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A SINGLE-RUN MULTI-MODE PUSHOVER ANALYSIS FOR SEISMIC EVALUATION OF TALL BUILDINGS

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Abstract

Pushover analysis has become an accepted tool for the seismic evaluation of structures in recent years. However, one of the shortcomings of this nonlinear static analysis is its inability to estimate the seismic demands of tall buildings. In this paper, a new procedure, called the single-run multi-mode pushover (SMP) analysis, is proposed to account for the effect of higher modes in estimating the seismic demands of tall buildings. The main simplification of this procedure is that the effect of higher modes is concentrated into a single invariant lateral force distribution computed by algebraically adding the modal story forces whereby a single-run multi-mode pushover analysis is implemented. An important advantage of the proposed procedure is that the spectral pseudo-acceleration of ground motions (or design spectrum) as a weighting parameter as well as the effective modal mass ratio is incorporated into the modal story forces. Then, the effect of the frequency content of ground motions is considered in the modal lateral forces. Another advantage of the SMP procedure is that the reversal of sign in the story forces of higher modes is taken into account. In this procedure, the seismic demands are finally obtained by enveloping the results of single-run conventional and single-run multi-mode pushover analyses. To assess the accuracy of the proposed procedure, two special steel moment-resisting frames are considered. The seismic demands resulting from the SMP procedure are compared to those from the nonlinear response history analysis (NL-RHA), as well as to those predicted from the modal pushover analysis (MPA) and the consecutive modal pushover (CMP) procedures. The results demonstrate that the SMP procedure can accurately estimate the seismic demands of tall buildings.

Keywords: single-run multi-mode pushover, higher modes effect, enhanced lateral force distribution, tall buildings

1. Introduction

Nonlinear response history analysis (NL-RHA) is a robust analytical tool for estimating the seismic demands of structures responding in the inelastic range. However, because of its conceptual and numerical complications, simplified procedures are being increasingly used in the structural engineering community. In practical engineering applications, the nonlinear static procedure (NSP) or pushover analysis is widely used as a suitable tool for seismic performance evaluation of building structures [1]. Indeed, despite of its simplicity, the NSP is able to provide an accurate estimation of seismic demands that cannot be obtained from an elastic static or dynamic analysis.

Conventional pushover analysis methods presented in various codes [2-4], are limited to the first-mode-dominated structures. In these methods, the structure is subjected to monotonically increasing lateral forces with an invariant height-wise distribution until a predetermined target displacement is reached. The basic assumption is that the response of structure is controlled by a single mode, and the mode shape remains constant throughout the analysis [5]. Therefore, there are two important shortcomings in the conventional pushover procedures: 1) they cannot take higher modes effect into consideration [5-6], and 2) they neglect the changes in the dynamic characteristics of structures that lead to a variant load distribution [7].

Much research effort has been devoted in recent years to overcome these limitations. In order to account for the progressive stiffness degradation of structures subjected to monotonic loading in the inelastic range, adaptive pushover methods have been developed [7-12]. The lateral force distribution in each step of an adaptive pushover method is updated based on an eigenvalue analysis. This procedure may provide accurate seismic responses; nevertheless, it is relatively sophisticated in practice and requires a lot of computational efforts.

Since more than a decade ago, researchers [6, 13-25] have developed enhanced pushover analysis procedures to take higher modes effect into account. Chopra and Goel [6, 13] proposed the modal pushover analysis (MPA) based on structural dynamics theory, which retains the computational attractiveness. This method uses an invariant modal lateral force distribution to implement pushover analysis for each mode, and the results obtained for each mode are combined with an appropriate modal combination rule by assuming linear elastic behavior. Also, a modified version of the MPA (MMPA) was proposed by Chopra et al. [16] wherein the response contributions of higher vibration modes were computed by assuming that the building remains linearly elastic. About the same time, an upper-bound pushover analysis procedure [17] was proposed in which a new formula was employed for determining the invariant load pattern using the absolute sum modal combination rule. Only the first two modes were considered in this method. An alternative method, which was named the consecutive modal pushover (CMP) procedure, was proposed [19-21] to take higher modes effect into account. This procedure utilizes multi-stage and single-stage pushover analyses. The final structural responses are determined by enveloping the results obtained from the multi-stage and single-stage pushover analyses. More recently, Kreslin and Fajfar [24] extended the N2 method [23] in order to take the effect of higher modes into account. The basic assumption is that the structure remains in the elastic range in higher vibration modes. In this method, the seismic demands are estimated by enveloping the results of basic pushover analysis and those from elastic modal analysis. The estimation of plastic hinge rotations was not demonstrated in the EN2 method.

The main objective of this study is to propose a single-run multi-mode pushover (SMP) procedure to take higher mode effect into account in computing the seismic demands of tall building frames. In this method, the seismic demands are estimated by enveloping the results of two or three single-run pushover analyses. The major simplification of this procedure in comparison with some other enhanced pushover analyses [6, 16, 19, 22] is that the effect of higher modes is concentrated into a single invariant lateral force distribution. Therefore, only one pushover analysis is sufficient without any need to utilize a modal combination rule. Also, the proposed procedure has an advantage that the spectral pseudo-acceleration is incorporated in the lateral force distribution. Moreover, the SMP procedure can provide an accurate estimation of seismic demands, especially plastic rotations of the hinges, as compared to the other single-run pushover methods [17, 18]. To verify the proposed procedure, two special steel moment-resisting frames are considered. The seismic responses resulting from the SMP procedure are compared to those from the NL-RHA as a benchmark solution, as well as to those predicted from the MPA and CMP procedures.

2. Proposed pushover procedure

2.1 The conceptual basis of modal response analysis

The governing equation of motion of a multi-degree-of-freedom (MDOF) system under a horizontal earthquake ground motion is given by [26]:

$$\boldsymbol{m}\ddot{\boldsymbol{u}} + \boldsymbol{c}\dot{\boldsymbol{u}} + \boldsymbol{k}\boldsymbol{u} = -\boldsymbol{m}\boldsymbol{i}\ddot{u}_g(t) \tag{1}$$

where $\boldsymbol{m}$, $\boldsymbol{c}$, and $\boldsymbol{k}$ are mass, damping, and stiffness matrices of structure, respectively, and $\boldsymbol{i}$ is the unit vector. The right hand side of the previous equation represents the effective earthquake forces, $p_{eff}(t)$, and can be written as:

$$p_{eff}(t) = -\boldsymbol{m}\boldsymbol{i}\ddot{u}_g(t) = -\boldsymbol{s}\ddot{u}_g(t) \tag{2}$$

where $\boldsymbol{s}$ is the distribution of effective earthquake forces over building's height and can be expanded as a summation of the modal inertia force distributions, $\boldsymbol{s_n}$, as follows:

$$\boldsymbol{s} = \boldsymbol{m}\boldsymbol{i} = \sum_{n=1}^{N}\boldsymbol{s_n} = \sum_{n=1}^{N}\Gamma_n\boldsymbol{m}\boldsymbol{\Phi_n} \tag{3}$$

where, Γ_n is the nth modal participating factor and $\boldsymbol{\Phi_n}$ is the corresponding mode shape. The displacement of an N degree-of-freedom system can be defined as:

$$\boldsymbol{u}(\boldsymbol{t}) = \sum_{n=1}^{N}\boldsymbol{\Phi_n}q_n(t) \tag{4}$$

where, $q_n(t)$ is the modal coordinate and is governed by:

$$\ddot{q}_n + 2\zeta_n\omega_n\dot{q}_n + \omega_n^2 q_n = -\Gamma_n\ddot{u}_g(t) \tag{5}$$

in which ω_n and ζ_n are the natural frequency and damping ratio of nth mode, respectively. Γ_n is obtained as follows:

$$\Gamma_n = \frac{\boldsymbol{\Phi_n^T}\boldsymbol{m}\boldsymbol{i}}{\boldsymbol{\Phi_n^T}\boldsymbol{m}\boldsymbol{\Phi_n}} \tag{6}$$

The solution of Eq. (5) is given by:

$$q_n(t) = \Gamma_n D_n(t) \tag{7}$$

where $D_n(t)$ is governed by the equation of motion for a single-degree-of-freedom (SDOF) system with vibration properties of the nth-mode of the MDOF system subjected to $\ddot{u}_g(t)$:

$$\ddot{D}_n + 2\zeta_n\omega_n\dot{D}_n + \omega_n^2 D_n = -\ddot{u}_g(t) \tag{8}$$

Substituting Eq. (7) into Eq. (4) gives the floor displacements:

$$\boldsymbol{u}(\boldsymbol{t}) = \sum_{n=1}^{N}\Gamma_n\boldsymbol{\Phi_n}D_n(t) \tag{9}$$

Some parameters, which were used in the SMP procedure, are introduced herein. Making use of Eq. (6), the effective modal mass, M_n^*, and the effective modal participating mass ratio for the nth mode, α_n, can be defined as:

$$M_n^* = L_n\Gamma_n \tag{10}$$

$$\alpha_n = \frac{M_n^*}{M^*} \tag{11}$$

in which,

$$L_n = \boldsymbol{\Phi_n^T}\boldsymbol{m}\boldsymbol{i} \tag{12}$$

$$M^* = \sum_{j=1}^{N} m_j \tag{13}$$

where M^* is the total mass of the structure obtained by summation of the lumped masses, m_j, over all floor levels. Using Eqs. (3), (11), and (13) indicates that the summation of effective modal participating mass ratios over all modes is equal to unity.

2.2 Pushover lateral force distribution

To incorporate the effect of higher modes into the NSP, some prior enhanced pushover analysis methods such as the modal pushover analysis (MPA) [6] and the modified modal pushover analysis (MMPA) [16] methods were proposed assuming that the effects of different modes are uncoupled. Then, the modal responses obtained for some modes are combined to produce the overall seismic demands of a structure. An alternative method was proposed by Poursha et al. [19, 20] to take higher modes into consideration. In this procedure, multi-stage and single-stage pushover analyses are used. In the multi-stage pushover analysis, a consecutive implementation of modal pushover analyses is employed, such that when one stage (one modal pushover analysis) is completely performed, the next stage (the next modal pushover analysis) begins with an initial structural state which is the same as the condition at the end of the previous stage. Finally, the seismic responses are determined by enveloping the results of multi-stage and single-stage pushover analyses. However, a relatively simpler way to overcome the deficiency of conventional NSP is to incorporate higher modes effect into a single invariant lateral force distribution. This section describes the invariant lateral force distribution employed in the proposed enhanced pushover analysis.

The external loading in the dynamic equation of motion can be obviously separated into a function of time and the one which shows spatial distribution of the effective earthquake forces over the height (see Eq. (2)). Eq. (3) indicates that the spatial distribution over the building's height then can be expanded as a summation of modal inertia force distributions. In order to introduce features of the earthquake loading for a static procedure, the most appropriate form is the application of a response spectrum. Therefore, the spatial distribution of lateral forces to be used in a pushover analysis is as follows:

$$\boldsymbol{f_n} = \Gamma_n \boldsymbol{m} \boldsymbol{\Phi_n} S_a\left(\zeta_n, T_n\right) \tag{14}$$

where $\boldsymbol{f_n}$ is the lateral force distribution for the nth mode and S_a is the spectral pseudo- acceleration as a function of vibration period T_n and damping ratio ζ_n of the nth mode for a given earthquake ground motion. The modal lateral forces are weighted by a weighting factor S_a to account for the effect of the frequency content of a particular input ground motion in the response of the structure. A previous research [8] elucidated that considering the spectral acceleration of a particular mode in computation of the modal lateral forces could improve the results of the NSP. A large number of researchers [8, 27, 28] employed Eq. (14) to represent the modal lateral force distribution and then combined them using an appropriate modal combination rule to obtain a single invariant lateral force distribution. However, in this paper, a new modal lateral force distribution is proposed such that the effective modal participating mass ratio calculated using Eq. (11) is employed instead of modal participation factor in Eq. (14). Therefore, the modal lateral force distribution for nth mode can be represented as follows:

$$\boldsymbol{f_n} = \alpha_n \boldsymbol{m} \boldsymbol{\Phi_n} S_a\left(\zeta_n, T_n\right) \tag{15}$$

Because the sum of effective modal participating mass ratios over all modes is equal to unity, the ratios can better display the contribution of a particular mode in the lateral force distribution. In order to combine the modal lateral forces to compute a single invariant lateral force distribution, some researchers [8, 29] have used the quadratic modal combination rules such as the square root of the sum of the squares (SRSS) or the complete quadratic combination (CQC). The major drawback of these rules is that the effect of the sign inversion in the storey forces of higher modes is not reflected in the applied load pattern. Therefore, some alternative modal combination rules [12, 27, 28] were used to estimate the overall seismic response of the structure. In this paper, the invariant lateral force distribution for pushover analysis is calculated by algebraically adding the modal story forces. The following expression is, therefore, used to compute the story forces:

$$\boldsymbol{F_k} = \sum_{i=1}^{k} \boldsymbol{f_i} = \sum_{i=1}^{k} \beta_i \boldsymbol{m\Phi_i} S_{ai}\left(T_i, \zeta_i\right) \tag{16}$$

where $\boldsymbol{F_k}$ is the lateral force vector to be applied at the floor levels, k is the number of vibration modes considered in obtaining the lateral force distribution, and the factor β_i is determined as:

$$\beta_i = \alpha_i \qquad i \le k-1 \tag{17}$$

$$\beta_i = 1 - \sum_{i=1}^{k-1} \alpha_i \qquad i = k \tag{18}$$

Thus, $\boldsymbol{F_2}$ and $\boldsymbol{F_3}$ can be computed as follows:

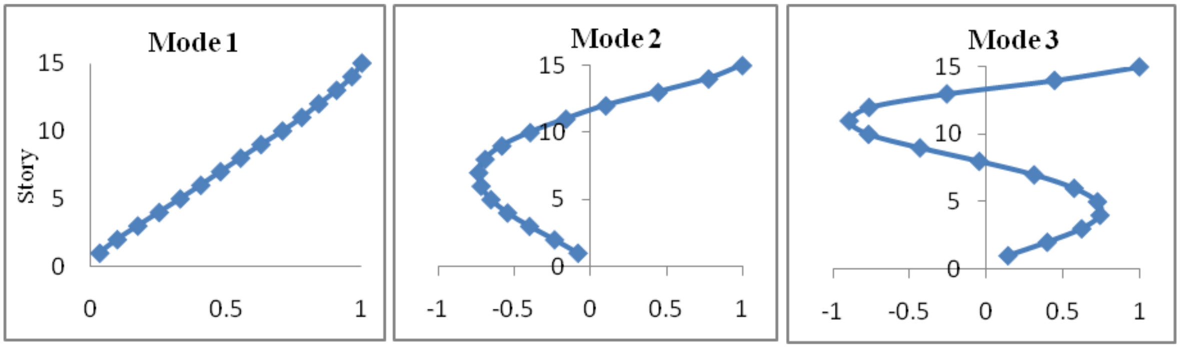
$$\boldsymbol{F}_2 = \boldsymbol{f}_1 + \boldsymbol{f}_2 = \alpha_1 \boldsymbol{m\Phi}_1 S_{a1}\left(T_1, \zeta_1\right) + \left(1-\alpha_1\right) \boldsymbol{m\Phi}_2 S_{a2}\left(T_2, \zeta_2\right) \quad \text{for two modes} \tag{19}$$

$$\boldsymbol{F}_3 = \boldsymbol{f}_1 + \boldsymbol{f}_2 + \boldsymbol{f}_3 = \alpha_1 \boldsymbol{m\Phi}_1 S_{a1}\left(T_1, \zeta_1\right) + \alpha_2 \boldsymbol{m\Phi}_2 S_{a2}\left(T_2, \zeta_2\right) + \left(1-\alpha_1-\alpha_2\right) \boldsymbol{m\Phi}_3 S_{a3}\left(T_3, \zeta_3\right) \quad \text{for three modes} \tag{20}$$

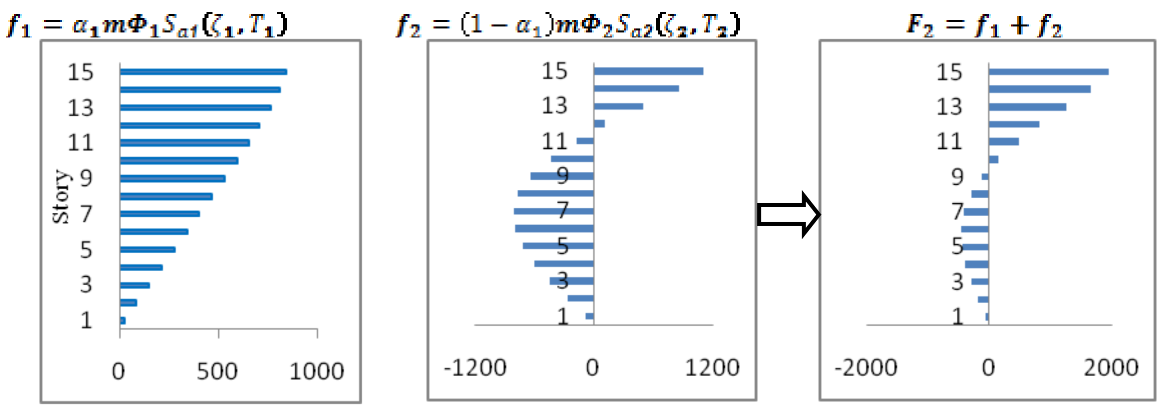
It is interesting to note that only a single-run multi-mode pushover analysis with the enhanced lateral force distribution is sufficient to take higher modes into account without any need to utilize a modal combination rule. In the proposed procedure, the effect of higher modes and the effect of the frequency content of a particular response spectrum on the load pattern are simultaneously considered. The process of determining the applied load pattern in the single-run multi-mode pushover analyses is schematically represented in Fig. 1. First of all, an eigenvalue analysis should be performed to determine the mode shapes of the structure (Fig. 1a). Then, the modal story forces associated to each mode (Fig. 1b and 1c) are computed by using Eq. (15) and finally, the enhanced lateral force distribution which to be applied in the proposed pushover analysis method is calculated using Eq. (16) (Fig. 1b and 1c). As can be seen in Fig. 1, the height-wise variation of the enhanced lateral force distributions is almost similar to the second and third mode shapes.

2.3 A single-run multi-mode pushover analysis

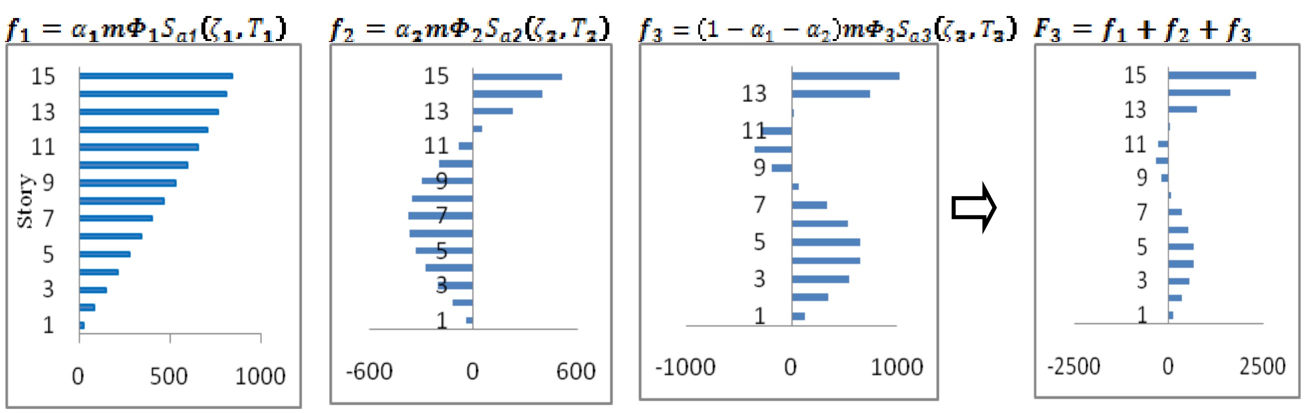
In this section, a single-run multi-mode pushover (SMP) analysis procedure is proposed to estimate the peak seismic responses of building structures subjected to earthquake ground motions. The SMP procedure benefits from the use of some separate single-run pushover analyses because it is possible to use different pushover analyses and to envelope the results [23]. A single-run pushover analysis is performed by employing a conventional lateral force distribution with a triangular or a uniform load pattern. Furthermore, one or two enhanced single-run pushover analyses are carried out using the force distributions proposed in this paper (see Eq. (16)). The number of single-run multi-mode pushover analyses using enhanced force distributions described above, as well as the number of modes participating in the enhanced force distributions depends on the fundamental period, T, of the structure; the number of modes is limited to two or three modes. For structures with the fundamental periods less than 2.2 s, a single-run multi-mode pushover analysis is performed with the lateral force distribution considering the first two modes (Eq. (19)). When the fundamental period of the structure is equal to or greater than 2.2 s, two single-run multi-mode pushover analyses are carried out using Eqs. (19) and (20) that account for the influence of two and three modes of the structure, respectively. Furthermore, a single-run conventional pushover analysis using an inverted triangular or a uniform force distribution should be performed in all cases. Finally, the seismic demands of the structure are obtained by enveloping the responses derived from the single-run conventional and single-run multi-mode pushover analyses. In order to compute the enhanced force distributions using Eq. (16), an eigenvalue analysis of the linearly elastic structure should be implemented. The changes in the modal properties of the structure are ignored when the structure experiences the nonlinear yielding under increasing lateral loads. It is noted that the limit period of 2.2 was suggested according to the investigation done in Reference [20] for steel moment resisting frames. This limit value is almost close to the limit period of T=2.5 s which has been specified in the equivalent lateral force (ELF) distribution in FEMA-356 [2]. For the single-run pushover analyses, the target displacement can be determined by using different approaches such as the displacement coefficient method [2], the capacity spectrum method [4], the N2 method [23], or the nonlinear dynamic analysis of the structure [24, 30, 31].



(a) Mode shapes



(b) Modal story forces and lateral force distribution considering the influence of two modes



(c) Modal story forces and lateral force distribution considering the influence of three modes

Fig. 1. The process of determining the applied lateral load pattern in the single-run multi-mode pushover analyses

The SMP procedure can be summarized as a sequence of the following steps:

1. Compute the natural frequencies, ω_n, and mode shapes, $\boldsymbol{\Phi_n}$, for linearly elastic vibration of the structure. These properties are determined by eigenvalue analysis of the structure for the first three modes. The mode shapes should be normalized such that the roof component of $\boldsymbol{\Phi_n}$ equals unity.
2. Obtain the enhanced lateral force distributions by using Eqs. (19) and (20) that account for the two and three modal story forces, respectively.
3. Calculate the target displacement of the structure at the roof level.
4. The SMP procedure is comprised of two or three single-run pushover analyses. First of all, gravity loads should be applied on the structure and then pushover analyses should be performed according to the steps described below:

4.1. Perform the first single-run pushover analysis using an inverted triangular or a uniform load distribution until the roof displacement reaches the predefined target displacement. The inverted triangular distribution is used for mid-rise buildings, while the uniform distribution is used for high-rise ones.
4.2. Perform the second single-run multi-mode pushover analysis by using the enhanced force distribution, which was obtained in Eq. (19) considering the influence of the first two modes, until the roof displacement sways to the target displacement.
4.3. The third single-run pushover analysis is only performed for structures whose period is equal to or greater than 2.2 s. In this analysis, the enhanced lateral force distribution computed by Eq. (20) is applied to the structure until the roof displacement reaches the target displacement.

5. Compute the interested seismic demands such as displacements, story drifts, and plastic hinge rotations for the single-run pushover analyses implemented in step 4. The responses resulting from the single-run pushover analyses in sub-steps 4.1, 4.2 and 4.3 are represented by r_1, r_2, and r_3, respectively.
6. Determine the envelope, r, of the responses as follows:

$$r = Max\ \{r_1, r_2\} \qquad T < 2.2s \tag{21}$$

$$r = Max\ \{r_1, r_2, r_3\} \qquad T \geq 2.2s \tag{22}$$

This implies that the seismic demands of the inelastic structure in the SMP procedure are obtained by enveloping the responses of different single-run pushover analyses with the invariant force distributions described earlier.

3. Validation of the proposed procedure

The proposed procedure is verified for two special steel moment resisting frames (MRFs) with different heights. The responses resulting from the SMP procedure are compared to those from the more accurate nonlinear response history analysis (NL-RHA) as a benchmark solution. Furthermore, the seismic responses estimated from the MPA and CMP procedures are presented for the sake of comparison. Twenty ground motion records were used to conduct the NL-RHA. Story drift ratios and plastic hinge rotations were computed to evaluate the accuracy of the proposed procedure.

3.1. Structural models

In this investigation, two structures of different heights including 15 and 20-story special steel moment resisting frames (MRFs) were selected from Reference [19] and evaluated. Both of the structures were three-bay frames and all the frames had 5 m bays. Each model had a uniform story height of 3.2 m. The configuration of the frames is shown in Fig. 2. All buildings were assumed to be found on firm soil type 2 of Iranian seismic code [32] (class C of NEHRP) and located in the region of highest seismicity. The characteristics of the building frames and the periods of the first three modes for linearly elastic vibration of the structures are listed in Table 1. A more detailed description of the analytical models can be found in References [15, 19].

In order to implement the nonlinear static and dynamic analyses, the Opensees software [33] was used. Geometrical nonlinearity and material inelasticity were taken into account in all the models. The material inelasticity was explicitly considered by employing a fiber modeling approach. The column and beam members were modeled using a force-Beam-Column element that considers the distributed plasticity in a specified length of the member ends.

3.2. Ground motion records

A total of 20 ground motion records from 13 different earthquake events were selected to develop a reliable set of benchmark responses. These records were selected from the strong ground motion Database of the Pacific Earthquake Engineering Research (PEER) Centre (http://peer.berkeley.edu). The ground motions included records from earthquakes of moment magnitude larger than 5.5 with closest distance greater than about 12 km. Also, the soil at the site corresponds to the NEHRP site class C. To ensure that the structures deform well into the inelastic range when subjected to ground motions, the records were scaled up to 0.7 g. The main properties of the considered records are summarized in Table 2.

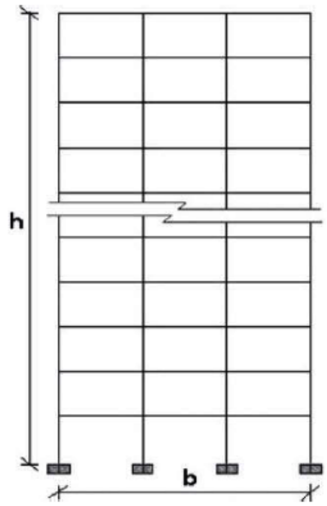


Fig. 2. Configuration of 2-dimensional frames [19]

Table 1. Characteristics of the analyzed frames [19].

No.	No. of stories	h (m)	b(m)	Seismic mass of floors (kg s^2/m)	Periods		
					T_1 (s)	T_2 (s)	T_3 (s)
S1	15	48	15	5546	2.331	0.852	0.492
S2	20	64	15	5600	3.058	1.125	0.667

3.3. Types of analysis

The numerical models of structural frames S1and S2 (see Table 1) were subjected to the scaled ground motions listed in Table 2. The NL-RHA was treated as a benchmark solution method. Then, the seismic demands resulting from different pushover analysis procedures were compared to the mean values of responses resulting from the NL-RHAs for each frame. The proposed SMP method was performed as described in detail earlier. Furthermore, the MPA and CMP procedures were carried out for the sake of comparison. In the CMP procedure, the seismic demands were obtained by enveloping the peak responses derived from the three-stage, two-stage and single-stage pushover analyses for the 15- and 20-story frames. In the CMP and SMP procedures, the target displacement at the roof was set equal to the mean value of the maximum top floor displacements resulting from the NL-RHAs for the selected set of the ground motions. The target displacements were equal to 33.58 and 38.40 cm for the frames S1 and S2, respectively. The MPA procedure was fulfilled including the contributions of three modes of vibration for the 15-story frame, and including the contributions of five modes for the 20-story frame. Because the original MPA procedure fails to accurately predict plastic hinge rotations for high-rise building frames [13, 19], the last version of the MPA [34] was employed to estimate plastic hinge rotations from the story drifts. For this purpose, first, the gravity loads were applied and then a set of displacements that are compatible with the calculated story drifts were imposed at the center of mass on the floor levels. It is noted that a step-by-step numerical integration based on Newmark's constant average acceleration method [26] was employed to perform the nonlinear response history analyses (NL-RHAs). For the NL-RHAs, the damping matrix was defined using Rayleigh damping [26] with a damping ratio of 5% for the first and third modes of vibration.

4. Discussion of the results

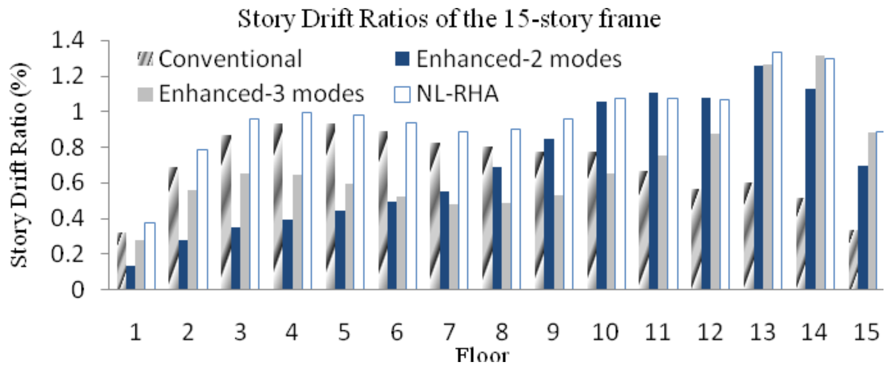
As mentioned previously, the SMP procedure employs some single-run pushover analyses. The seismic demands are then obtained by enveloping the peak responses of single-run pushover analyses performed using the conventional and enhanced lateral load patterns. The peak values of story drift ratios for the 15-story frame resulting from the single-run conventional and multi-mode pushover analyses in the SMP procedure as well as from the NL-RHA are shown in Fig. 3. The figure illustrates that in the SMP method the single-run conventional

Table 2. List of the ground motions used.

No.	Earthquake	Date	Station	Magnitude	Component	Fault Distance(km)	PGA(g)	PGV(cm/s)	PGD(cm)
1	Duzce, Turkey	11/12/1999	Lamont 1061	7.1	E	15.60	0.13	13.69	8.20
2	Hollister	1/26/1986	SAGO South - surface	Ml(5.5)	295	-	0.09	9.27	1.70
3	Imperial Valley	10/15/1979	Parachute Test Site	6.5	315	14.20	0.20	16.06	9.97
4	Imperial Valley	10/15/1979	Cerro Prieto	6.5	147	26.50	0.17	11.58	4.24
5	Imperial Valley	10/15/1979	Superstition Mtn Camera	6.5	135	26.00	0.20	8.78	2.78
6	Kern County	7/21/1952	Taft Lincoln School	7.4	111	41.00	0.18	17.48	8.84
7	Livermore	1/24/1980	CSUH	5.8	146	31.00	0.07	4.11	0.75
8	Loma Prieta	10/18/1989	Anderson Dam	6.9	250	21.40	0.24	20.28	7.69
9	Loma Prieta	10/18/1989	Coyote Lake Dam	6.9	285	22.30	0.18	22.63	13.18
10	Loma Prieta	10/18/1989	Hayward- BART Sta	6.9	220	58.90	0.16	15.06	3.74
11	Morgan Hill	4/24/1984	Corralitos	6.2	310	22.7	0.109	10.788	2.133
12	N. Palm Springs	7/8/1986	Cranston Forest Station	6	315	35.30	0.17	11.70	1.15
13	Northridge	1/17/1994	Featherly Park	6.7	0	84.20	0.10	7.64	0.81
14	Northridge	1/17/1994	LA- Baldwin Hills	6.7	90	31.70	0.24	14.85	6.22
15	Northridge	1/17/1994	Inglewood-Union Oil	6.7	90	44.70	0.10	10.25	3.21
16	Northridge	1/17/1994	LA-Chalon Rd	6.7	70	23.70	0.23	16.59	3.39
17	San Fernando	2/9/1971	Palmdale Fire Station	6.6	210	25.40	0.15	8.09	1.87
18	Trinidad, California	11/8/1980	Rio Dell Overpass FF	Ms(7.2)	270	-	0.15	8.48	3.25
19	Victoria, Mexico	6/9/1980	Cerro Prieto	Ms(6.4)	45	-	0.62	31.58	13.08
20	Westmorland	4/26/1981	Parachute Test Site	5.8	225	-	0.24	39.23	26.89

pushover analysis (with an inverted triangular or a uniform force distribution) controls the responses at the lower stories, whereas the single-run multi-mode pushover analyses with the enhanced force distributions are dominated at the upper stories. For instance, the story drift ratios derived from the single-run conventional pushover analysis for the 15-story frame are close to those of the NL-RHA at the eight lower stories, while the single-run multi-mode pushover analyses considering two and three modes govern the responses at the subsequent four and three stories, respectively (see Fig. 3). Similar illustrations can be expressed for the other seismic demands.

The story drift ratios obtained by the MPA, CMP and SMP procedures, as well as the mean values of NL-RHA, for the 15- and 20-story frames are shown in Fig. 4. Also, the mean values plus the standard deviations of story drift ratios are illustrated in this figure. The figure demonstrates that the MPA, CMP, and SMP procedures predict the story drifts with sufficient accuracy. As can be seen in the figure, in most cases, the CMP and SMP procedures provide a better estimation of story drifts in comparison with the MPA at the upper stories, while the errors in the MPA procedure are less than those in the CMP and SMP procedures at the lower stories, in some cases. As can be seen in the figure, the results obtained for the SMP procedure at the lower stories are completely coincident with those of the CMP procedure because the single-run conventional pushover analysis with an inverted triangular or a uniform force distribution controls the responses at the lower stories for both the CMP and SMP procedures. Furthermore, the results derived from the CMP and SMP procedures are very similar at the upper stories. However, the use of the SMP procedure has some advantages over the CMP procedure. First, the SMP procedure only employs some single-run pushover analyses, whereas the CMP procedure uses both single-stage and multi-stage pushover analyses that the lateral force distribution varies during the stages of the multi-stage pushover analysis. In fact, the effect of higher modes in the SMP procedure is concentrated into a single invariant lateral force distribution applied to the structure, while the CMP procedure benefits from the consecutive implementation of modal pushover analyses in the multi-stage pushover analysis. Therefore, the

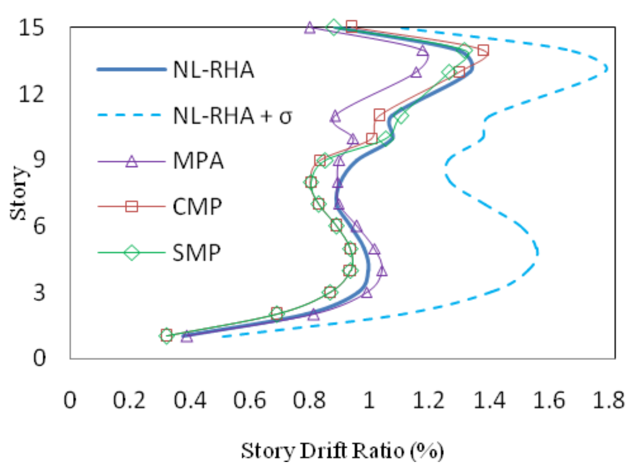


15-story frame

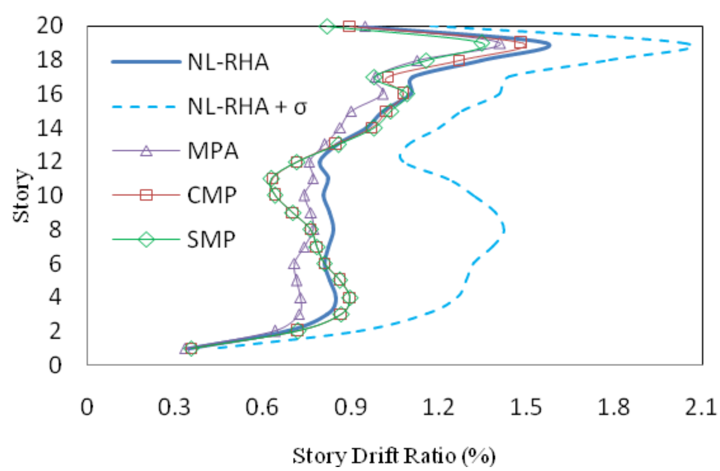
Fig. 3. Peak values of story drift ratios derived from the single-run pushover analyses used in the SMP procedure and from the NL-RHA

fulfillment of the SMP procedure is easier than the CMP procedure. The other advantage of the SMP procedure over the CMP is that the effect of the frequency content of a particular input ground motion or the characteristics of pseudo-acceleration response spectrum are incorporated into the enhanced lateral force distribution proposed in this paper.

The height-wise distribution of plastic hinge rotations for the beam in the middle span of the frames is shown in Fig. 5. As described previously, since the first version of the MPA procedure fails to accurately predict plastic hinge rotations at the upper stories [19], the last version of the MPA [34] was used to compute plastic hinge rotations from the story drifts. As can be seen in Fig. 5, the MPA procedure is more accurate than the CMP and SMP procedures at some lower stories, and vice versa. It is noted that the plastic hinge rotations obtained by the NL-RHA are small at the lower stories. The CMP and SMP procedures give more accurate estimation of plastic rotations than the MPA procedure at the upper stories. Figs. 4 and 5 illustrate that the height-wise distribution of story drifts and plastic hinge rotations derived from the SMP and CMP procedures are more similar to that of the NL-RHA than that of the MPA procedure. The achievement in estimating the more accurate plastic rotations by the SMP procedure is due to the use of the enhanced lateral force distributions obtained by algebraically adding the modal force distributions. This accounts for the sign inversion in story forces of the higher modes. In this manner, the effect of higher modes as well as of the first mode is simultaneously considered in the enhanced lateral force distributions. In addition, the spectral pseudo-acceleration as a weighting parameter as well as the effective modal mass ratio is incorporated into the modal story forces.

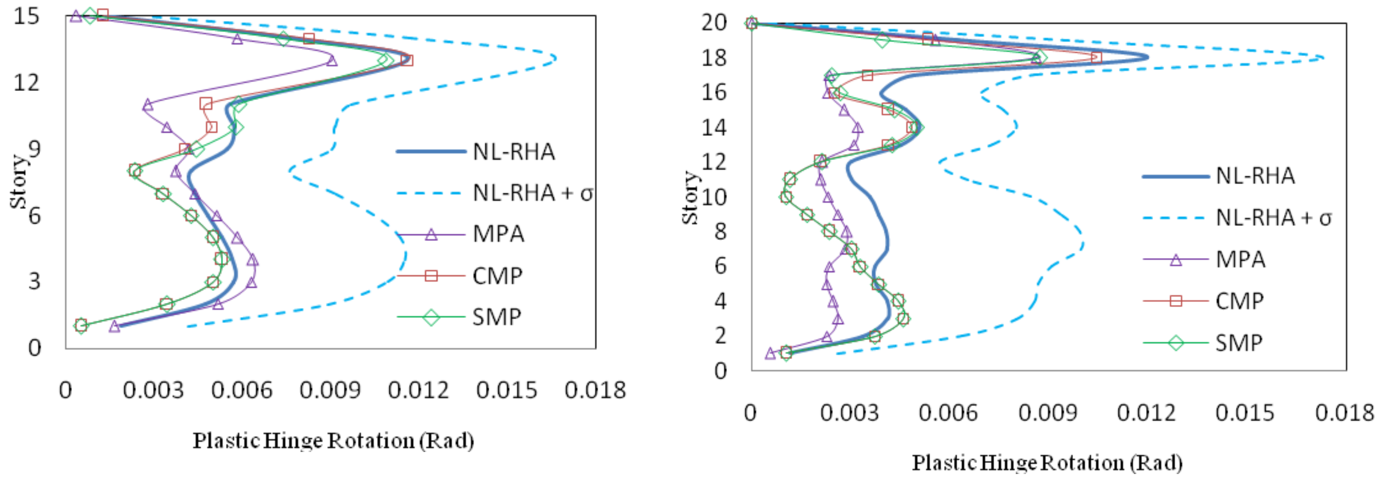


(a) 15-story frame



(b) 20-story frame

Fig. 4. Height-wise variation of the story drifts



(a) 15-story frame (b) 20-story frame

Fig. 5. Height-wise variation of the plastic hinge rotations

5. Conclusion

In the present study, a single-run multi-mode pushover (SMP) procedure was developed to take the effect of higher modes into account. The proposed procedure employs some separate single-run pushover analyses. One or two single-run multi-mode pushover analyses are carried out using the enhanced force distribution(s) proposed in this paper. The enhanced force distributions are calculated by algebraically adding the modal story forces that are weighted by a weighting factor S_a (spectral pseudo-acceleration) to account for the effect of the frequency content of a particular input ground motion in the modal lateral force distribution. Furthermore, a single-run conventional pushover analysis is performed by using an inverted triangular or a uniform load pattern. Finally, the seismic demands of the structure are obtained by enveloping the responses derived from the single-run conventional and single-run multi-mode pushover analyses. The single-run conventional pushover analysis controls the responses at the lower stories, whereas the single-run multi-mode pushover analysis with the enhanced force distribution(s) is dominated at the upper stories of tall buildings.

The results show that the story drifts and plastic hinge rotations can be estimated with acceptable accuracy by the SMP procedure as well as by the CMP method. In most cases, the CMP and SMP procedures provide a better estimation of story drifts in comparison with the MPA at the upper stories, while the errors in the MPA procedure are generally less than those in the CMP and SMP procedures at the lower stories. Furthermore, the height-wise distribution of story drifts and plastic hinge rotations derived from the SMP and CMP procedures are more similar to that of the NL-RHA than that of the MPA procedure. Although the accuracy of the SMP procedure is of the same order as that of the CMP procedure, the use of the SMP procedure has some advantages over the CMP procedure. The effect of higher modes in the SMP procedure is concentrated into a single invariant lateral force distribution applied to the structure, while the CMP procedure benefits from the consecutive implementation of modal pushover analyses in the multi-stage pushover analysis. Therefore, the fulfillment of the SMP procedure is simpler than the CMP procedure that makes it easier to use in engineering practice.

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