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Modal spectra combination method for pushover analysis of special steel moment resisting frames

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Abstract

The nonlinear static procedures (NSPs) proposed by design codes do not lead to reliable results especially for tall buildings. They generally provide inconsistent estimates of inelastic seismic demands, especially for the top floors due to their inabilities in considering the higher modes effects. In this paper, a new enhanced pushover procedure is proposed which is based on the envelope of the structural responses resulting from two separate pushover analyses as a combination rule. Also, the suggested pushover analyses are performed using a newly proposed modal load pattern, i.e., the Modal Spectra Combination (MSC), and the ASCE41-06 required first mode load pattern. The MSC load pattern is consisted of a number of mode shapes combined with appropriate weighting factors that depend on their modal participation factors, modal frequencies and design spectral values. A number of 2-D steel moment resisting frame models with different number of stories are used to investigate the efficiency of the proposed method. The inter-story drifts and the maximum plastic beam moment and curvature responses are used as a measure to compare the results obtained from the nonlinear time-history analyses (NL-THA) and some other NSPs. The results obtained through rigorous nonlinear dynamic analyses show that the application of the proposed method leads to acceptable results for steel MRF systems in comparison to other available enhanced NSPs. The OpenSees program is used for numerical analysis.

Keywords: Nonlinear static analysis, Pushover analysis, Lateral load pattern, Nonlinear dynamic analysis.

1. Introduction

Nonlinear dynamic procedure (NDP) can in general provide more realistic results than nonlinear static procedures (NSPs) as it considers the effect of higher modes and the shifts in inertia load patterns when structural softening occurs. However, engineers are more likely to use NSPs because of considerable difference in modeling restrictions, ground motion characteristic, computational effort, and other existing difficulties for NDP.

In recent years, increasing demand for using the performance based design methods have made researchers to intensify their efforts to modify and enhance the accuracy of the NSPs on variety of structural models. A number of those methods have been implemented in design codes and guidelines such as ATC-40 [1], FEMA356 [2], FEMA440 [3] and ASCE41-06 [4]. These procedures apply constant load patterns such as inverse triangular, Equivalent Lateral Force (ELF), first mode shape, uniform, and SRSS modal response combination load patterns in performing pushover analyses.

Application of constant load patterns has two disadvantages. These load patterns are not able to consider the effects of higher modes, especially in structures with large fundamental periods as well as progressive stiffness degradation and shifts in inertia load patterns. To overcome these drawbacks, enhanced pushover procedures have been developed by researchers to minimize the inaccuracies of a static analysis in predicting the real nonlinear response of structures while maintaining its simplicity. These attempts which aimed to evaluate the seismic demands of buildings more accurately can be classified in the following four categories:

1.1. Modal combination methods:

These methods are based on utilizing a single load vector that is obtained by combination of the fundamental mode shape and a number of higher mode shapes with appropriate weighting factors. The difference between these procedures is

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basically the coefficients used for different modes. Kalkan and Kunnath [5] proposed the method of modal combination (MMC) for pushover analysis of building structures. Park et al. [6] suggested a factored modal combination (FMC) method, to predict the actual story shear profiles for the structural models. Barros et al. [7] established a new multi-mode load pattern based on the relative participation of each mode to be used in pushover analyses of asymmetric three-dimensional building frames. Also Jan et al. [8] improved an upper-bound pushover analysis procedure.

1.2. Modal pushover procedures:

In these procedures the nonlinear pushover analyses are performed for a number of modes of the structural model as the load patterns and also nonlinear dynamic analyses are performed on the SDOF systems based on obtained pushover curves. The final result is obtained using SRSS or CQC combination rules [9]. Chopra and Goel [10,11] proposed the modal pushover analysis (MPA) and modified modal pushover analysis (MMPA) procedures to deal with the higher mode effects. Kim et al. [12] improved the mass proportional pushover procedure, claiming that this method is more simplified than MPA. Gianmeng et al [13] suggested the Improved MPA procedure in which the pushover analysis is performed in two phases.

1.3. Adaptive pushover procedures:

These procedures attempt to update the load vectors progressively to take into account the effect of higher modes and change in system modal properties during inelastic phase. The adaptive spectra based pushover [14], adaptive modal combination [15], story shear based adaptive pushover procedure [16], adaptive displacement based pushover procedure [17], and adaptive Pushover analysis [18, 19] are some of the adaptive procedures that have been developed in recent years. Although, these approaches seem to be conceptually superior, but there is no agreement on the merits of adaptive load patterns [20]. On the other hand, these procedures are usually complicated and computationally expensive to update the force distributions at each step for application in structural engineering practices.

1.4. Energy based approaches:

These procedures are based on energy method for performing the nonlinear static procedure. Hernandez et al. [20] proposed the energy based multi-mode pushover procedure with an energy based pushover curve. Leelataviwat et al. [21] introduced a new energy based method for seismic evaluation of structures, focusing on the fundamental mode effects. Li et al. [22] established a modified approach of energy balance concept based multi-mode pushover analysis to estimate the seismic demands of the buildings structures.

The modal combination methods need the least effort to conduct, since only one pushover analysis is performed for the considered models. Nevertheless, utilizing a constant load pattern may not be able to capture the re-distribution of inertia forces and the change in dynamic properties of the structural models which may occur when local mechanisms form. The target displacement can be obtained from design code approaches such as displacement coefficient method [2, 4], or capacity spectrum method [1].

In the following, some of major existing NSPs are briefly reviewed. Then, a new procedure is introduced to improve the shortcomings of the existing NSPs. The proposed procedure is based on the envelope of the structural demands obtained from two separate pushover analyses as the combination rule. On the other hand, the suggested pushover analyses include a newly proposed modal load pattern, i.e., Modal Spectra Combination (MSC), and the ASCE41-06 required first mode load pattern. The inter-story drifts obtained from the application of the new procedure is compared to those of MMC, MPA and the nonlinear dynamic time history analyses (NL-THA) to demonstrate the efficiency of the proposed lateral load pattern as well as the combination rule. Furthermore, the moment and curvature of plastic hinges formed in the structural models resulting from the proposed procedure is compared with those of NL-TH analyses.

2. Evaluation of the Existing Lateral Load Patterns

Lateral load patterns that have widely been used in the literature can be divided into the two major categories, i.e., code based lateral load patterns and the enhanced lateral load patterns.

2.1. Code-Based Lateral Load Patterns

FEMA-356 used to recommend the application of two lateral load patterns to determine the design actions that may occur during actual dynamic response. The first load pattern supposedly was one of the (a) equal lateral force (ELF) load pattern, (b) fundamental mode shape, and (c) story shear distribution calculated by combining modal responses from a response spectrum analysis. The load patterns (a) and (b) were permitted only when the fundamental mode had more than 75% of the total effective mass of the structural system. The load pattern (c) should have been used when the period of the fundamental mode exceeded 1.0 second. The second load pattern comprised of a mass proportional part together with an adaptive load distributions. FEMA-356 allowed using adaptive load patterns such as story forces proportional to the deflected shape of the structure, load patterns based on mode shapes derived from secant stiffness at each load step, and load patterns proportional to the story shear resistance at each step [2]. Since, application of multiple load patterns recommended by FEMA-356 did not considerably increase the accuracy of the NSPs as expected [3], ASCE41-06 required using a single load pattern based on the fundamental mode shape [4].

2.2. Enhanced Lateral Load Patterns

As it was mentioned earlier, the described load patterns which are based on first mode are not able to estimate the story demands accurately due to negligence of higher modes. So, it was persuading to look for new enhanced load patterns that involve higher mode shapes. The MPA procedure which proposed by Chopra and Goel [10, 11] was among these methods that received considerable attention. This method utilizes separate pushover analyses with different mode shapes as the lateral load patterns to obtain the modal pushover capacity curves. Having employed the idealized capacity curves as the force-displacement characteristics of nonlinear SDOF systems representing different structural modes, their peak responses are calculated performing nonlinear dynamic analyses. For each mode, the static modal response is multiplied by the peak response as the scaling factor. Finally, the obtained modal responses are combined using SRSS or CQC methods. In fact, MPA method uses a number of SDOF nonlinear dynamic analyses beside nonlinear static analyses, so it can be very complicated for any practical applications.

The MMC procedure proposed by Kalkan and Kunnath [5], is based on using a constant load pattern that consists of factored modal shapes for the pushover analysis. The proposed load pattern is defined as:

$$LP_{MMC} = \sum_{i=1}^{n} \alpha_n \Gamma_n m \phi_n S_a(\xi_n, T_n) \quad (1)$$

Where, α_n is a positive or negative modification factor; Γ_n is the n^{th} mode participation factor; ϕ_n is the n^{th} mode shape vector, and S_a is the spectral acceleration at the period corresponding to the mode n. The envelope of the demands resulted from the first two modes was the output of the MMC method. Using parametric analysis, Park et al. [6] proposed the factored modal combination (FMC) load pattern formed by summation of the modal responses multiplied by certain coefficients as below:

$$LP_{FMC} = R_{10}^{m} S_{a1} \Gamma_1 m \phi_1 \pm R_{20}^{m} S_{a2} \Gamma_2 m \phi_2 \pm \ldots \quad (2)$$

Where, R_{n0} is modal combination coefficient defined as:

$$R_{n0} = \left| \frac{\phi_n^T m u_0}{\phi_n^T m \phi_n} \right| \frac{1}{\Gamma_n S_{dn}} \quad (3)$$

and, u_0 is the maximum floors displacement vector obtained from linear dynamic analyses. For this purpose, several earthquake records have been employed to investigate the distribution of modal contribution coefficients R_{n0} , and finally the average value of these coefficients is used as a combination factor.

3. The Proposed Procedure

In general, the modal combination lateral load patterns can be generated as a linear combination of different modes in the following form to improve the efficiency of NSPs in predicting the true nonlinear response parameters of structural models:

$$LP = \sum \beta_i \phi_i = \beta_1 \phi_1 + \beta_2 \phi_2 + \beta_3 \phi_3 + \ldots \quad (4)$$

Where, β is the modal combination coefficient which can be selected as any of the vibrational characteristics of the dynamic system such as modal participation factor, modal frequency, elastic response spectrum, etc. In this study the so-called, Modal Spectra Combination (MSC) lateral load pattern is proposed as the following:

$$LP_{MSC} = \sum_{i=1}^{n} \frac{(S_a + S_v)_i}{2} (\Gamma_i m \Phi_i) = \sum_{i=1}^{n} \frac{1}{2} (1 + 1/\omega_i) S_{ai} (\Gamma_i m \Phi_i) \quad (5)$$

In which Γ_i , ϕ_i and ω_i are the i^{th} modal participation factor, mode shape, and mode frequency respectively. Also, S_{ai} is the spectral acceleration of i^{th} mode. The spectral acceleration of each mode of the system can be obtained from the response spectrum. The reason for suggesting this load pattern is due to the fact that the fundamental period of medium to tall building structures is usually in the constant velocity zone of the response spectrum. Also, the period of the higher modes of these structural systems may be located in the constant acceleration zone of the response spectrum. Therefore, application of coefficients that depend on both the spectral velocity (S_{vi}=S_{ai}/ω_i) and spectral acceleration (S_{ai}) of the first few modes of the system may lead to more accurate results. Clearly there is no need to consider dimensional adaption in the proposing a load pattern, because the load pattern is not the floors force but the floors force relation. In this paper only the first two modes are considered for generating the new lateral load pattern. Depending on the height of the building models, more number of modes may be required to be used for the proposed load pattern [23].

Using the proposed MSC load pattern would lead to acceptable results (especially drifts) for the higher floors, while underestimating the response parameters of the lower floors. On the other hand, as it was described before, the first mode load pattern can provide acceptable results for lower floors while it fails to estimate the response of the top floors properly. Therefore, it is suggested that the envelope of the results of two separate pushover analyses using the MSC and the ASCE41-06 required first mode load pattern be used for determining the demand parameters of the structural system. A numerical example demonstrates the efficiency of the proposed load pattern and the concept of using the envelope of two separate pushover analyses in estimating the response parameters of the building structures.

4. Description of the Structural Models

Three 2-D steel moment resisting frame models with 8 and 15 stories shown in Figure 1 are considered for evaluation of the proposed lateral load pattern. The 8 story model (model A) is considered as a mid-rise building, while the 15 story models (models B and C) represent tall buildings. The structural frames are located on soil type D of ASCE7-10 soil category and have three bays, each one 6m wide. Story height is considered to be typically 3.2m. The floors dead and live loads are considered to be 6 kN/m^2 and 2.5 kN/m^2 respectively and the roof live load is assumed to be 1.5 kN/m^2. The dimension and the shear distortion of the panel zones are ignored. The P-Δ effect is considered and the structural models are designed according to IBC-2006 and AISC360-05 using

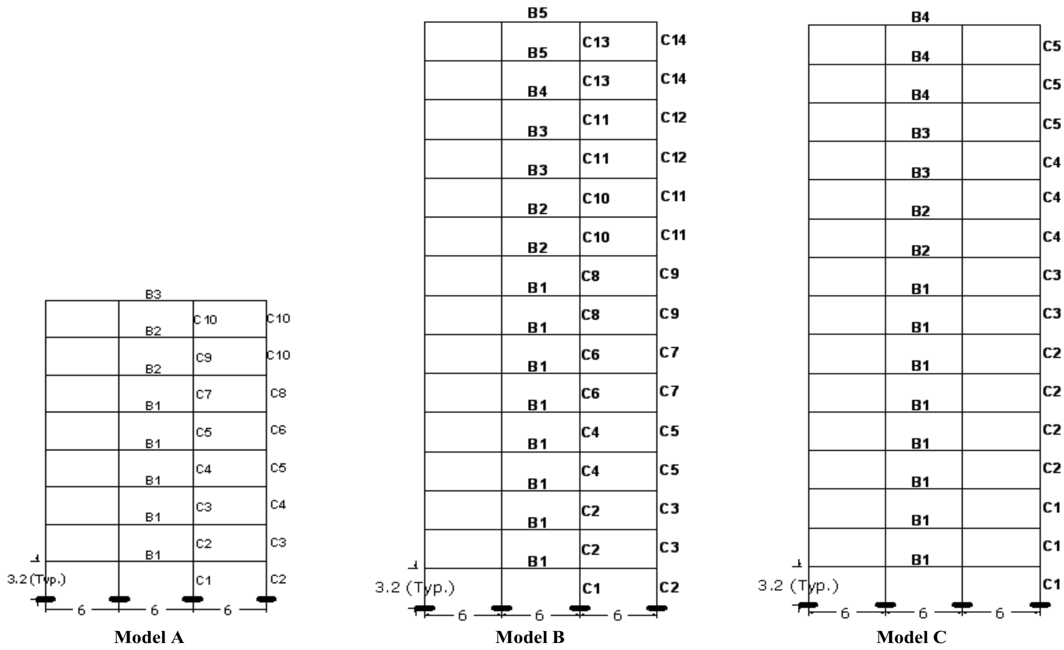


Fig. 1. Structural configuration of models

LRFD method. The maximum story drifts of models A and C are controlled using allowable maximum drift. However, the model B is not controlled for the maximum story drift for comparison purposes. The stress ratios of the beams are selected to be within 0.9 to 1.03 in order to have an optimal design. The member sections are listed in Table 1. Ten far-field earthquake records are selected from the recommended set in ATC-63 [24] that are recorded on soil type D, and all of them are scaled according to the ASCE 7-05 procedure [25]. The selected ground motions and their scale factors are listed in Table 2. The open source finite element framework, OpenSees [26] is used to carry out the nonlinear dynamic analyses. A nonlinear beam-column element with 'fiber' section considering distributed plasticity was utilized to model all components in the frame models. Nonlinear time history analyses are performed using implicit Modified Newton-Raphson method in which the tangent stiffness is not updated within each time step to avoid lengthy calculations.

Table 1. Structural details of models A, B and C

Model A		Model B				Model C	
element	Section	element	section	element	Section	element	section
C1	HE650A	C1	TUBE 400x350x30	C14	TUBE 220x120x20	C1	TUBE 600x450x30
C2	HE550A	C2	TUBE 400x280x30	B1	HE360A	C2	TUBE 600x400x30
C3	HE500A	C3	TUBE 400x200x30	B2	HE340A	C3	TUBE 480x350x25
C4	HE450A	C4	TUBE 380x280x30	B3	HE320A	C4	TUBE 450x350x25
C5	HE400A	C5	TUBE 380x190x25	B4	HE300A	C5	TUBE 320x200x20
C6	HE340A	C6	TUBE380x260x30	B5	HE280A	B1	HE400A
C7	HE320A	C7	TUBE380x180x25			B2	HE360A
C8	HE300A	C8	TUBE380x240x25			B3	HE340A
C9	HE280A	C9	TUBE 320x160x25			B4	HE320A
C10	HE260A	C10	TUBE 320x180x25				
B1	HE320A	C11	TUBE 300x150x22				
B2	HE300A	C12	TUBE 240x150x20				
B3	HE280A	C13	TUBE 220x100x20				

Table 2. Details of ground motion records used for NL-THA

No.	EQ ID	Earthquake			Site Data	Source (Fault Type)	Lowest Freq (Hz.)	PGA_{max} (g)	PGV_{max} (cm/s.)	Scale Factor	
		M	Year	Name						Model A	Model B,C
1	12011	6.7	1994	Northridge	D	Thrust	0.25	0.52	63	1.43	1.79
2	12012	6.7	1994	Northridge	D	Thrust	0.13	0.48	45	1.54	1.94
3	12041	7.1	1999	Duzce, Turkey	D	Strike-slip	0.06	0.82	62	0.9	1.14
4	12062	6.5	1979	Imperial Valley	D	Strike-slip	0.25	0.38	42	1.95	2.45
5	12072	6.9	1995	Kobe, Japan	D	Strike-slip	0.13	0.24	38	3.09	3.88
6	12081	7.5	1999	Kocaeli, Turkey	D	Strike-slip	0.24	0.36	59	2.06	2.59
7	12092	7.3	1992	Landers	D	Strike-slip	0.13	0.42	42	1.77	2.22
8	12102	6.9	1989	Loma Prieta	D	Strike-slip	0.13	0.56	45	1.32	1.66
9	12141	7.6	1999	Chi-Chi, Taiwan	D	Thrust	0.05	0.44	115	1.68	2.12
10	12151	6.6	1971	San Fernando	D	Thrust	0.25	0.21	19	3.53	4.43

In case of no convergence, the program would use other methods such as Broyden and Newton-Raphson algorithms to maintain that. The Rayleigh damping matrix is defined considering 5% damping ratio for the first and third modes of the structural models. The initial stiffnesses of the building structures are used in constructing the Rayleigh damping matrix.

The modal properties and the spectral accelerations corresponding to different modes of the structural models are listed in Table 3. The average 5% damped spectral pseudo-accelerations that were obtained from the nonlinear dynamic analyses using the scaled ground motion records, are shown in Figure 2. As expected, the fundamental periods of the structural models are in the constant velocity region of the response spectrum, while the periods of higher modes are located in the constant acceleration zone of the response spectrum.

5. Evaluation of the MSC Lateral Load Pattern

The efficiency of the proposed MSC lateral load pattern and the suggested combination rule in estimating different response parameters is compared with the results of nonlinear time-history analyses and the output of a number of other enhanced NSPs. To compare the load pattern effect on the seismic response, it is needed to consider the same target displacement for each method. In this study, the target displacement is considered to be equal to the average roof displacement responses obtained from the NTHA. Figures 3 and 4 show the individual and the average floors maximum displacement and drift responses obtained from the nonlinear time history analyses respectively.

To evaluate the efficiency of proposed procedure, the inter-story drift results were compared with those obtained from nonlinear time-history analysis, MMC and MPA procedures, considering the first three modes. The results are shown in Figure 5 and the errors in the inter-story drift obtained from these procedures are shown in Figure 6. The maximum errors in floors drift response in MMC procedure are -39% and +106% for model A, -45% and +205% for model B and -37% and +258% for model C. These values for MSC load pattern reduce to -21% and +6% for model A, -27% and +11% for model B and -27% and +9% for model C. The errors in the results of MPA procedure are -17% and +6% for model A, -14% and +24% for model B and -10% and +23% for model C. The errors of results obtained from various procedures in the model B are more than other models. This is due to the fact that no story drift limit was used in designing the model B.

The MMC results for higher and lower floors are largely overestimated, while for middle floors the results are underestimated. This is due to consideration of higher modes with large coefficient to form the MMC load pattern. The results obtained from MSC method are comparable with MPA method noticing that MPA procedure is more difficult for possible application. To perform MPA procedure, it is needed to perform several static pushover and NL-THA analyses on the equivalent SDOF systems. However, for the MSC procedure, only two separate pushover analyses needs to be done in which only one of them is required by ASCE41-06(the first mode load pattern). Furthermore, in this study the corresponding target displacement to be used in MSC procedure is considered to be equal to NL-THA result for roof displacement. If the target displacement is calculated according to design code approach, the results for MSC method seem to be more conservative than MPA procedure.

Table 3. Modal properties of the structural models

	Period (sec)			Modal Participation factor			Modal Mass Participation factor			Spectral Acceleration Response (g)		
Model	A	B	C	A	B	C	A	B	C	A	B	C
mode 1	1.82	3.19	2.49	1.38	1.42	1.4	0.79	0.75	0.73	0.33	0.20	0.28
mode 2	0.66	1.23	0.92	-0.56	-0.65	-0.61	0.13	0.11	0.12	1.30	1.01	1.22
mode 3	0.37	0.73	0.51	0.3	0.37	0.36	0.03	0.04	0.04	1.59	1.56	1.90
mode 4	0.25	0.51	0.35	-0.17	-0.23	-0.25	0.01	0.03	0.03	-	1.90	2.21
mode 5	0.18	0.38	0.25	0.07	0.16	0.19	0.004	0.02	0.02	-	2.11	2.37

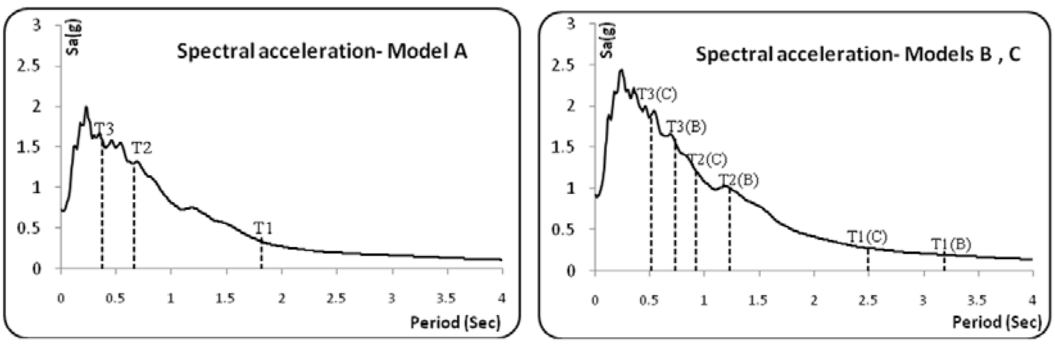


Fig. 2. Average acceleration response spectrum for the considered structural models

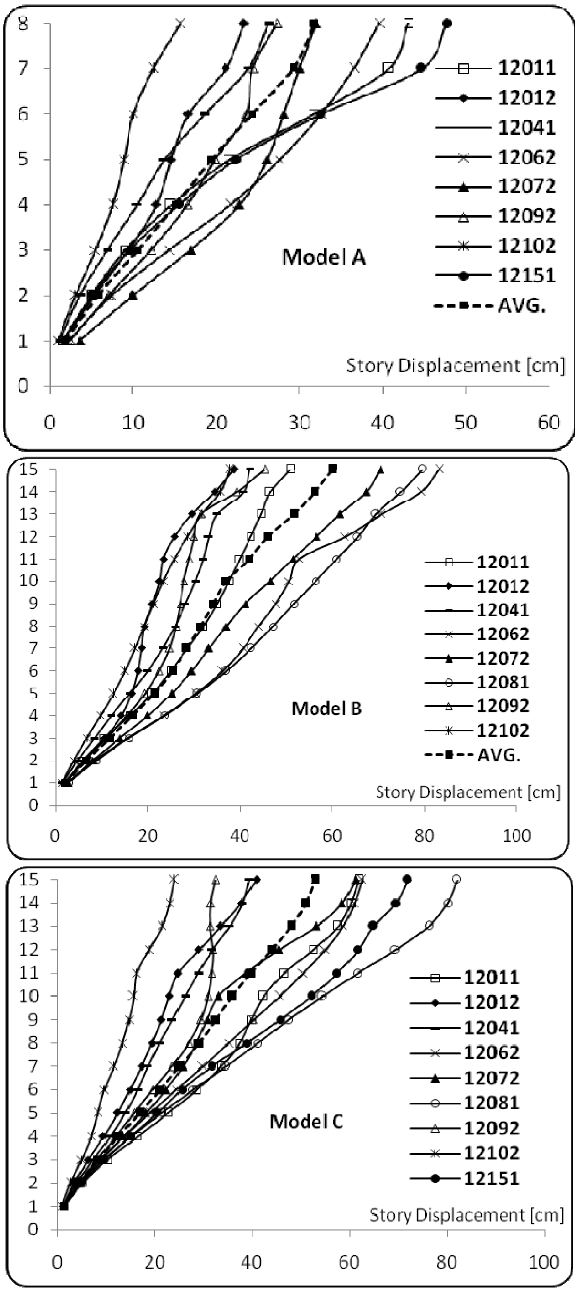


Fig. 3. The Maximum floor displacement demand obtained from the Nonlinear Time-History analyses for used models

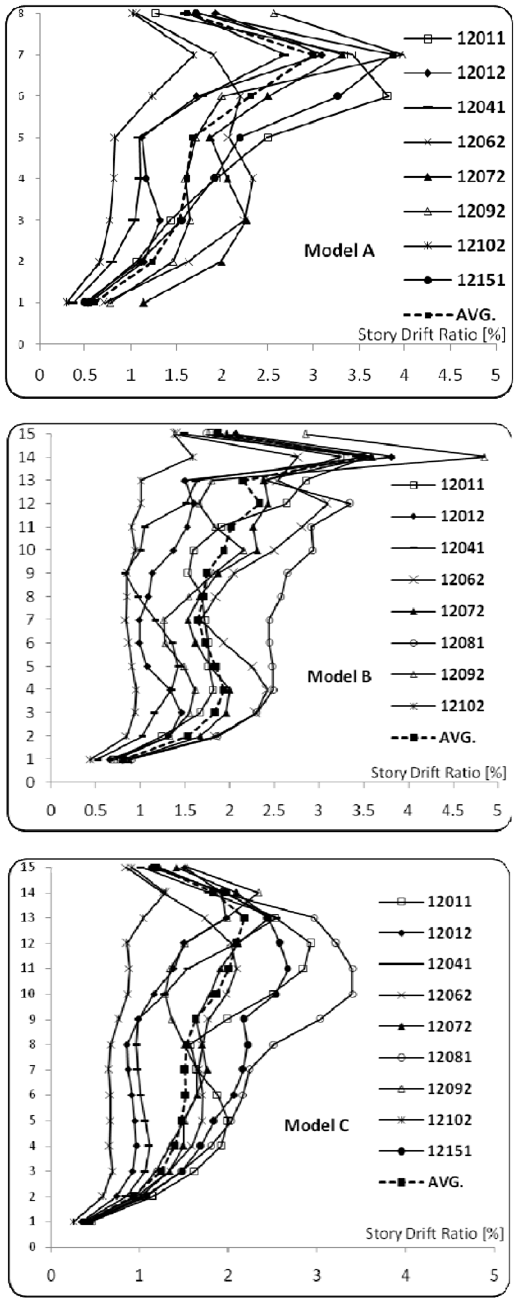


Fig. 4. The Maximum inter-story drift demand obtained from the Nonlinear Time-History analyses for used models

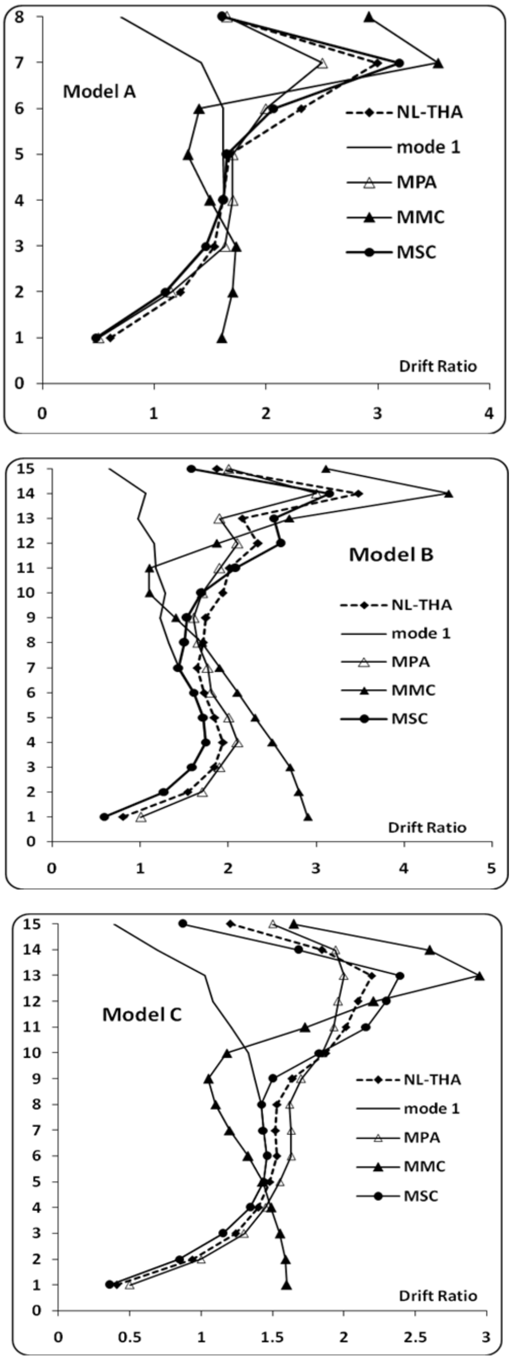
Considering the obtained results, one may recommend the MSC procedure to be used for any nonlinear static analysis.

To evaluate the seismic demands obtained from the proposed lateral load pattern, the plastic moment and the curvature of the inner support of corner beams are selected. The results are compared to those of NL-THA results. As it can be seen from Figures 7 and 8, these response parameters are well predicted by the proposed method.

The error in determining the beam plastic curvature responses are larger than plastic moment responses. But in general, the results are in good agreement with NL-THA analysis output. The errors in response prediction by model B are larger than the other models that were mainly caused by ignoring the story drift limit is its design.

6. Conclusion

In recent years, the researchers have proposed various enhanced nonlinear static procedures that aim to capture the true seismic-induced structural demands. Some of the introduced procedures are very complicated thus compromising the simplicity of the static pushover analysis approach. In this study, a new simple multi-mode lateral load pattern, i.e., the Modal Spectra Combination (MSC) was proposed in which a number of mode shapes were combined together with weighting factors that depend on the modal properties of structures and their spectral values. The envelope of the inelastic responses resulting from the proposed load pattern and the ASCE 41-06 required first mode load pattern was considered as a combination rule to determine



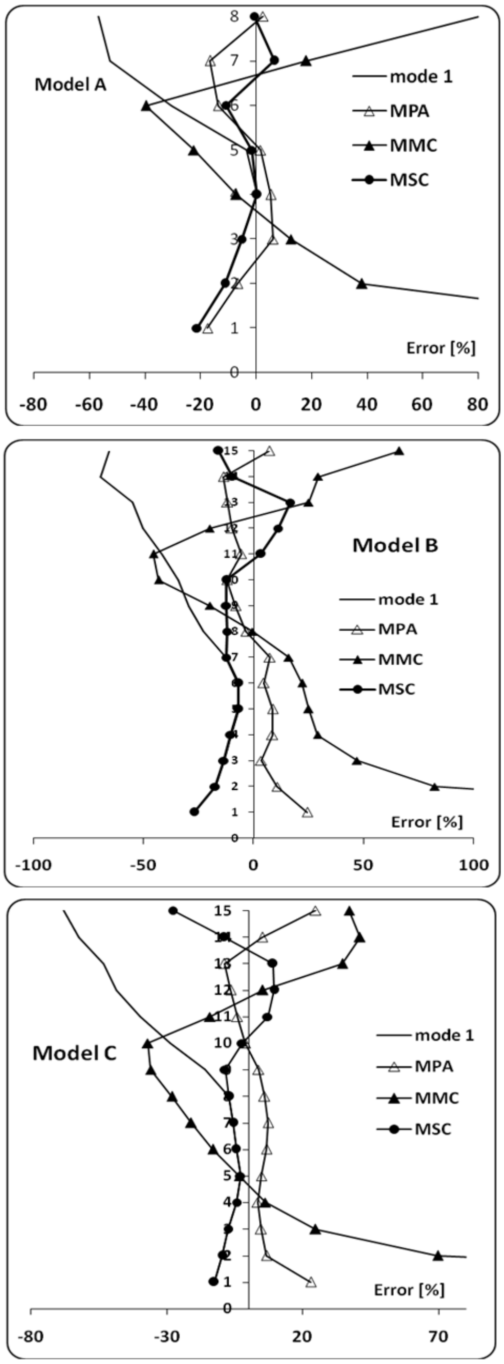


Fig. 5. Evaluation of inter-story drift ratio using different procedures

Fig. 6. Errors of inter-story drift ratio using different procedures

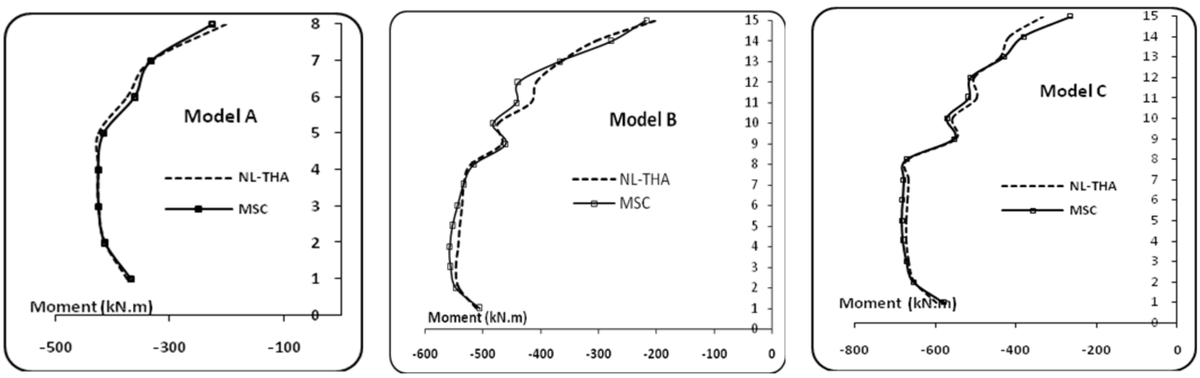


Fig. 7. Evaluation of beam plastic moment response obtained from MSC procedure

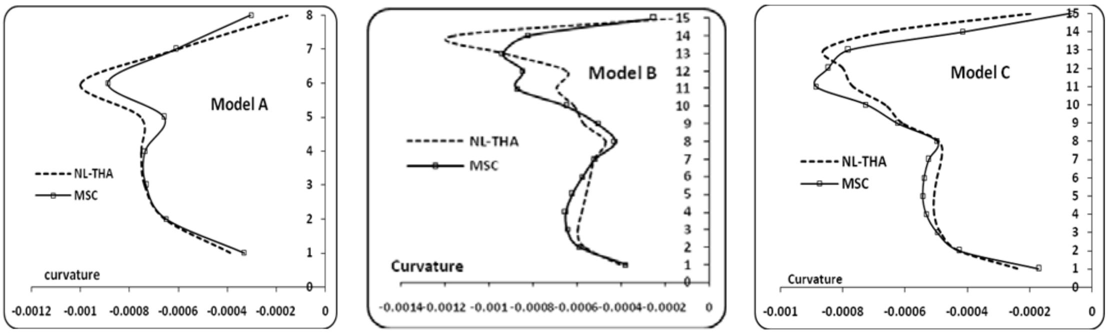


Fig. 8. Evaluation of beam plastic curvature response obtained from MSC procedure

the seismic demand parameters in the structures. To investigate the efficiency of the proposed load pattern in estimating the inelastic response of structure, various nonlinear time-history analyses were performed on a number of 2-D special moment resisting steel frame models with 8 and 15 stories. Besides, the performance of some existing enhanced NSPs procedures were studies for comparison purposes. The story drift demands obtained from different procedures including the proposed MSC method were compared with time-history results. It was shown that among the presented procedures, the proposed lateral load pattern MSC, and the related modal combination rule (the envelope of the results of 2 NSP) provides acceptable results. As the results indicated, the MPA and MSC procedures closely estimate the system response parameters while the proposed MSC procedure is simpler for any practical use by engineers. To evaluate the MSC procedure, the results for plastic moments and the beam curvatures were compared to those obtained from NL-THA. It was shown that the MSC method closely estimates the response parameters in the considered structural models.

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