PRACTICAL IMPLEMENTATION OF GENERALIZED PUSHOVER ANALYSIS

F.S. ALICI, K. KAATSIZ & H. SUCUOĞLU
Department of Civil Engineering, Middle East Technical University, Ankara, Turkey

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SUMMARY
A generalized pushover analysis procedure was developed for estimating the inelastic seismic response of structures under earthquake ground excitations (Sucuoğlu and Günay, 2011). A practical implementation of the proposed generalized pushover analysis is presented in this study where the number of pushovers is reduced in view of the number of significant modes. It has been demonstrated that the reduced generalized pushover analysis is equally successful in estimating maximum member deformations and exact in determining member forces under a ground excitation with reference to nonlinear response history analysis. It is further shown that the results obtained by using the mean spectrum of a set of ground motions are almost identical to the mean of the results obtained from separate generalized pushover analyses under each ground motion in the set. These results are also very close to the mean results of the nonlinear response history analyses.

Keywords: Pushover analysis, generalized force vector, target drift, higher mode effects

1. INTRODUCTION

The ease of application and conceptual simplicity of single mode conventional pushover analysis enables to develop multi mode pushover analysis procedures which supersede nonlinear response history analysis in practical application (Sasaki et al. 1998, Chopra and Goel 2002, Gupta and Kunnath 2000, Aydınoğlu 2003, Antoniou and Pinho 2004). Generally, these methods, except one, are adaptive. In adaptive methods, eigenvalue analysis is conducted at each step of load increment according to the formation of nonlinear deformations in the system. This approach removes the simplicity of pushover analysis procedure, and requires special programming or modification of the current analysis programs. On the other hand, in multi mode pushover analysis, results are obtained for each mode independently, and then the modal results are combined by statistical rules (SRSS or CQC) for combining elastic modal responses. There are several shortcomings in the modal combination of inelastic modal responses. They are approximate, and the internal forces obtained by statistical combinations exceed capacities, hence they require correction at each load increment.

In this study, a recently developed multi mode pushover analysis (Sucuoğlu and Günay, 2011) which accounts for the contribution of all significant modes to inelastic seismic response is described, and its practical implementation is developed. In this procedure, a set of pushover analyses are conducted by employing different generalized force vectors, derived for each story. Therefore, for an N story building, N number of pushover analyses is required. Each generalized force vector is derived as a different combination of modal lateral forces in order to simulate the effective lateral force distribution when the interstory drift at a selected story reaches its maximum value during seismic response. Pushover analysis of a story proceeds in a step-by-step manner until the target interstory drift value of that story is achieved. Target interstory drift in any story can be estimated from linear elastic response spectrum analysis by considering the equal displacement rule. The contribution of the first mode response can also be obtained from the solution of inelastic SDOF system response. This suggested procedure can be implemented by using any structural analysis software (SAP, OpenSees, Drain2D, etc.) which facilitate displacement controlled pushover analysis.

This study focuses on the practical implementation of generalized pushover analysis (GPA) which requires less computational effort. Performance of GPA and its practical implementation (RGPA) is compared with the benchmark nonlinear response history analysis, based on the results obtained from the analyses of a twelve story RC frame.

2. GENERALIZED PUSHOVER ANALYSIS

The GPA procedure is based on an effective force vector $\mathbf{f}_j$ acting on the system when the interstory drift Δ_j at the j'th story reaches its maximum value during dynamic response. This effective force vector is a generalized force vector, since it includes contributions from all modal forces at the time of maximum response of the interstory drift at the j'th story. If this force vector is defined, it can be applied to the system as a static force in order to produce the maximum value of the j'th interstory drift. In GPA, generalized effective force vectors are derived from the dynamic response of linear elastic MDOF systems to earthquake ground excitations by using the response spectrum analysis (RSA) procedure (Sucuoğlu and Günay, 2011).

$$\mathbf{f}_j = \sum_n \left(\Gamma_n \mathbf{m} \boldsymbol{\varphi}_n A_n \frac{\Delta_{j,n}}{\Delta_{j,max}} \right) \tag{1}$$

Here, $\Gamma_n = L_n / M_n$; $L_n = \boldsymbol{\varphi}_n^{\mathrm{T}} \mathbf{ml}$; $M_n = \boldsymbol{\varphi}_n^{\mathrm{T}} \mathbf{m} \boldsymbol{\varphi}_n$; $\boldsymbol{\varphi}_n$ is the n'th mode shape; $\mathbf{m}$ is the mass matrix, $\mathbf{l}$ is the influence vector, and A_{n} is the spectral acceleration at the n'th mode. In Equation (1), $\Delta_{j,n}$ is the n'th mode contribution to the maximum interstory drift of the j'th story determined from RSA, and $\Delta_{j,max}$ is the quadratic combination of the $\Delta_{j,n}$ terms according to Equation (2).

$$(\Delta_{j,max})^2 \approx \sum_n \left[\Gamma_n D_n (\varphi_{n,j} - \varphi_{n,j-1}) \right]^2 \tag{2}$$

The target interstory drift demand Δ_{jt} at the j'th story can be obtained consistently with the generalized force vector $\mathbf{f}_j$,

$$\Delta_{jt} = \sum_n \Gamma_n \frac{\Delta_{j,n}}{\Delta_{j,max}} D_n (\varphi_{n,j} - \varphi_{n,j-1}) \tag{3}$$

by invoking the modal scaling rule of GPA:

$$D_n(t_{max}) = \frac{\Delta_{j,n}}{\Delta_{j,max}} D_n \tag{4}$$

$D_n(t_{\mathrm{max}})$ is the modal displacement amplitude at t_{max} which satisfies the equation of motion of the SDOF system representing the n'th mode under ground motion excitation, $\ddot{u}_{\mathrm{g}}(t)$. $D_n(t_{\mathrm{max}})$ satisfies the equation of motion in Equation (5)

$$\ddot{D}_n(t_{\mathrm{max}}) + 2\varsigma_n \omega_n^2 \dot{D}_n(t_{\mathrm{max}}) + \omega_{\mathrm{n}}^2 D_n(t_{\mathrm{max}}) = -\ddot{u}_{\mathrm{g}}(t_{\mathrm{max}}) \tag{5}$$

where t_{max} is the time when Δ_j reaches its maximum value under $\ddot{u}_{\mathrm{g}}(t)$. In order to improve the prediction of Equation (3), the first mode linear elastic spectral displacement demand D_1 can be replaced with the first mode inelastic spectral displacement demand D_1^*. This operation requires conducting an *'a priori'* first mode pushover analysis. Then, D_1^* can be estimated from the nonlinear response history analysis of the equivalent SDOF system representing the first mode behavior.

GPA uses the higher-order interstory drift parameter as target demand rather than a story (roof) displacement. Accordingly, when the associated generalized force vector $\mathbf{f}_j$ pushes the system to the target drift Δ_{jt}, the system adopts itself in the inelastic deformation range, and the higher-order deformation parameters (rotations, curvatures) and force parameters (moments, shears) take their inelastic values with more effective contributions of the higher modes. On the other hand, if story (roof) displacement is used as target demand, the contribution of higher modes becomes less significant. If different local response parameters are primary considerations during inelastic dynamic response, interstory drift values are more effective representatives of local maximum response parameters, because they are well synchronized with the local response parameters.

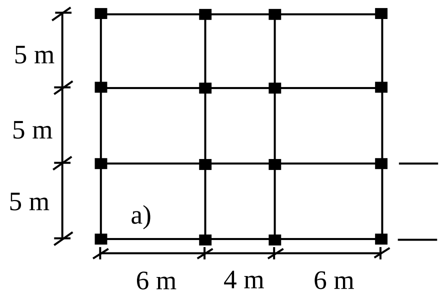
2.1. Generalized Pushover Algorithm

The GPA algorithm contains the following six basic steps. These steps can be summarized as below:
1. *Eigenvalue analysis*: Natural frequencies ω_n (natural periods T_n), modal shape vectors $\boldsymbol{\varphi}_n$, and modal participation factors Γ_n are obtained from the eigenvalue analysis.
2. *Response spectrum analysis* (RSA): Modal spectral amplitudes A_n and D_n are determined from elastic spectra of the corresponding ground motion. Modal interstory drift ratios of the *j'*th story, $\Delta_{j,n}$ and the maximum interstory drift ratio of the *j'*th story, $\Delta_{j,max}$ are obtained from RSA.
3. *Generalized force vectors*: Generalized force vectors $\mathbf{f}_j$, which act on the system when the interstory drift at the *j'*th story becomes maximum, are computed from Equation (1).
4. *Target interstory drift demand*: Target interstory drift demands for each story are calculated from Equation (3). If the first mode inelastic spectral displacement demand D_1^* is utilized instead of the elastic demand D_1 in order to improve the accuracy, a first mode pushover analysis is conducted to determine the first mode capacity curve. After approximating the capacity curve with a bi-linear curve and converting it to the acceleration-displacement spectrum format, nonlinear dynamic analysis or inelastic response spectrum analysis of the equivalent bi-linear SDOF system can be conducted in order to obtain D_1^*. D_n values for *n* = 2-*N*, are taken from the elastic response spectrum of the corresponding ground motion.
5. *Generalized pushover analysis*: *N* number of GPA's is conducted sequentially. In the *j'*th story GPA (*j*=1-*N*), the structural system is pushed incrementally in the lateral direction with the force distribution proportional to the corresponding generalized force vector $\mathbf{f}_j$. At the end of each loading increment *i* during the pushover analysis, the interstory drift value Δ_{ji} obtained at the *j*'th story is compared with the target interstory drift Δ_{jt} computed from Equation (3). Displacement-controlled pushover analysis is conducted until Δ_{ji} reaches Δ_{jt}.
6. *Maximum response values*: All member deformations and member internal forces at the *j'*th story are directly obtained from the *j'*th story GPA at the target interstory drift demand Δ_{jt}. After completing all GPA for *j*=1-*N*, member deformations and member internal forces are determined by taking envelopes of the related GPA results, and these envelope values are registered as the maximum seismic response values.

2.4. Case Study Results: 12 Story RC Concrete Frame with Full Capacity Design

Generalized pushover analysis is tested on a 12-story reinforced concrete building with symmetrical floor plan shown in Figure 1.a. The building is designed according to the regulations of Turkish

Earthquake Code (2007) in accordance with capacity design principles and enhanced ductility level. The design spectrum is shown in Figure 1.b. Concrete and steel characteristic strengths are 25 MPa and 420 MPa, respectively. The slab thickness is 1400 mm, and live load is 3.5 kN/m^2. The member dimensions for beams are 30x55 cm^2 for the first four stories, 30x50 cm^2 for the consequent four stories, and 30x45 cm^2 for the top four stories. The columns dimensions are 50x50 cm^2, 45x45 cm^2, and 40x40 cm^2 in the first four, the second four, and the last four stories, respectively. The story heights are 4 m for the first story, and 3.2 m for all other stories. Ground excitation is applied in the horizontal direction (*x*). Analytical model of each twelve story frame is generated by using the OpenSees software. In nonlinear modeling of members, cracked section properties are employed for initial stiffness computations. The first three periods are 2.39, 0.82, and 0.48 seconds, respectively.



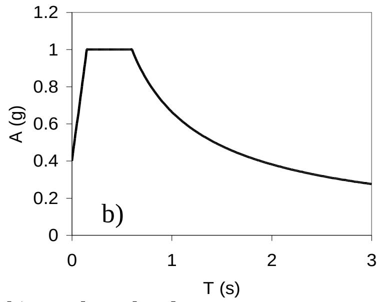


Figure 1. a) Floor plan of 12 story building b) Earthquake design spectrum

The ground motion set employed in the case study consists of seven ground motions, including pulse and ordinary types. Acceleration records of these seven ground motions were generated from the selected reference data set of ground motions which have similar properties (Hancock et al., 2006; Hancock and Bommer, 2007). The spectrum of each ground motion is adjusted with the Turkish Earthquake Code (TEC 2007) design spectrum. These reference ground motions were selected to be capable of generating higher mode effects on the structural system, and downloaded from the PEER strong motion database. Important features of reference ground motions are presented in Table 1.

Table 1. Reference ground motion properties

#	GM Code	Earthquake (Mw)	Station-Component	CD (km)	Site Geol.	PGA (g)	PGV (cm/s)	PGD (cm)	GM Type
1	CLS090	Loma Prieta, 10/18/89 (7)	Corralitos-090	3.9	A	0.479	45.2	11.3	Pulse
2	LEX000	Loma Prieta, 10/18/89 (7)	Los Gat. - Lex. Dam-000	5.0	A	0.420	73.5	20.0	Pulse
3	PCD254	San Fer., 02/09/71 (6.6)	Pacoima Dam-254	2.8	B	1.160	54.1	11.8	Pulse
4	CHY006-E	Chi-Chi, 09/20/99 (7.6)	CHY006-E	9.8	B	0.364	55.4	25.6	Pulse
5	Bolu000	Duzce, 11/12/99 (7.1)	Bolu-000	12.0	D	0.728	56.4	23.1	Ordinary
6	ORR090	Northridge, 01/17/94 (6.7)	Cast.-Old Rdg Route-090	20.7	B	0.568	51.8	9.0	Ordinary
7	ERZ-EW	Erzincan,03/13/92 (6.9)	Erzincan-EW	4.4	D	0.496	64.3	21.9	Pulse

Maximum interstory drift ratios obtained from nonlinear response history analysis (NRHA) and generalized pushover analysis (GPA) are presented comparatively for four ground motions in Fig. 2. GPA estimates NRHA results quite well, especially at the upper stories. Maximum average beam end plastic rotations are given in Fig. 3 under the same ground excitations. Beam-end plastic rotations calculated by GPA matches the NRHA results quite well. Therefore, it can be suggested that higher mode effects are taken into consideration effectively by GPA. Maximum bending moments of beam ends at the 1st, 5th and 10th stories under GM2 and GM4 are given in Fig. 4. It is clear that GPA predicts NRHA results for member internal forces almost exactly.

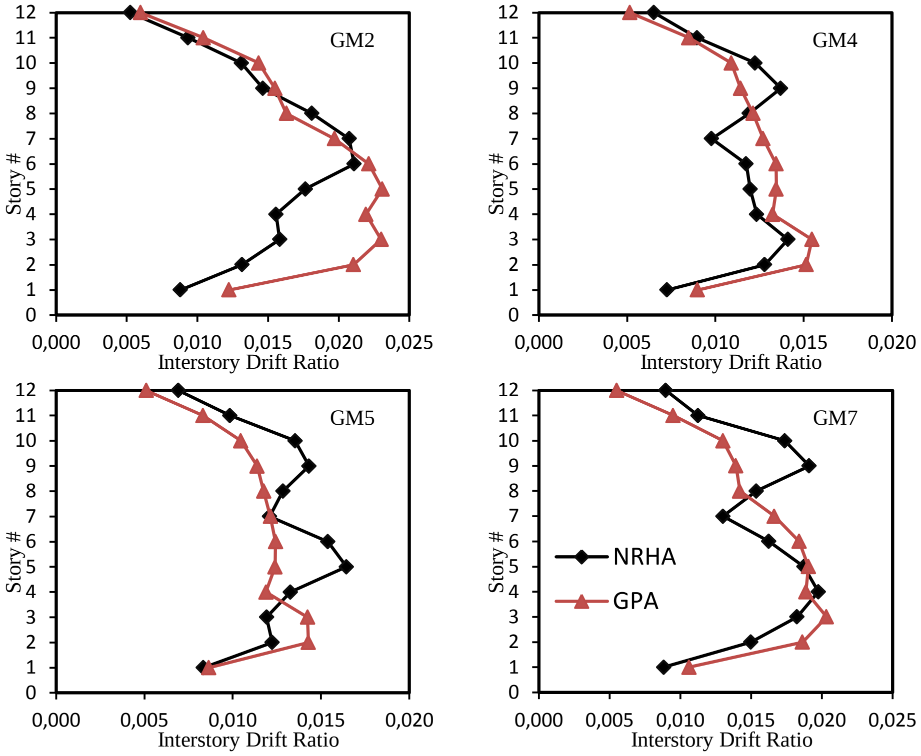


Figure 2. Maximum interstory drift ratios under four ground motions

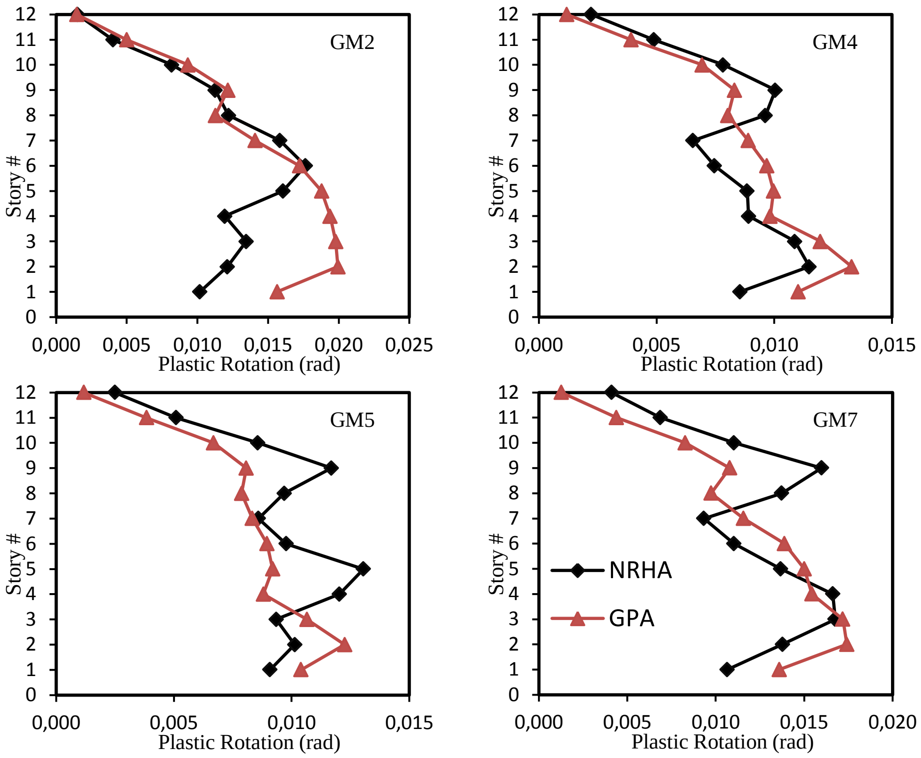


Figure 3. Maximum average beam plastic rotations under four ground motions

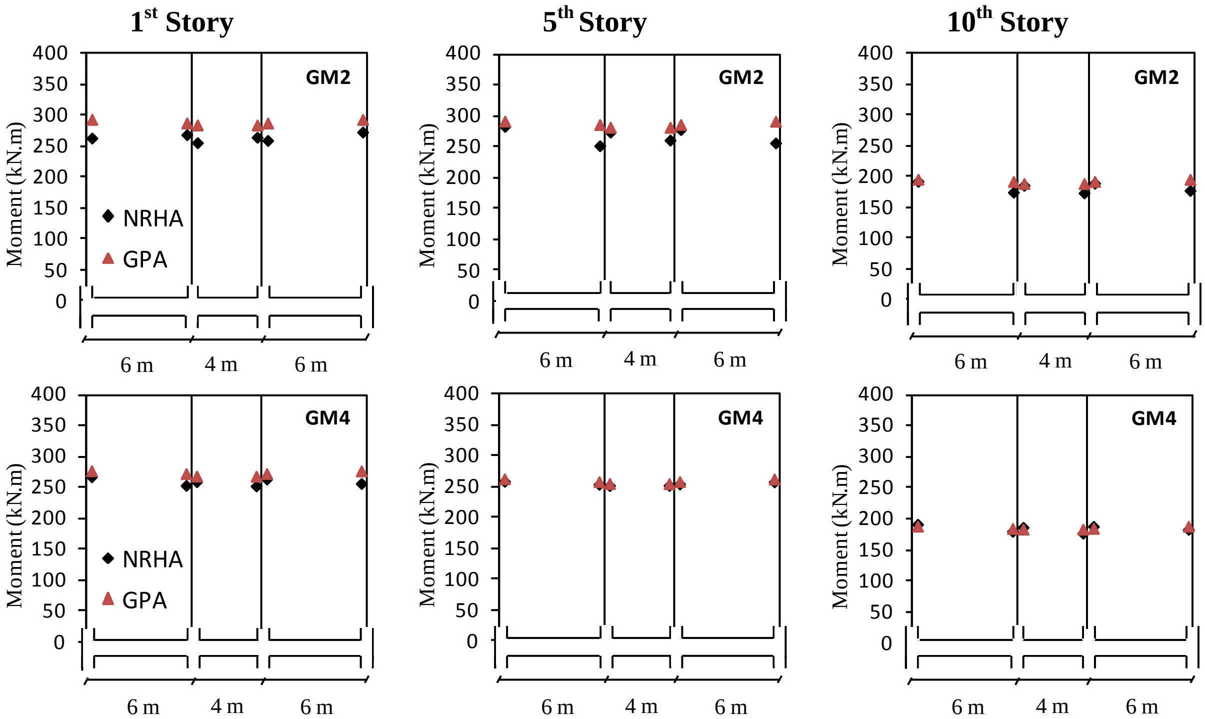


Figure 4. Maximum beam-end moments under GM2 and GM4

3. REDUCED GENERALIZED PUSHOVER ANALYSIS

GPA is based on the general assumption that the interstory drift ratios Δ_j occur independently at each story (j=1-N) at different instants $t_{j,\max}$, j=1-N. However if there are n modes contributing significantly to the total dynamic response (n<N), then there are only $2^{(n-1)}$ possible combinations of the n modes leading to the maximum values of interstory drifts at specific stories. Hence there are $2^{(n-1)}$ independent instants $t_{\max}$ for calculating $\mathbf{f}_j$ and $\Delta_{j,max}$ in the N DOF system.

Consider the positive drift profile for the first mode, and both positive and negative drift profiles for the second and third modes for the 12-story RC frame under GM4 shown in Fig. 5, where

$$\Delta_{j,n} = \sum_n \left[\Gamma_n D_n(\varphi_{n,j} - \varphi_{n,j-1})\right] \tag{6}$$

is the n'th mode contribution to the drift ratio at the j'th story. There are $2^{(n-1)}$ = 4 combinations for n=3 number of significant modes contributing to interstory drifts. They are shown in Fig. 5, lower box. Δ_1-Δ_2+ Δ_3 combination controls the upper 9th-12th stories whereas Δ_1+ Δ_2+ Δ_3 controls the lower 1st-3rd stories. For the middle stories, Δ_1+ Δ_2- Δ_3 and Δ_1- Δ_2- Δ_3 combinations control the story maxima of the 4th-5th, and 6th-8th stories, respectively. Accordingly, one story level from each story group can be selected, and the related 4 force vectors can be employed in GPA instead of the N numbers of force vectors. For the 12-story frame, 2nd, 5th, 7th and 11th stories were selected from each story group, and only four generalized pushover analysis were conducted by applying $\mathbf{f}_2$, $\mathbf{f}_5$, $\mathbf{f}_7$ and $\mathbf{f}_{11}$ in accordance with Eq.(1). Finally, the envelopes of these four generalized pushover analyses are used for calculating the maximum response parameters. Thus, the computation effort in GPA is reasonably reduced from 12 to 4 pushovers. This procedure is called the reduced GPA (RGPA). MPA carries out 3 pushovers for the three significant modes. Hence, their computational efforts are similar although the accuracy of results is different.

The upper bound modal combinations introduced in Fig. 5 for interstory drifts were previously employed by Matsumori et al. (1999), Kunnath (2004) and Jan et al. (2004) for calculating the lateral force distributions in pushover analysis to account for the higher mode effects.

Figures 6 and 7 show the maximum interstory drift and maximum average beam plastic rotations calculated by NRHA, GPA and RGPA. It can be observed that the results of RGPA are very close to the GPA results, and sufficiently close to the benchmark results of NRHA.

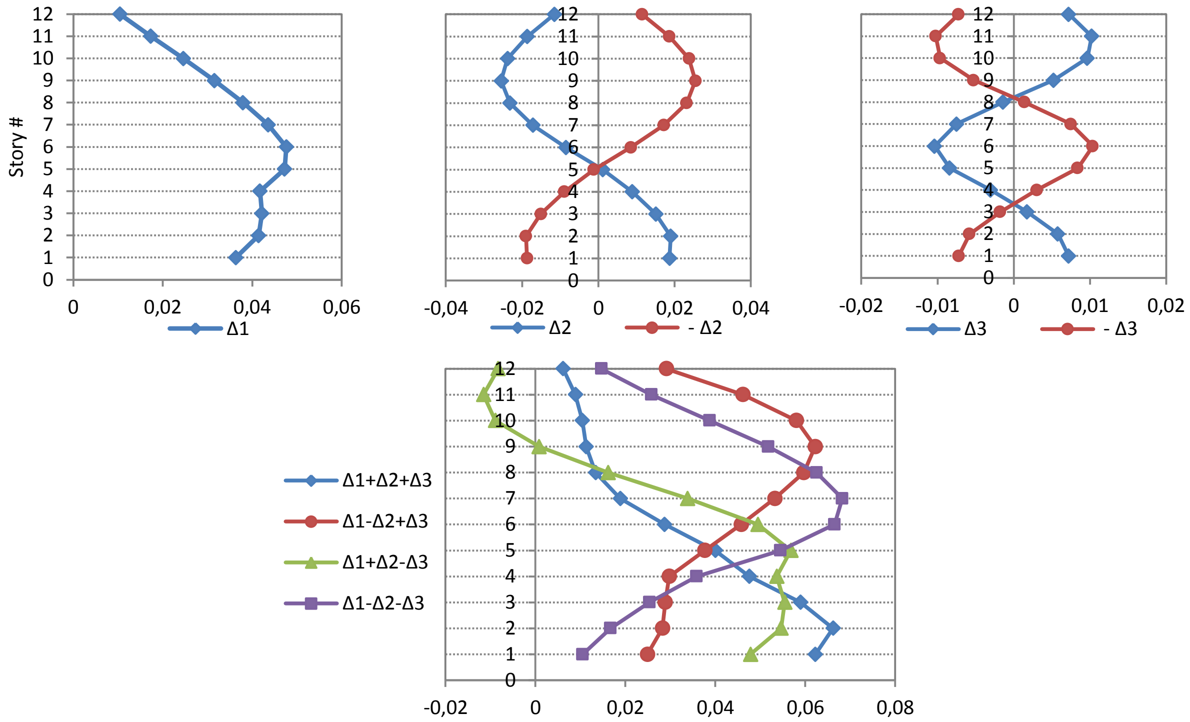


Figure 5. Elastic interstory drift profiles of the 12 story RC frame and their upper bound combinations

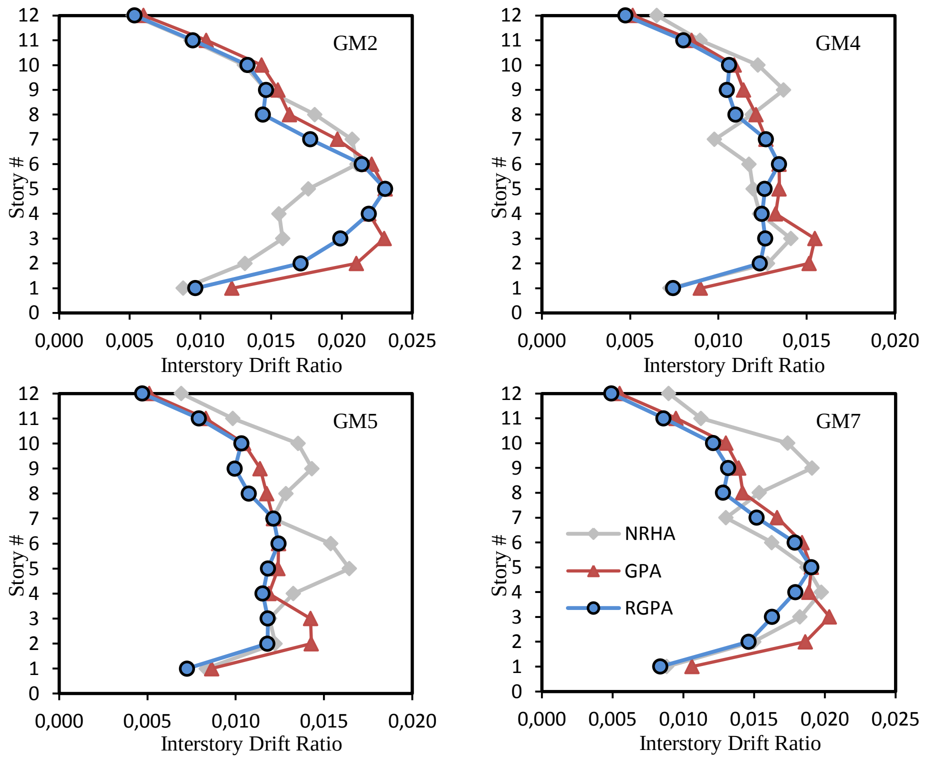


Figure 6. Maximum interstory drift ratios under four ground motions

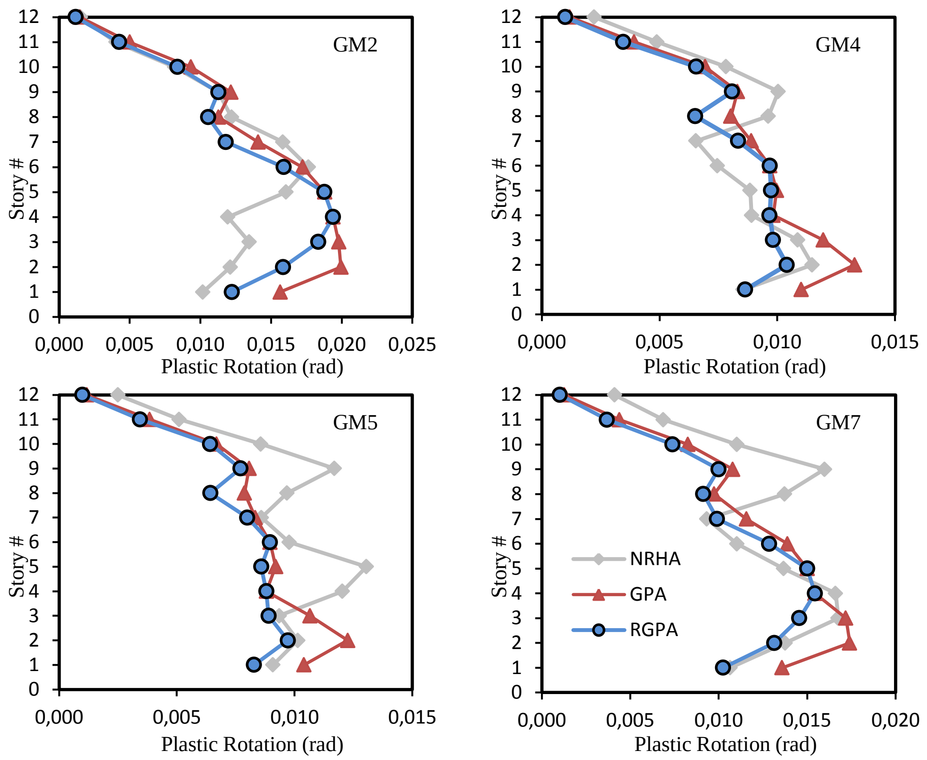


Figure 7. Maximum average beam plastic rotations under four ground motions

4. COMPARATIVE RESULTS

Seismic performance of the 12 story frame under the 7 ground motions in Table 1 is calculated by RGPA and compared with the results of MPA and the benchmark NRHA in this section. Maximum average column-end chord rotations at the first story column bases and maximum average beam-end plastic rotations at all stories are shown comparatively in Table 2 and Figure 8, respectively. Column bases yield slightly, hence comparison of chord rotations is more meaningful than comparing the plastic rotations. There are no other yielding sections in columns.

RGPA results are sufficiently close to the NRHA results. NRHA indicates significant yielding at the 9'th story under all ground motions. This is both due to higher mode effects, and reduction of column and beam sizes at the 9'th story. Amplification of plastic beam-end rotations at the 9'th story is not captured properly by RGPA and MPA. Non-adaptive nature of RGPA and MPA does not permit prediction of changing mode shapes during inelastic response.

Maximum bending moment values at beam ends are also presented in Figure 9 under GM2 and GM4. RGPA captures NRHA results exactly. It can be concluded that the RGPA procedure takes into account higher mode effects effectively, similar to the original GPA.

Table 2. Maximum average chord rotations of the first story column under seven ground motions

	Chord Rotations of the First Story Column Bases (*rad*)						
	GM1	GM2	GM3	GM4	GM5	GM6	GM7
NRHA	0.0066	0.0058	0.0040	0.0050	0.0053	0.0047	0.0061
MPA	0.0051	0.0079	0.0043	0.0052	0.0051	0.0032	0.0066
RGPA	0.0050	0.0069	0.0040	0.0050	0.0049	0.0040	0.0059
Yield Rotation = 0.0049 rad							

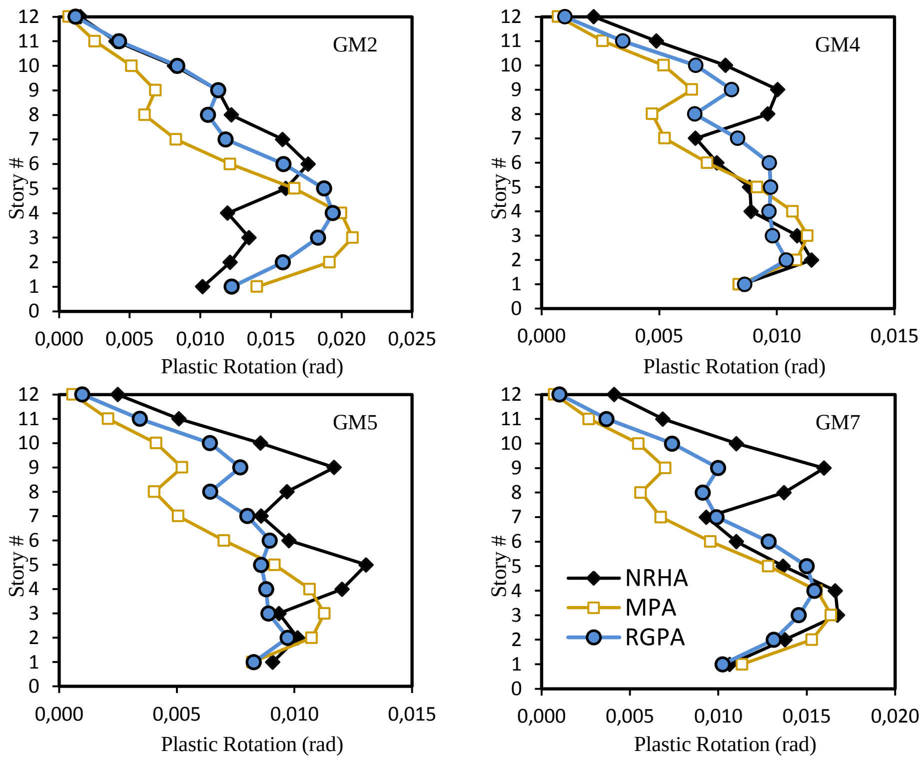


Figure 8. Maximum average beam-end plastic rotations under four ground motions

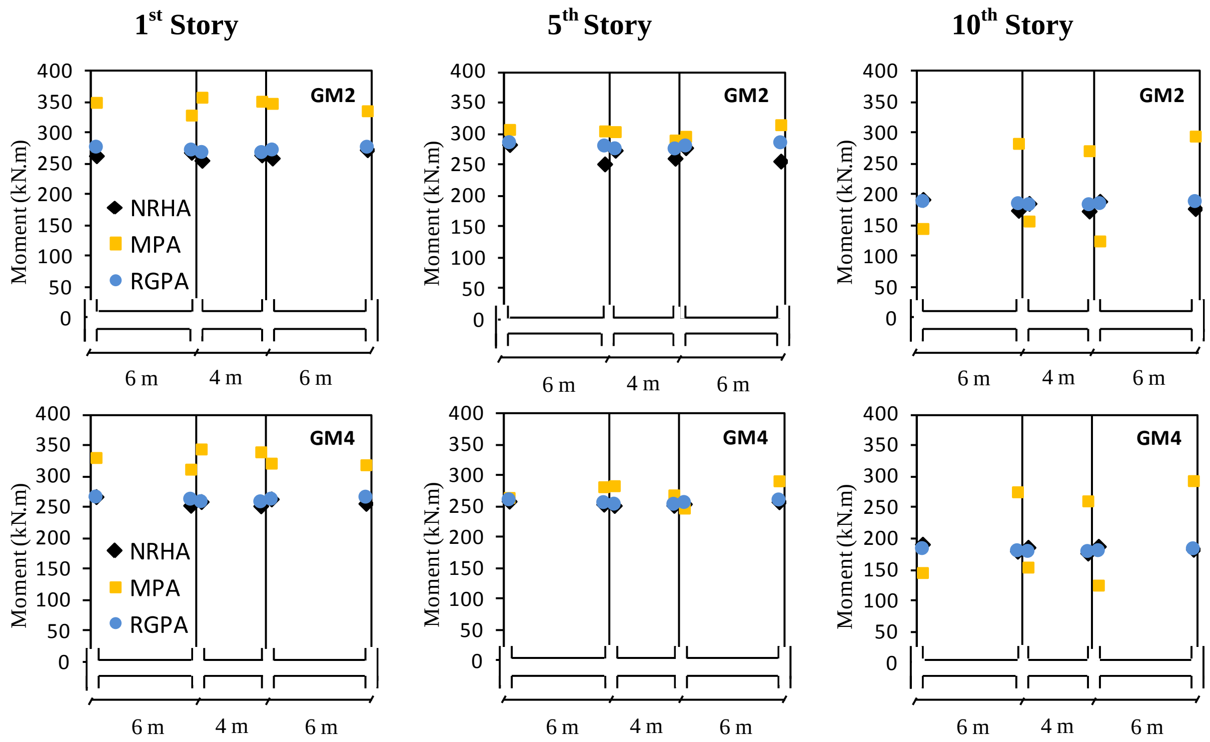


Figure 9. Maximum beam end moments under GM2 and GM4

Mean spectrum of seven ground motions in Table 1 is employed for the RGPA analysis, and these results obtained by a single RGPA analysis are compared with the mean results of NRHA, RGPA, and MPA obtained by using seven ground motions. Comparison of interstory drift ratios and maximum average beam-end plastic rotations are presented in Figure 10. The results of single RGPA under mean spectrum and mean results of RGPA under 7 ground motions are very close to each other. These RGPA results are also well synchronized with the NRHA results. Single RGPA results under mean spectrum indicate that RGPA can be employed effectively under any code or design spectrum which represents the statistical average of several ground motions.

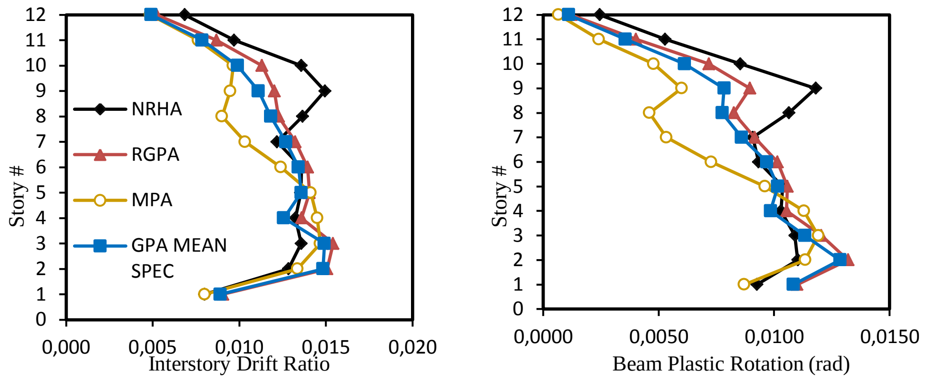


Figure 10. Comparison of the mean results of NRHA, RGPA and MPA with the results of single RGPA under mean spectrum

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