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A SINGLE-RUN PUSHOVER PROCEDURE UNDER SIMULTANEOUS BI-DIRECTIONAL SEISMIC EXCITATION

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Abstract

In this paper a new pushover procedure based on the modal story shear and torque is proposed for seismic assessment of asymmetric-plan buildings under bi-directional ground motions. In the proposed method, the combined modal story shear and torque profiles are computed for each direction of excitation (x and y) and then using SRSS (Square Roots of Sum of Squares) combination rule, combined modal story shear and torque due to simultaneous excitation of x and y directions are calculated. The proposed load pattern is derived from the resulted combined modal story shear and torque profiles, so only a single-run pushover analysis is required for simultaneous excitation of x and y directions. In this procedure, the contribution of the higher and torsional modes and the frequency content of a specific ground motion are considered. The proposed method is evaluated through an asymmetric-plan building under different ground motion records. The results are compared to those obtained from nonlinear time history analysis and establish the accuracy of the proposed method in estimation of the structural responses.

Keywords: 3D pushover, Bi-directional excitation, Asymmetric-plan

1. Introduction

In the recent years, nonlinear static analysis method is widely used as a practical tool for estimation of the structural responses in guidelines and codes [1-2]. Since conventional pushover procedure of the guidelines is restricted to a single-mode and cannot consider the contributions of the higher modes and changes in the modes shape due to structural yielding, the accuracy of this procedure in estimation of the structural responses is not suitable [3-5]. In order to consider the effects of the higher modes and improve the mentioned shortcomings, several multi-mode and adaptive modal procedures have been proposed by numerous researchers [6-13].

It is obvious that in order to obtain an accurate estimation of structural responses, using a complete 3D model of the structures is inevitable. In this regard, many efforts have been done in order to consider the effects of the higher modes and torsional behavior of the structure. In some of them, asymmetric 3D plan buildings were subjected to one-directional ground motion [14-18]. Although the effect of the torsional modes was considered in these procedures, however, considering the influence of the simultaneous bi-directional ground motions in order to improve the accuracy of the pushover method in estimation of the desired responses of structure seems inevitable [19-24].

Based on the above observations, the necessity of conducting research on the pushover analysis under simultaneous bi-directional seismic excitations in asymmetric buildings is obvious. In this study, a new single-run pushover analysis under bi-direction excitation is proposed. The effects of the higher and torsional modes and the interaction between them in the nonlinear phase are considered through the proposed modal load pattern.

2. Proposed Pushover Procedure

In this paper, spectral dynamic analysis of asymmetric-plan buildings under bi-directional excitation in linear phase is intuitively extended for nonlinear phases. Since the inter-story drift profile of the structure, as a crucial index in damage assessment, is affected by the amount of the story shear and torque, the load pattern of the proposed method is derived from the combined modal story shear and combined modal story torque of the 3D model of the structure. In the proposed load pattern, the effects of higher and torsional modes and the interaction between them are considered. Furthermore, the frequency content of the selected ground motion is also considered by using the response spectrum of the applied ground motion [11]. In the proposed method, only a single load pattern is calculated for simultaneous excitation of x and y directions, thus only a single-run pushover analysis is required for the seismic assessment of structures under simultaneous bi-directional excitation (x and y). Subsequently, the structural responses are obtained by a single-run pushover analysis rather than multi-run procedures and there is no need to push structure individually in two directions (x and y). This leads to reduce the computational operations and makes the proposed pushover procedure more simple and practical in comparison to multi-run pushover procedures.

In the proposed method, the capacity curves of the structure in x and y directions are established, independently and in order to obtain them, the MDOF system is transformed to an adaptive equivalent inelastic SDOF system based on the instantaneous deformed shape of the MDOF system using the adaptive capacity spectrum method (ACSM) [25].

In order to establish the capacity curve according to the ACSM method, the deformed shape of the structure under the applied load pattern, which can be recorded during the analysis, is considered as the assumed fundamental mode shape. Thus, instantaneous changes in the dynamic characteristics of the structure during the nonlinear analysis and as a result of converting MDOF system into SDOF system are considered.

The proposed procedure is summarized in the sequential steps here. As the first stage, a single load pattern is calculated for simultaneous excitation of x and y directions through steps 1-11.

1. Create the 3D model of the structure.

2. Perform an eigenvalue analysis in order to compute the natural frequencies, ω_j, and the mode shapes Φ_j.

3. Provide the elastic pseudo acceleration spectra for two components of the ground motion records (x and y).

4. Calculate the modal story forces and torques for the considered modes in the x and y directions, independently.

$$F^x_{x_{ij}} = \Gamma^x_j \, \Phi_{x_{ij}} m_{x_i} S^x_{a_j} \quad , \quad F^y_{x_{ij}} = \Gamma^y_j \, \Phi_{x_{ij}} m_{x_i} S^y_{a_j} \tag{1}$$

$$F^x_{y_{ij}} = \Gamma^x_j \, \Phi_{y_{ij}} m_{y_i} S^x_{a_j} \quad , \quad F^y_{y_{ij}} = \Gamma^y_j \, \Phi_{y_{ij}} m_{y_i} S^y_{a_j} \tag{2}$$

$$T^x_{\theta_{ij}} = \Gamma^x_j \, \Phi_{\theta_{ij}} I_{\theta_i} S^x_{a_j} \quad , \quad T^y_{\theta_{ij}} = \Gamma^y_j \, \Phi_{\theta_{ij}} I_{\theta_i} S^y_{a_j} \tag{3}$$

where i and j are the story and mode numbers, respectively; $\Gamma^x_j = \phi^T_j M \iota_x / \phi^T_j M \phi_j$ and $\Gamma^y_j = \phi^T_j M \iota_y / \phi^T_j M \phi_j$ are the modal participation factor of jth mode in x and y directions, respectively; $\iota_x = \langle 1\ 0\ 0 \rangle^T$ and $\iota_y = \langle 0\ 1\ 0 \rangle^T$ are the influence vector for seismic excitation in x and y direction, respectively; M is the mass matrix based on a 3D model of the structure, $\Phi_j = \langle \Phi_{x_j}\ \Phi_{y_j}\ \Phi_{\theta_j} \rangle^T$ is mode shape vector of jth mode consisting of two translational vectors in x and y directions: $\Phi_{x_j} = \langle \phi_{x_{1j}} \phi_{x_{2j}} \ldots \phi_{x_{nj}} \rangle^T$, $\Phi_{y_j} = \langle \phi_{y_{1j}} \phi_{y_{2j}} \ldots \phi_{y_{nj}} \rangle^T$ and a rotational vector: $\Phi_{\theta_j} = \langle \phi_{\theta_{1j}} \phi_{\theta_{2j}} \ldots \phi_{\theta_{nj}} \rangle^T$, $\phi_{x_{ij}}$, $\phi_{y_{ij}}$, $\phi_{\theta_{ij}}$ are mode shape components in x, y and rotational directions of ith story in jth mode; m_{x_i} and m_{y_i} are the translational mass of the ith story in x and y directions, respectively; I_{θ_i} is the rotational mass of the ith story; $S^x_{a_j}$ and $S^y_{a_j}$ are respectively the spectral acceleration in x and y directions corresponding to the jth mode; $F^x_{x_{ij}}$ and $F^x_{y_{ij}}$ are the maximum induced modal forces in story i respectively in x and y directions corresponding to mode j due to excitation in x direction; $T^x_{\theta_{ij}}$ is the maximum induced modal torque in ith story corresponding to jth mode due to excitation in x direction; $F^y_{x_{ij}}$, $F^y_{y_{ij}}$ and $T^y_{\theta_{ij}}$ are the same parameters as $F^x_{x_{ij}}$, $F^x_{y_{ij}}$ and $T^x_{\theta_{ij}}$, respectively, but due to excitation in y direction.

5. Calculate the modal story shear and the total modal story torque associated with each considered mode (j) in the x and y direction, independently.

$$SS^x_{x_{ij}} = \sum_{h=i}^{n} F^x_{x_{hj}} \quad , \quad SS^y_{x_{ij}} = \sum_{h=i}^{n} F^y_{x_{hj}} \tag{4}$$

$$SS^x_{y_{ij}} = \sum_{h=i}^{n} F^x_{y_{hj}} \quad , \quad SS^y_{y_{ij}} = \sum_{h=i}^{n} F^y_{y_{hj}} \tag{5}$$

$$ST^x_{\theta_{ij}} = \sum_{h=i}^{n} T^x_{\theta_{hj}} \quad , \quad ST^y_{\theta_{ij}} = \sum_{h=i}^{n} T^y_{\theta_{hj}} \tag{6}$$

where $SS^x_{x_{ij}}$ and $SS^x_{y_{ij}}$ are the story shears in floor *i* corresponding to mode *j* in *x* and *y* directions respectively, due to excitation in x direction and the $ST^x_{\theta_{ij}}$ is story torque in floor *i* corresponding to mode *j* due to excitation in x direction. $SS^y_{x_{ij}}$, $SS^y_{y_{ij}}$ and $ST^y_{\theta_{ij}}$ are the same parameters as the $SS^x_{x_{ij}}$, $SS^x_{y_{ij}}$ and $ST^x_{\theta_{ij}}$ respectively, but due to excitation in y direction.

6. By using complete quadratic combination (CQC) rule, compute the combined modal story shear and the combined modal total story torque profiles corresponding to the x and y directions, independently.

$$CSS_{x_i}^{x} = \sqrt{\sum_{j}^{m}\sum_{k}^{m} \rho_{jk} SS_{x_{ij}}^{x} SS_{x_{ik}}^{x}} \quad , \quad CSS_{x_i}^{y} = \sqrt{\sum_{j}^{m}\sum_{k}^{m} \rho_{jk} SS_{x_{ij}}^{y} SS_{x_{ik}}^{y}} \tag{7}$$

$$CSS_{y_i}^{x} = \sqrt{\sum_{j}^{m}\sum_{k}^{m} \rho_{jk} SS_{y_{ij}}^{x} SS_{y_{ik}}^{x}} \quad , \quad CSS_{y_i}^{y} = \sqrt{\sum_{j}^{m}\sum_{k}^{m} \rho_{jk} SS_{y_{ij}}^{y} SS_{y_{ik}}^{y}} \tag{8}$$

$$CST_{\theta_i}^{x} = \sqrt{\sum_{j}^{m}\sum_{k}^{m} \rho_{jk} ST_{\theta_{ij}}^{x} ST_{\theta_{ik}}^{x}} \quad , \quad CST_{\theta_i}^{y} = \sqrt{\sum_{j}^{m}\sum_{k}^{m} \rho_{jk} ST_{\theta_{ij}}^{y} ST_{\theta_{ik}}^{y}} \tag{9}$$

where $CSS_{x_i}^{x}$ and $CSS_{y_i}^{x}$ are the combined modal story shears in floor i in x and y directions, respectively, due to excitation in x direction; $CST_{\theta_i}^{x}$ is the combined modal total story torque in floor i due to excitation in x direction, associated with all of the considered modes; m is the number of the considered modes; $CSS_{x_i}^{y}$, $CSS_{y_i}^{y}$ and $CST_{\theta_i}^{y}$ are the same parameters as $CSS_{x_i}^{x}$, $CSS_{y_i}^{x}$ and $CST_{\theta_i}^{x}$, respectively, but due to excitation in y direction and ρ_{jk} is the correlation coefficient between two modes which is calculated using the following equation:

$$\rho_{jk} = \frac{8 \times \sqrt{\xi_j \xi_k} (\beta_{jk}\xi_k + \xi_j)\beta_{jk}^{1.5}}{(1-\beta_{jk}^2)^2 + 4\xi_j\xi_k\beta_{jk}(1+\beta_{jk}^2) + 4(\xi_j^2 + \xi_k^2)\beta_{jk}^2} \tag{10}$$

where ξ_j and ξ_k are the damping ratios corresponding to modes j and k, respectively and $\beta_{jk} = \omega_j/\omega_k$ is the frequency ratio between two considered modes (j, k).

7. Calculate the combined modal story shear and the combined modal total story torque profiles due to simultaneous excitation of x and y directions. For this purpose, the computed values in step 6 corresponding to the x and y directions are combined using SRSS (Square Roots of Sum of Squares) combination rule.

$$CSS_{x_i}^{xy} = \sqrt{(CSS_{x_i}^{x})^2 + (CSS_{x_i}^{y})^2} \tag{11}$$

$$CSS_{y_i}^{xy} = \sqrt{(CSS_{y_i}^{x})^2 + (CSS_{y_i}^{y})^2} \tag{12}$$

$$CST_{\theta_i}^{xy} = \sqrt{(CST_{\theta_i}^{x})^2 + (CST_{\theta_i}^{y})^2} \tag{13}$$

where $CSS_{x_i}^{xy}$ and $CSS_{y_i}^{xy}$ are the combined modal story shears in floor i in x and y directions, respectively, due to simultaneous excitation of x and y directions; $CST_{\theta_i}^{xy}$ is the combined modal total story torque in floor i due to simultaneous excitation of x and y directions.

8. Determine the components of the load pattern vector in each story due to simultaneous excitation of x and y directions by subtracting the combined modal story shear and combined total story torque of consecutive stories.

$$\begin{cases} F_{x_n}^{xy} = CSS_{x_n}^{xy} \\ F_{x_i}^{xy} = CSS_{x_i}^{xy} - CSS_{x_{i+1}}^{xy} \qquad i = 1, 2, ..., (n-1) \end{cases} \tag{14}$$

$$\begin{cases} F_{y_n}^{xy} = CSS_{y_n}^{xy} \\ F_{y_i}^{xy} = CSS_{y_i}^{xy} - CSS_{y_{i+1}}^{xy} \qquad i = 1, 2, ..., (n-1) \end{cases} \tag{15}$$

$$\begin{cases} T_{\theta_n}^{xy} = CST_{\theta_n}^{xy} \\ T_{\theta_i}^{xy} = CST_{\theta_i}^{xy} - CST_{\theta_{i+1}}^{xy} \qquad i = 1, 2, ..., (n-1) \end{cases} \tag{16}$$

where $F_{x_i}^{xy}$, $F_{y_i}^{xy}$ are the force components of the calculated load vector in x and y translational directions, respectively; $T_{\theta_i}^{xy}$ is the torque component of the calculated load vector in story i due to simultaneous excitation of x and y directions.

9. Normalize the calculated load pattern vector with respect to the summation of the force components in x (or y) direction. In this study, x direction is considered.

$$\overline{F}_{x_i}^{xy} = F_{x_i}^{xy} \;/ \sum F_{x_i}^{xy} \tag{17}$$

$$\overline{F}_{y_i}^{xy} = F_{y_i}^{xy} / \sum F_{x_i}^{xy} \tag{18}$$

$$\overline{T}_{\theta_i}^{xy} = T_{\theta_i}^{xy} / \sum F_{x_i}^{xy} \tag{19}$$

10. Multiply the normalized components of the load pattern by the amount of the increment in the base shear of the structure in the considered direction in step 9.

$$\Delta F_{x_i}^{xy} = \Delta V_b^x \times \overline{F}_{x_i}^{xy} \tag{20}$$

$$\Delta F_{y_i}^{xy} = \Delta V_b^x \times \overline{F}_{y_i}^{xy} \tag{21}$$

$$\Delta T_{\theta_i}^{xy} = \Delta V_b^x \times \overline{T}_{\theta_i}^{xy} \tag{22}$$

where ΔV_b^x is the incremental amount of the base shear in x direction excitation (considered direction in step 9); $\Delta F_{x_i}^{xy}$, $\Delta F_{y_i}^{xy}$ and $\Delta T_{\theta_i}^{xy}$ are the components of the load pattern corresponding to simultaneous excitation in x and y directions.

11. Apply the calculated load pattern to the structure until the structure becomes unstable to resist any load. Record the desired responses at each step of the pushover analysis.

In the second stage, the capacity curves of the structure in x and y directions are established, independently through steps 12-17. Finally, the desired responses of the structure due to simultaneous excitation in x and y directions are computed in step 18.

12. Extract the displacement vector in the mass center of stories (along two translational directions and the torsional direction) at each step of the pushover analysis (D_k) from the database of the recorded responses.

13. Calculate the instantaneous effective mass of the structure in x direction by assuming the obtained displacement vector of step 12 as the instantaneous fundamental mode shape of the structure at k[th] step of the pushover analysis.

$$M_k^{*x} = \frac{\left(D_k^T M \iota_x\right)^2}{D_k^T M D_k} \tag{23}$$

where, D_k is the vector of the deformed shape of the structure (consisting of two orthogonal translational displacements and a torsional rotation at the mass center of all stories) at k[th] step of the pushover analysis.

14. Develop the force–displacement curve of the adaptive equivalent inelastic SDOF system in the x direction and idealize it as a bilinear curve.

$$S_{a,k}^{x} = \frac{V_{b,x_k}^{xy}}{M_k^{*x}} \tag{24}$$

$$S_{d,k}^{x} = \frac{D_k^T M D_k}{D_k^T M \iota_x} \tag{25}$$

where V_{b,x_k}^{xy} is the base shear of structure in x direction due to simultaneous excitation in x and y directions at k[th] step of the pushover analysis.

15. Determine the target displacement in x direction as the maximum displacement of the adaptive equivalent bilinear inelastic SDOF system corresponding to the x direction. For this purpose, Plot the inelastic demand spectrum against the capacity curve of the structure in x direction in the acceleration–displacement response spectrum format. The intersection point between these two spectra is the target displacement. In this study, in order to verify the proposed method against the nonlinear time history analysis (NTHA), the target displacement is directly computed through the NTHA of the SDOF system under the individual component of the ground motion in the desired direction.
16. Determine the corresponding step to the target displacement of x direction in the pushover procedure and obtain the seismic demands of the structure (r^x).
17. Return to step 13 and obtain the seismic demands of structure in y direction (r^y), repeating steps 13-16 for y direction ($M_k^{*y} = \frac{(D_k^T M \iota_y)^2}{D_k^T M D_k}$, $S_{a,k}^{y} = \frac{V_{b,y_k}^{xy}}{M_k^{*y}}$, $S_{d,k}^{y} = \frac{D_k^T M D_k}{D_k^T M \iota_y}$).
18. Calculate the total seismic demand (r) due to simultaneous excitation in x and y directions by combing the individual demands due to excitation in x and y directions (r^x and r^y), using SRSS combination rule.

3. Analytical Model and Ground Motions

The selected building for evaluation of the accuracy of the proposed method is a 20-story building, denoted as SAC-20. This building is designed according to 1994 UBC seismic code [26] for phase II of the SAC project for Los Angeles, California. The structural system of this building consists of perimeter steel moment-resisting frames (SMRF). It is 30.5 m by 36.6 m in plan. The height of its first story is 5.5 m and the height of the other stories is 4 m. The translational seismic mass of the selected building is equal to 1128579 kg-s^2/m. Detailed information about this building can be found in reference [27]. In order to simulate the effects of the torsion in the structure and to evaluate the efficiency of the proposed method in bi-axial asymmetric plans, the mass center of each story is moved as much as 10% of the plan dimension in both horizontal directions. The plan of the selected building is presented in Fig.1, which shows only the moment resistant frames.

The nonlinear 3D model of the considered building is generated in OpenSees finite element platform [28]. Nonlinear-Beam-Column element with fiber section is used to model all of the structural elements. Floors of the building are assumed to be rigid in plane. Rayleigh damping ratio of 5% has been assigned to the first mode with the fundamental period of vibration, T_1, and a mode with a period of $0.1T_1$. The vibration periods of the analytical model in six modes are presented in table 1.

Table 1 – The vibration periods of SAC-20 building

	T_1	T_2	T_3	T_4	T_5	T_6
Period (sec)	3.73	3.34	1.87	1.30	1.17	0.77

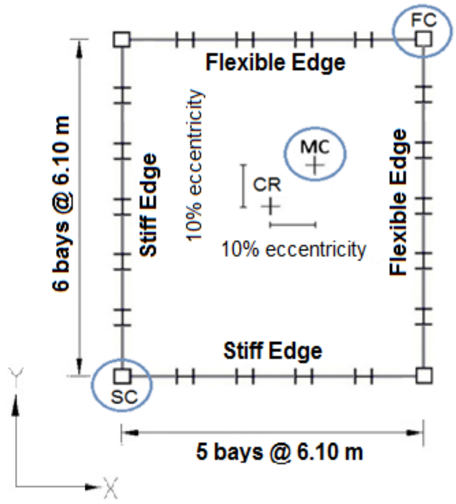

Fig. 1 – Asymmetric plan of SAC-20 building with10% mass eccentricity in each of two horizontal directions, illustrating mass center (MC), flexible corner (FC) and stiff corner (SC)

The structural models are subjected to an ensemble of seven horizontal pairs of ground motion records belonging to NEHRP site classification D [29]. The properties of the considered records are listed in Table 2. In Fig.2, the 5%-damped pseudo-acceleration response spectra for two components of the selected records are shown. All considered records are available in the Pacific Earthquake Engineering Research ground motion database (http://peer.berkeley.edu).

Table 2 – Ground motions characteristics

Ground motion ID	Earthquake	Year	Magnitude (Mw)	Closest distance to fault (km)	X Direction[a] PGA (g)	Y Direction[a] PGA (g)
1	Imperial Valley	1979	6.5	0.6	0.463	0.338
2	Landers	1992	7.3	19.7	0.417	0.283
3	Duzce, Turkey	1999	7.1	8.2	0.535	0.348
4	Kocaeli, Turkey	1999	7.4	2.6	0.349	0.268
5	San Fernando	1971	6.6	22.8	0.225	0.195
6	Superstition Hills	1987	6.7	0.7	0.455	0.377
7	Northridge	1994	6.7	6.2	0.593	0.424

[a]Applied direction of the ground motion component in the building plan.

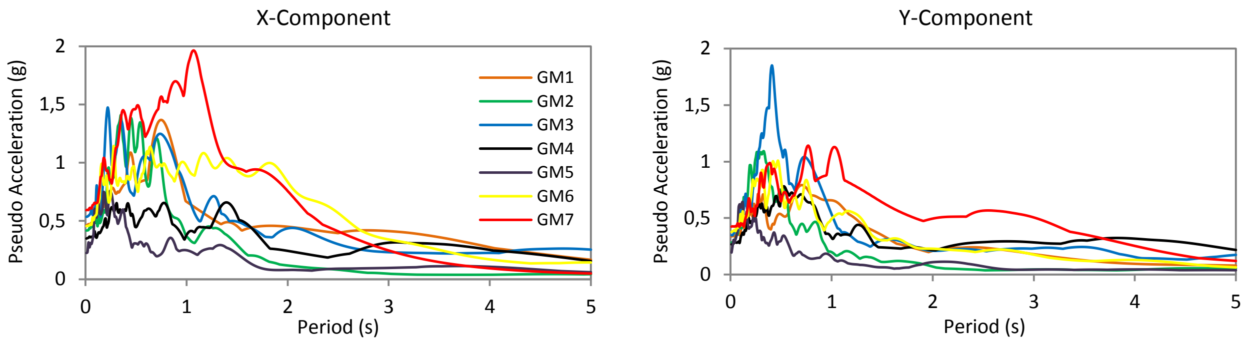

Fig. 2 – Elastic acceleration spectra of seven ground motion records for x and y components; $\zeta = 5\%$

4. Evaluation of the proposed method

In this study, the inter-story drifts are investigated in order to evaluate the accuracy of the proposed method (PM) in estimating the seismic responses of the structures. These quantities are monitored at the mass center (MC), the flexible corner (FC) and the stiff corner (SC). FC and SC are two corners of the plan in the extreme opposite sides (Fig. 1). The responses resulted from the proposed method are compared to those resulted from the nonlinear time history analysis (NTHA). In addition, response estimations of the M1 method (pushover analysis with the load pattern based on distribution of the effective seismic forces at the first dominated mode in each direction of excitation) are also included.

In this study, the first dominated mode in each direction of excitation is considered as the load pattern of M1 procedure in that direction. The pushover procedure is run separately for each direction, and then the overall responses due to excitation in both directions are obtained by the SRSS combination of the responses from each direction.

Fig.3 shows the mean drift profiles resulted from the NTHA under seven pairs of ground motions at the monitoring points in x and y directions and also the mean drift profile of each pushover method. As shown in Fig. 3 the mean drift profiles of the considered building estimated by the proposed method are closer to NTHA in comparison to those resulted from M1 procedure. Furthermore, the trend of the mean story drift profiles resulted from the proposed method are appropriately compatible with the trend of the NTHA.

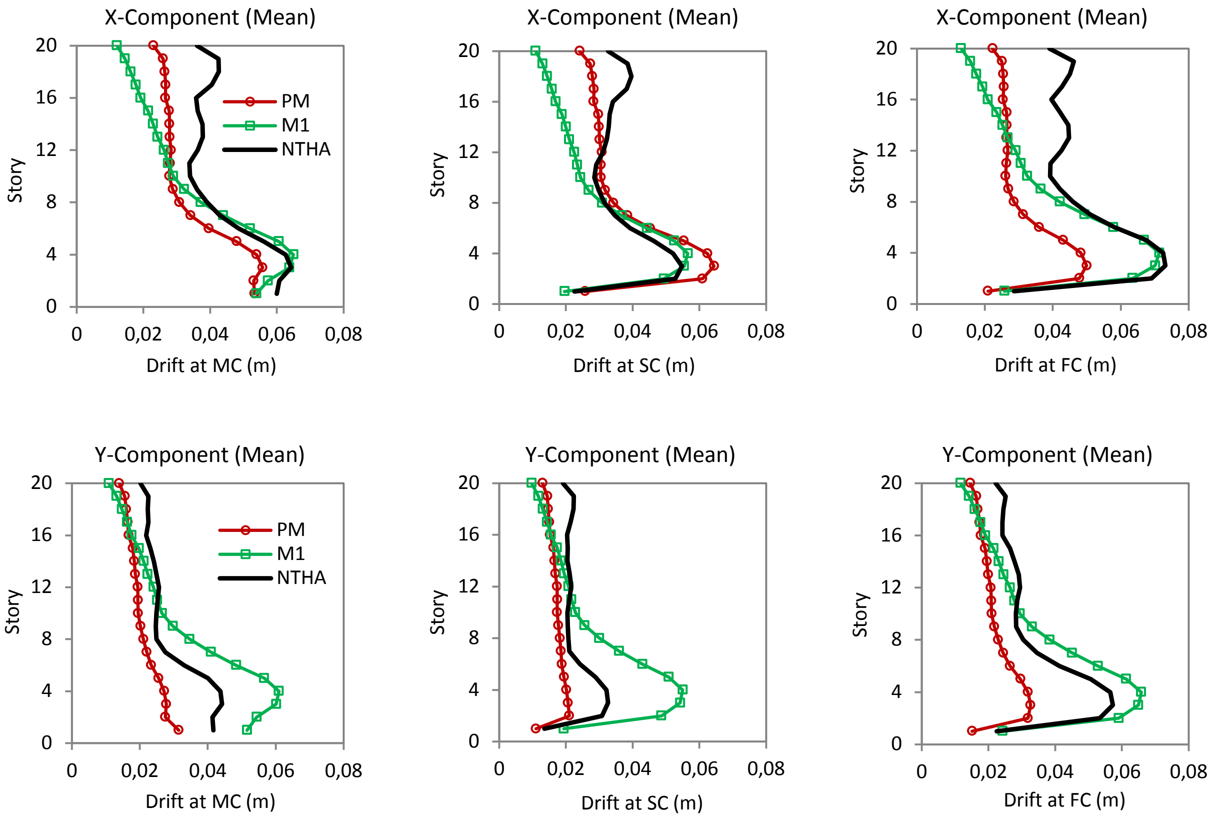

Fig. 3 – The x and y components of the Mean story drift profiles at MC, SC and FC subjected to two components of seven ground motion records simultaneously

In order to evaluate the accuracy of the considered pushover methods in estimating the structural responses, the results of the NTHA are assumed to be the exact responses [30] and the total error of each pushover procedure on the inter-story drift profile is calculated using Eq. 26.

$$Total\_Error(\%) = 100 \times \frac{1}{n} \times \sqrt{\sum_{i=1}^{n} \left(\frac{\Delta_{i-NTHA}^{x\,(or\,y)} - \Delta_{i-NSP}^{x\,(or\,y)}}{\Delta_{i-NTHA}^{x\,or\,(y)}} \right)^2} \tag{26}$$

where $\Delta_{i-NTHA}^{x\,(or\,y)}$ and $\Delta_{i-NSP}^{x\,(or\,y)}$ are the maximum x (or y) component of the inter-story drift in i^{th} story resulted from the NTHA and the considered nonlinear static analysis (pushover) procedure, respectively; n is the number of the stories of the building.

The total error on the x and y components of the inter-story drift in CM, SS and FS points for the considered pushover methods under each ground motion record are presented in Fig.4. As shown in this figure, the resulted errors from the M1 procedure for most of the considered motions at monitoring points in x or y directions are more than those resulted from the proposed method.

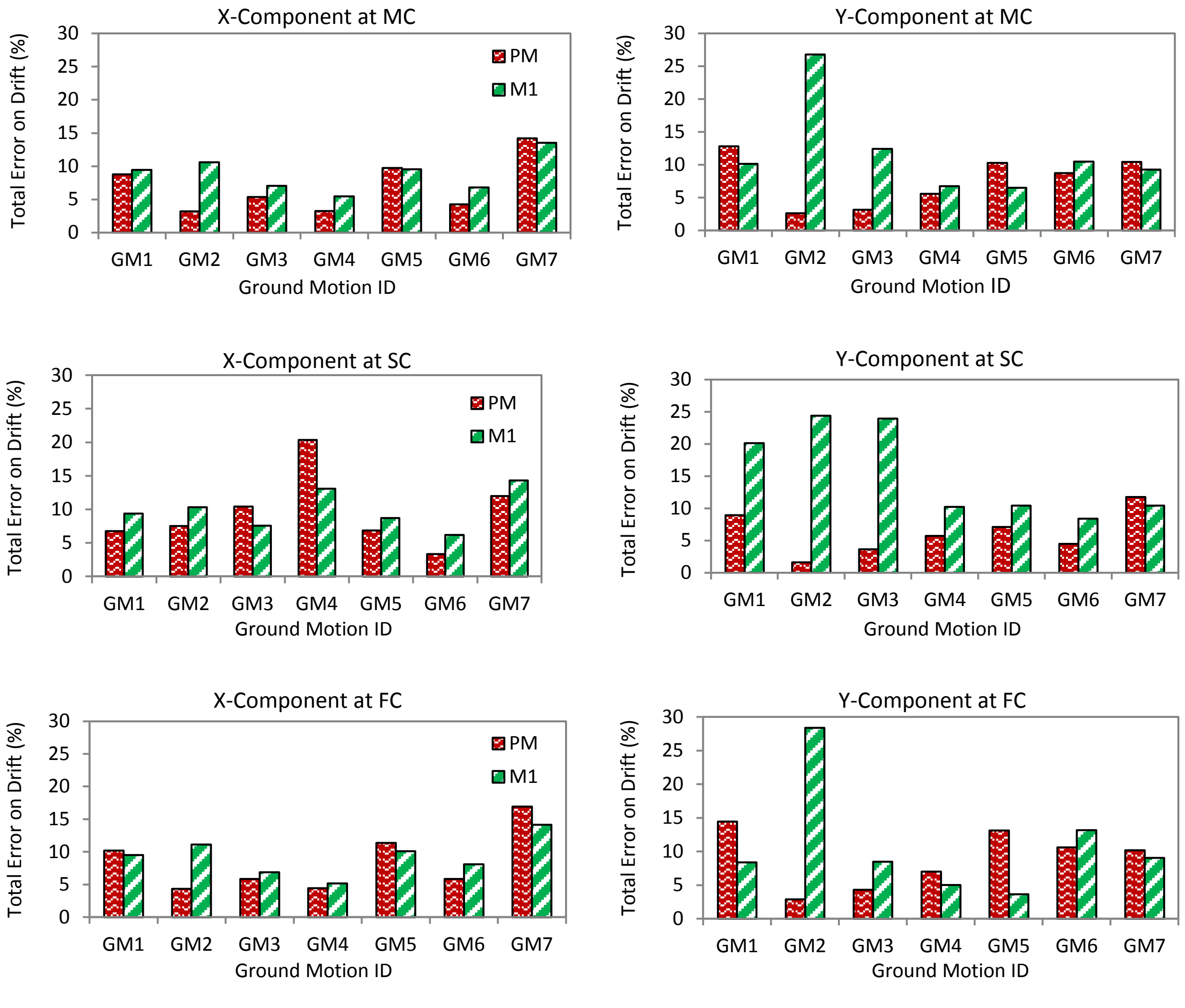

Fig. 4 – Total errors on the x and y components of the story drift at MC, SC and FC points for each of the considered ground motion record

Furthermore, the total error of the mean story drift profiles at the MC, SC and FC points are represented in Fig.5. These errors are calculated using Equation (26), in which the $\Delta_{i-NTHA}^{x\,(or\,y)}$ and $\Delta_{i-NSP}^{x\,(or\,y)}$ are replaced with the corresponding mean values. As presented in Fig. 5, the total errors for the x and y components of the proposed method at MC and SC monitoring points are less than those resulting from the M1 procedure. Furthermore, the resulting errors from the proposed method and M1 procedure are close to each other in the x component of the FC monitoring point but the error of the proposed method in the y component of the FC monitoring point is more than the error of the M1 procedure.

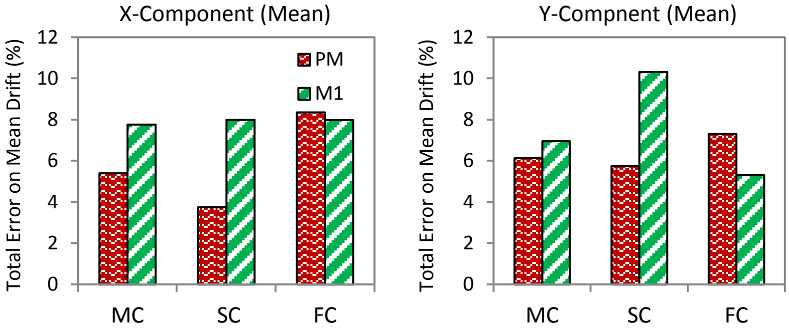

Fig. 5 – Total errors on the x and y components of the Mean story drift at MC, SC and FC points

5. Conclusions

A single-run pushover procedure is proposed for seismic assessment of the asymmetric-plan buildings under simultaneous bi-directional seismic excitations. The load pattern of the proposed procedure is derived from the combined modal story shear and torque profiles of the structure due to simultaneous excitation in x and y directions. So only a single-run pushover analysis is needed in order to estimate the structural responses due to simultaneous excitation in two orthogonal directions. The effects of the higher modes, the interaction between them and the spectral characteristics of the applied ground motion records are considered through the proposed load pattern. In the proposed method, the instantaneous changes of the dynamic characteristics of the structure in the nonlinear phase is considered in the capacity curve of the structure which is obtained based on the instantaneous deformed shape of the structure according to the adaptive capacity spectrum method (ACSM).

The proposed method is evaluated through a 20-story building with 10% two-way eccentricity in the plan under seven horizontal pairs of ground motion records and the resulted responses are compared with those resulted from the nonlinear time history analysis (NTHA) of the building subjected to the bi-directional excitation. The responses resulted from the M1 method are also considered in the evaluation. For this purpose, the amount of the inter-story drifts are monitored in three points of each story of the considered plan including the mass center (MC), flexible corner (FC) and the stiff corner (SC). The main conclusions are as follow:

1. The proposed method is a single-run pushover procedure for seismic assessment of asymmetric-plan buildings under simultaneous excitation in two translational directions (x and y). So, the main advantage of the proposed method lies in its simplicity and less computational demand in comparison to the multi-run procedures.
2. Regarding the consideration of the spectral characteristic of the applied ground motion in defining the proposed load pattern, the trend of the mean inter-story drift profiles resulted from the proposed method are compatible with the trend of NTHA.
3. In the considered building, the mean inter-story drift profiles resulted from the proposed method are closer to those obtained from the NTHA in comparison to the responses resulted from the M1 procedure.
4. The total errors of the mean inter-story drifts resulted from the proposed method in most of the cases are smaller than those obtained from the M1 procedure.
5. Based on the resulted total errors on mean inter-story drift at monitoring points, the proposed method is more accurate in comparison to the M1 method at MC and SC points in both x and y directions. At FC point, the M1 and proposed methods approximately result in equal responses in x direction. However, the accuracy of the proposed method is slightly less than the accuracy of the M1 method in y direction.

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