in target ductility.

C) Higher mode effects on maximum story drift and ductility demand:

- Vertical distribution of story drift and ductility in height of the frames show sudden increase in higher stories. The reason is the contribution of higher modes which is of more significance for long-period frames.
- $\alpha^{d}_{H.M}$ modification factor, which is a criteria of higher mode effects on maximum story drift demands, mostly increases with a rise in period and level of *SDOF* ductility. In other words, the difference between maximum story and global drift demands increases in long-period structures.
- $\alpha^{\mu}_{H.M}$ modification factors, implying higher mode effects on maximum story ductility demand, mostly increase with period and level of *SDOF* ductility, which indicates the importance of higher modes.

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