A BREAKTHROUGH IN ESTIMATING THE SEISMIC DEMANDS OF TALL BUILDINGS

Mehdi Poursha[1], Faramarz Khoshnoudian[2] and A.S. Moghadam[3]

[1] *Phd Candidate, Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran*
[2] *Assistant Professor, Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran*
[3] *Assistant Professor, International Earthquake and Seismology Research Centre, Tehran, Iran*
Email: mehdip@aut.ac.ir, khoshnud@aut.ac.ir, moghadam@iiees.ac.ir

ABSTRACT

The nonlinear static procedure (NSP) based on pushover analysis is restricted with a single mode response. Then, the NSP is valid for low-rise buildings where the behavior is dominated by fundamental vibration mode. It is of significance to take into account of higher mode effects in pushover analysis of tall buildings. The present paper attempts to evaluate consecutive modal pushover (CMP) procedure recently proposed to consider higher mode effects. This procedure and modal pushover analysis (MPA) are applied to steel special moment-resisting frames. It is demonstrated that the MPA and CMP procedures are able to overcome the limitation of traditional pushover analysis and to accurately predict the storey drifts of tall buildings. Hinge plastic rotations are noticeably improved by the CMP procedure particularly at top storeys of tall buildings in comparison with those obtained by the MPA procedure.

KEYWORDS: Consecutive Modal Pushover (CMP), nonlinear response history analysis (NL-RHA), higher mode effects, tall buildings

1. INTRODUCTION

Nonlinear static procedure (NSP) has been gaining importance during recent years as a standard tool for building assessment and design verification. However, pushover analysis suffers from several inherent limitations [Kim and D'Amore, 1999]. Among them, invariant load distribution in traditional NSP is one of the most important deficiencies and it is not able to take into consideration the higher mode effects [Krawinkler and Seneviratna, 1998; Fajfar, P. 2000; Chopra and Goel, 2002]. Then, attempts have been recently made to develop enhanced pushover procedures such as adaptive pushover [Bracci et al. 1997; Gupta and Kunnath, 2000], multi-mode pushover (MMP) [Sasaki et al. 1988], pushover results combination (PRC) [Moghadam, 2002] and incremental response spectrum analysis [Aydinoglu, 2003]. Modal pushover analysis (MPA) [Chopra and Goel, 2002] was also developed in which the seismic demands were separately determined for each of the modal pushover analyses and combined together using the appropriate modal combination scheme. It was demonstrated that the MPA would be accurate enough for practical application in building evaluation and design verification. Nevertheless, the errors of the MPA procedure were large in predicting plastic rotations of hinges [Chopra and Goel, 2002; Goel and Chopra, 2004]. To improve hinge plastic rotations, consecutive modal pushover (CMP) procedure [Poursha et al. 2008] was recently developed in which the seismic demands are derived by enveloping the results of some pushover analyses. The current paper demonstrates its applicability and efficiency and evaluates this procedure together with the MPA. Seismic demands obtained by approximate pushover procedures are compared with exact solutions derived from NL-RHA. The results indicate significant improvement through the CMP in predicting hinge plastic rotations of tall buildings.

2. CONSECUTIVE MODAL PUSHOVER PROCEDURE

Consecutive modal pushover (CMP) procedure [Poursha et al. 2008] was introduced to estimate the peak response of the inelastic structure subjected to earthquake excitation. Some separate pushover analyses are employed in the CMP procedure because it is possible to use different pushover analyses and to envelope the results [Fajfar, 2000]. In the CMP, modal pushover analyses are continuously implemented in two and three stages such that a modal pushover is terminated, subsequent one is commenced from state (stress and deformation) at the end of previous modal pushover. Consecutive modal pushover analyses are conducted with force distributions using mode-shapes obtained from eigen analysis of the linearly-elastic structure. The number of stages (modes) in consecutive modal pushover analysis depends on the period of building structure. When the period of resisting-moment frame is less than 2.2 seconds, consecutive modal pushover analysis is conducted in two stages. For periods of 2.2 seconds or more, both two- and three-stage consecutive modal pushover analyses are utilized. The displacement increment, u_{ri} , at the roof in stage i of consecutive modal pushover analysis is calculated as follow:

$$u_{ri} = \beta_i \delta_t \tag{2.1}$$

in which

$$\beta_i = \alpha_i \qquad \text{for stages before the last stage} \tag{2.2}$$

$$\beta_i = 1 - \sum_{j=1}^{N_s - 1} \alpha_j \qquad \text{for the last stage} \tag{2.3}$$

where δ_t and N_s are the total target displacement at the roof and the number of stages (modes) considered in consecutive modal pushover analysis, respectively. α_i is the effective modal participating mass ratio for the i-th mode and it is obtained as follow:

$$\alpha_i = \frac{M_i^*}{M^*} \tag{2.4}$$

in which

$$M_i^* = L_i \Gamma_i \qquad \text{and} \qquad M^* = \sum_{j=1}^{N} m_j \tag{2.5}$$

where

$$L_i = \phi_i^T mi \qquad \text{and} \qquad \Gamma_i = \frac{\phi_i^T mi}{\phi_i^T m \phi_i} \tag{2.6}$$

Γ_i and M_i^* are modal participating factor and effective modal participating mass for the i-th mode [Chopra, 2001]. M^* is the total mass of the structure derived from summation of lumped masses, m_j (j=1,2, …N), over N floor levels. ϕ_i , m and i are mode-shape of i-th mode, the mass matrix of the structure and the unit vector, respectively.

In addition to multi-stage modal pushover analyses, another pushover analysis is separately performed with either triangle or uniform load distribution. Finally, the seismic demands are obtained by enveloping the peak responses derived from former and latter pushover analyses. The details of the CMP procedure are expressed as a sequence of following steps:

1. Calculate the natural frequencies, ω_n and mode-shapes, ϕ_n for the first three modes. Mode-shapes are normalized so that the roof component of ϕ_n equals unity ($\phi_{rn} = 1$).

2. Compute $s_n^* = m\phi_n$ [Chopra and Goel, 2002] where s_n^* shows distribution of forces over the height of the structure for the *n*th mode (stage).

3. Compute the total target displacement of the structure, δ_t, at the roof.

4. The CMP procedure consists of some pushover analyses with a displacement control at the top of the building. The pushover analyses are implemented according to the following sub-steps until the total target displacement at the roof, δ_t is reached.

4.1. The first pushover analysis is implemented using inverted triangle load pattern for medium-rise buildings and uniform force distribution for high-rise ones until the control node at the roof sways to predefined total target displacement, δ_t.

4.2. The second pushover analysis is performed in two stages. In the First stage, nonlinear static analysis is implemented using invariant lateral forces according to $s_1^* = m\phi_1$ until the displacement increment at the roof reaches $u_{r1} = \beta_1\delta_t$ (Equation (2.1); $i = 1$) where $\beta_1 = \alpha_1$ (Equation (2.2); $i = 1$).

The second stage of analysis starts from stressed and deformed state at the last step of the previous stage. Therefore, in the second stage, the analysis continues with lateral forces according to $s_2^* = m\phi_2$ until the displacement increment at the roof equals $u_{r2} = \beta_2\delta_t$ (Equation (2.1); $i = 2$) where $\beta_2 = 1 - \alpha_1$ (Equation (2.3); $i = 2$).

4.3. The third analysis in the CMP is a three-stage consecutive modal pushover analysis. It is only performed for buildings having a period of 2.2 sec or more. The first stage is exactly the same as the first stage in two-stage consecutive modal pushover analysis. After the first stage, the nonlinear static analysis continues with lateral forces according to $s_2^* = m\phi_2$ until the displacement increment at the roof reaches $u_{r2} = \beta_2\delta_t$ (Equation (2.1); $i = 2$) where $\beta_2 = \alpha_2$ (Equation (2.2); $i = 2$).

Thereafter, the third (last) stage of three-stage modal pushover analysis is carried out using lateral force distribution according to $s_3^* = m\phi_3$. The displacement increment at the roof in this stage is equal to $u_{r3} = \beta_3\delta_t$ (Equation (2.1); $i = 3$) where $\beta_3 = 1 - \alpha_1 - \alpha_2$ (Equation (2.3); $i = 3$).

5. Calculate peak value of desired responses for pushover analyses described above. The peak values resulted from steps 4.1, 4.2 and 4.3 are denoted by r_1, r_2 and r_3, respectively.

6. Calculate the envelope, r, of peak responses as follow:

$$r = Max\left\{ r_1,\ r_2 \right\} \qquad \text{for } T < 2.2 \text{ seconds} \tag{2.7}$$

$$r = Max\left\{ r_1,\ r_2,\ r_3 \right\} \qquad \text{for } T \geq 2.2 \text{ seconds} \tag{2.8}$$

3. ANALYTICAL MODELS, ASSUMPTIONS AND TYPES OF ANALYSIS

The structures considered are three bay frames with heights of 10 and 20 storeys. All frames comprise of 5 m bays. A story height of 3.2 m was assumed for the frames. Configuration of the frames is shown in Figure 1. Lateral load-resisting system of the structures is steel special moment-resisting frame (SMRF). Some characteristics of the frames and the first three natural-vibration periods are listed in Table 3.1. More details of the structures and assumptions can be found in [Poursha et al. 2008]. The nonlinear behavior of the structures occurs in discrete hinges for nonlinear static and dynamic analyses. Hinges are assigned at the end locations along the frame members. Hinge properties and modeling parameters are considered according to FEMA-273 [BSSC, 1997].

The CMP and MPA procedures are carried out for these frames. The MPA is conducted for 10-storey frame including three modes and for 20-storey building including five modes. Gravity loads and $P-\Delta$ effects are taken into account in all nonlinear static and dynamic analyses. $P-\Delta$ effects are also included in the MPA and CMP for all modes. Nonlinear response history analyses are accomplished using seven ground motion records which include Imperial valley(1979), Trinidad(1980), Victoria(1980), Morgan hill(1984), Hollister(1986), Landers(1992), Northridge(1994) and Duzce(1999) earthquakes. To ensure that the structures respond into the inelastic range when subjected to ground motions, the records were scaled up to 0.7g. The elastic pseudo acceleration and displacement and the mean spectra for 5% damping ratio are presented in Figure 2. NL-RHA is performed using numerical implicit $wilson-\theta$ time integration method in which parameter θ determines the stability and accuracy characteristics. The parameter is assumed to be 1.4. A damping ratio of 5% is considered for the first and third modes of vibration to define the Rayleigh damping matrix. In pushover analyses, the target displacement at the roof is obtained as the mean of maximum top floor displacements resulted from NL-RHA for described ground motions. The response resulted from pushover analysis is compared with the mean of maximum seismic demands computed by rigorous NL-RHA.

Table 3.1. Characteristics of analytical cases

No.	No. of storeys	h (m)	b (m)	Seismic mass of floors (kg-sec^2/m)	Periods		
					T_1 (Sec)	T_2 (Sec)	T_3 (Sec)
S1	10	32	15	5440	1.697	0.605	0.347
S2	20	64	15	5600	3.092	1.135	0.670

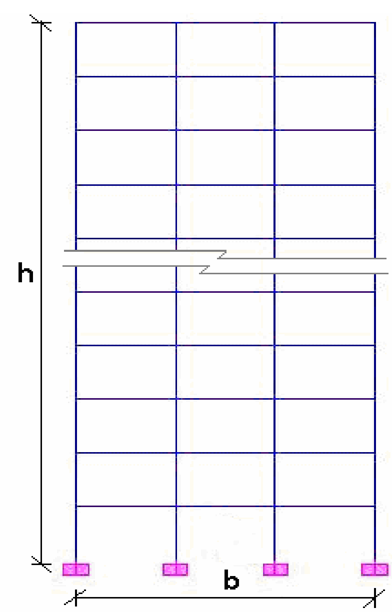

Figure 1. Configuration of two dimensional frames

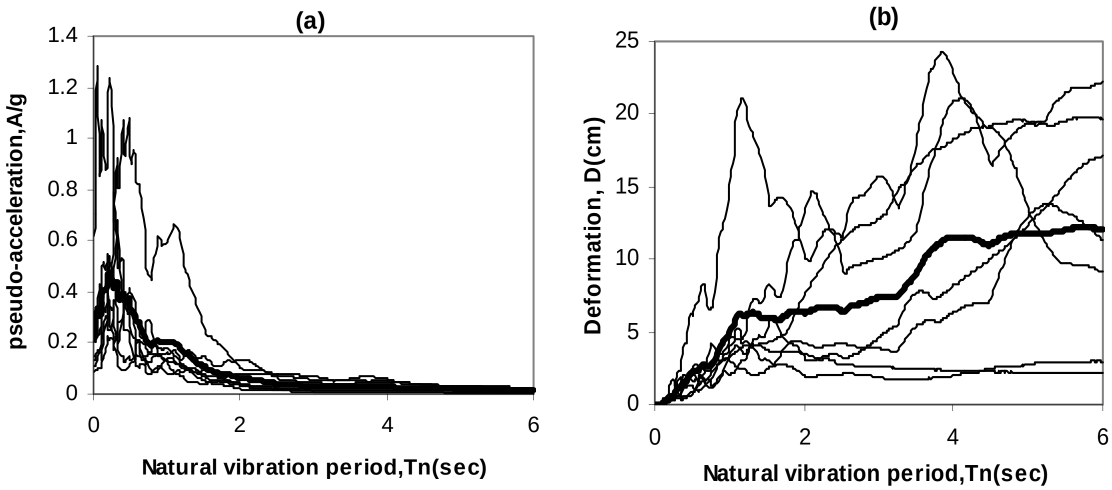

Figure 2 (a) Pseudo acceleration spectra and (b) displacement spectra of far field records set of ground motions, damping ratio=5%.

4. DISCUSSION OF RESULTS

Shown in Figures 3 and 4 are the story drift ratios obtained by described pushover procedures and NL-RHA for 10- and 20-storey frames. The figures illustrate that the MPA and the CMP procedures produce satisfactory estimates of storey drifts. The CMP provides better estimates of storey drifts than the MPA at some (upper) storeys, whereas the MPA errors are less than the CMP at some other (lower) storeys. Hinge plastic rotations of the frames are shown in

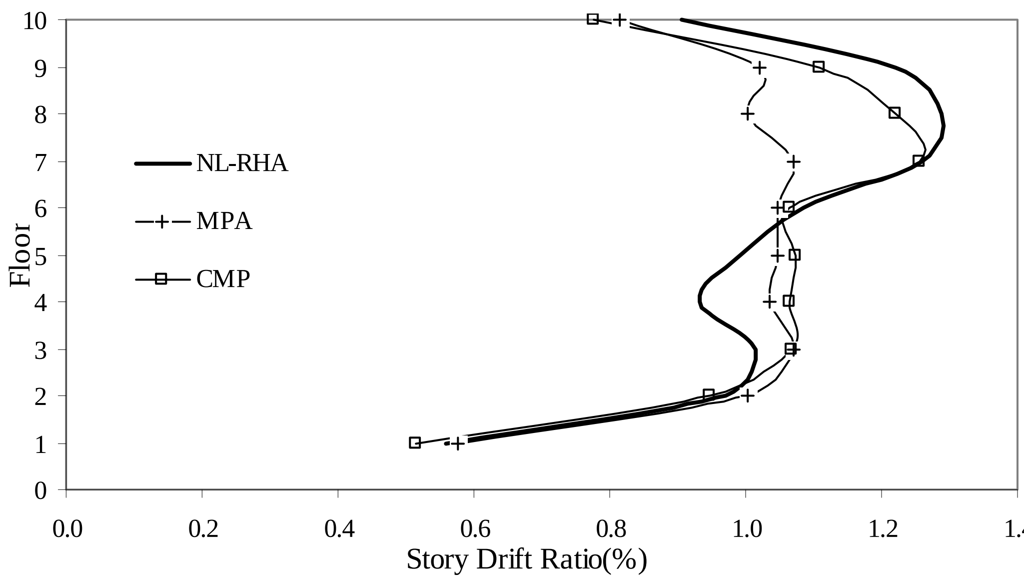

Figure 3 Height-wise variation of story drifts for 10-storey frame

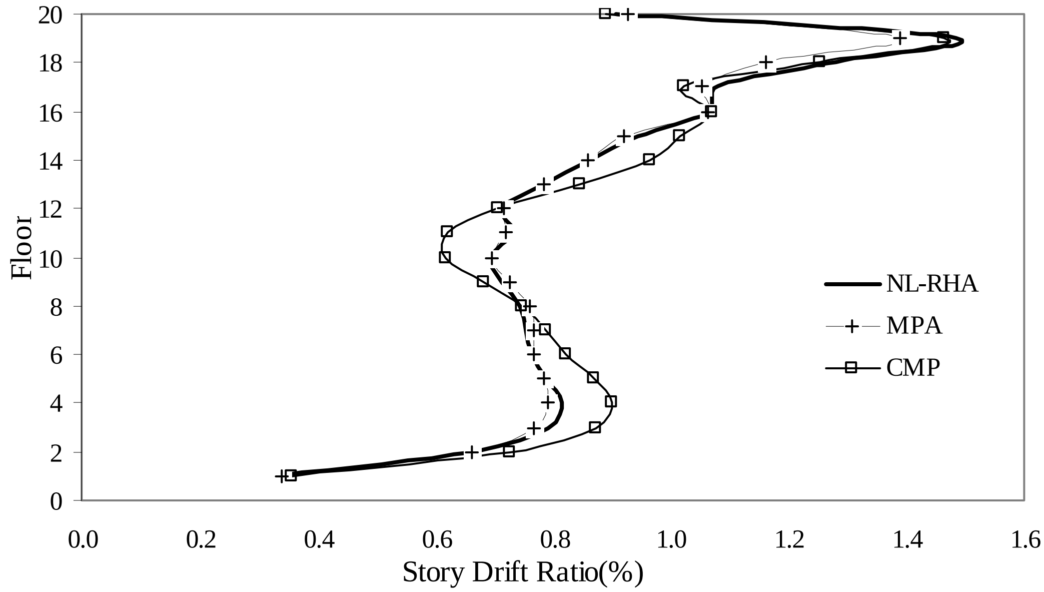

Figure 4 Height-wise variation of story drifts for 20-storey frame

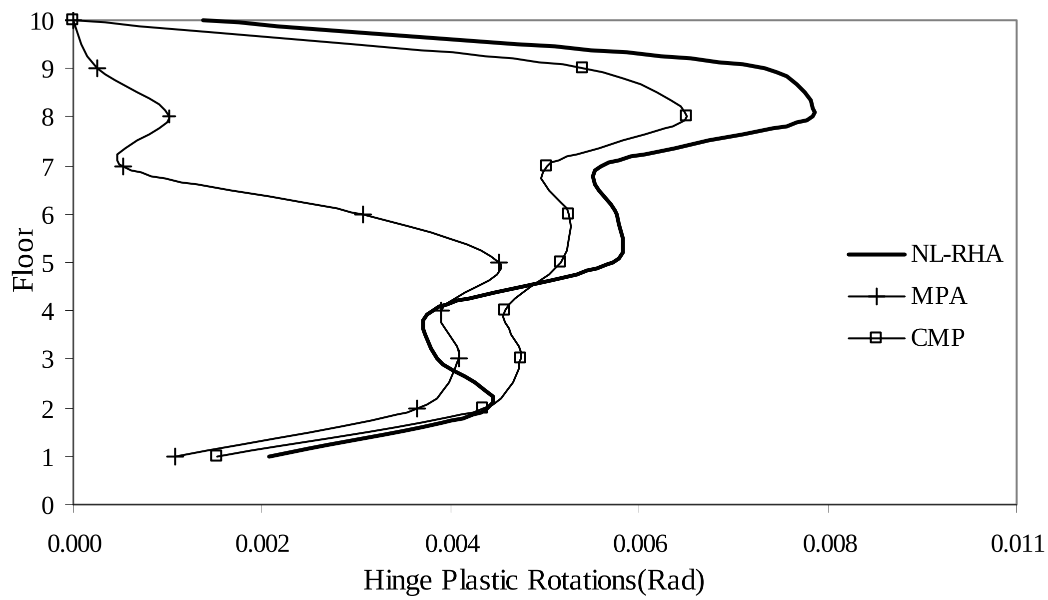

Figure 5 Height-wise variation of hinge plastic rotations for 10-storey frame

Figures 5 and 6. The MPA fails to accurately predict hinge plastic rotations at upper floor levels of 10- and 20-story frames, while noticeable improvement has been achieved in the estimates derived from the CMP procedure so that the CMP procedure results in the closest agreement with NL-RHA. Hinge plastic rotations obtained by the CMP are significantly more accurate than the MPA especially at mid and upper floors. It's noted that the 100% error resulted from the CMP at the last floor of 20-storey is ignored because plastic rotations predicted by the CMP are zero, whereas rotations obtained by NL-RHA are very small. At some lower floor levels, CMP procedure occasionally provides better estimates than the MPA, and vice versa. Also, the CMP has inclination to overestimate plastic

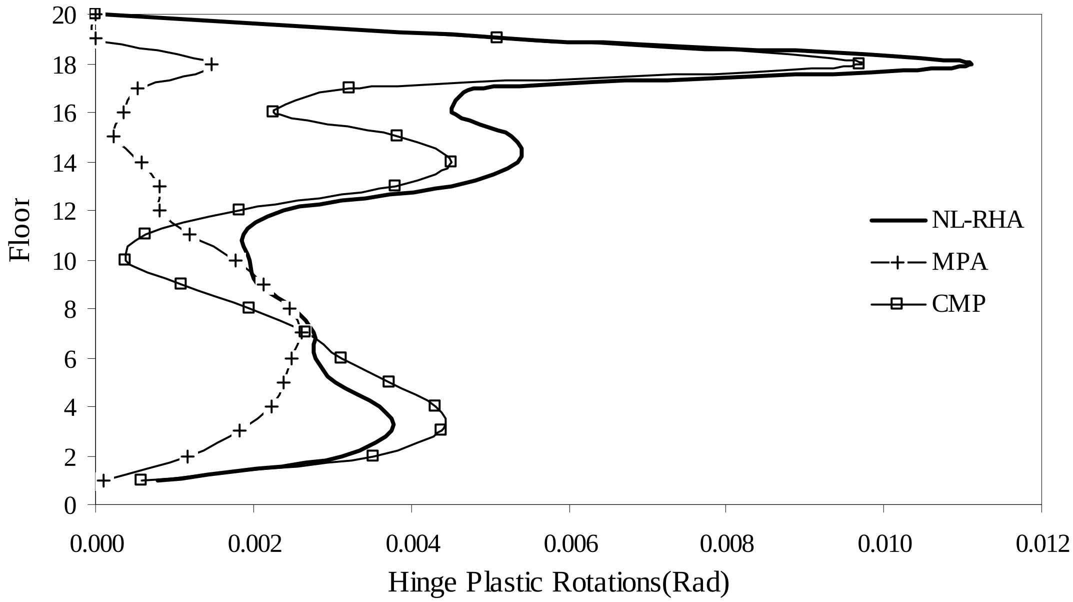

Figure 6 Height-wise variation of hinge plastic rotations for 20-storey frame

rotation of the hinges at some lower floor levels. It's notable that a key aspect of the CMP procedure is the fact that modal pushover analyses are carried out continuously. The consecutive implementation of modal pushover analyses in the CMP leads plastic rotations of the hinges to be continuously cumulated at mid and upper floor levels through the modes of interest in a single multi-stage modal pushover analysis, while the MPA procedure proposes to estimate total response quantities by combining the individual peak responses obtained separately for each mode. Therefore, the trend in the CMP results in more significant improvement than the MPA in the estimates of plastic hinge rotations at mid and upper floor levels [Poursha et al. 2008]. However, pushover procedure suffers from limitation that it is not able to take into account of cumulative rotation of plastic hinges due to cyclic hysteretic behavior [Kim and D'Amore, 1999]. It is also notable that the CMP procedure not only achieves significant improvements in the estimates of hinge plastic rotations for tall frames but also gives computational time savings in relation to MPA procedure particularly for long period structures in which a large number of modes are needed to be taken into account in the MPA. The MPA procedure is conceptually more elegant. However, it needs additional computational effort for each individual mode of interest. As seen from Figures 3 to 6, the height-wise distribution of storey drifts and hinge plastic rotations derived from the CMP procedure is more similar to that obtained by benchmark solution (NL-RHA). This achievement is more remarkable for plastic rotations of the hinges.

6. CONCLUSIONS

To take into account of higher mode effects in pushover analysis for predicting seismic demands of tall building structures, consecutive modal pushover (CMP) procedure was recently proposed. The procedure employs some pushover analyses. In the CMP, modal pushover analyses are consecutively conducted with force distributions using mode shapes derived from eigen analysis of the linearly-elastic structure. Furthermore, a separate pushover analysis is carried out utilizing triangle or uniform load distribution. The seismic demands are then determined by enveloping the peak responses resulted from specified pushover analyses.

The MPA and the CMP procedures produce satisfactory estimates of storey drifts. Significant improvement has been achieved in the estimates of hinge plastic rotations through the CMP procedure. Plastic rotations produced by the CMP are substantially better than by the MPA, especially at mid and upper floor levels when compared to NL-

RHA. The improvement in the CMP is resulted from consecutive implementation of modal pushover analyses leading plastic rotations to be continuously cumulated at mid and upper floor levels through the modes of interest in a single multi-stage pushover analysis. Also, the height-wise distribution of hinge plastic rotations produced by the CMP procedure is generally more similar to that obtained by benchmark solution (NL-RHA) than by the MPA.

References

Aydinoglu, M.N., 2003. An incremental response spectrum analysis procedure on inelastic spectral displacements for multi-mode seismic performance evaluation, Bulltein of Earthquake engineering, 1, pp. 3-36

Bracci, J.M., Kunnath, S.K. and Reinhorn, A.M. 1997. Seismic performance and retrofit evaluation for reinforced concrete structures, J. Struct. Engrg., ASCE 123(1), pp.3-10.

Building Seismic Safety Council (BSSC), 1997. NEHRP Guidelines for the Seismic Rehabilitation of Buildings, FEMA-273, Federal Emergency Management Agency, Washington, D.C.

Chopra , A.K., 2001. Dynamics of Structures. Theory and Applications to Earthquake Engineering, Second Edition, Prentice Hall, Englewood Cliffs, NJ.

Chopra, A.K. and Goel, R.K., 2002. A modal pushover analysis procedures for estimating seismic demands for buildings. Earthquake Engineering and Structural Dynamics, 31, pp. 561-582.

Fajfar, P. 2000. A nonlinear analysis method for performance based seismic design, Earthquake Spectra, 16(3), pp. 573-592.

Goel, R.K. and Chopra, A.K., 2004. Evaluation of modal and FEMA pushover analysis: SAC Buildings, Earthquake Spectra, 20(1), pp. 225-254.

Gupta, B. and Kunnath, S.K. 2000. Adaptive spectra-based pushover procedure for seismic evaluation of structures. Earthquake Spectra, 16(2), pp.367–391.

Kim, S. and D'Amore, E., 1999. Pushover analysis procedure in earthquake engineering, Earthquake Spectra, 15, pp. 417-434

Krawinkler, H., and Seneviratna, G.D.P.K., 1998. Pros and cons of a pushover analysis of seismic performance evaluation, Engineering Structures, 20(4-6), pp. 452-462

Moghadam, A.S., 2002. A pushover procedure for tall buildings, proc. 12th European Conference on Earthquake Engineering, paper 395. Elsevier Science Ltd.

Poursha, M., Khoshnoudian, F., and A.S. Moghadam, Consecutive modal pushover procedure for estimating the seismic demands of tall buildings, submitted to journal of Engineering Structures.

Sasaki, K.K., Freeman, S.A. and Paret, T.F., 1988. Multi mode pushover procedure (MMP) –A method to identify the effects of higher modes in a pushover analysis, Proc. 6th U.S. Nat. Cof. on Earthq. Eng., Seattle, Washington.