Iran J Sci Technol Trans Civ Eng (2019) 43 (Suppl 1):S23–S36
https://doi.org/10.1007/s40996-018-0119-y

RESEARCH PAPER

Adaptive Load Patterns Versus Non-adaptive Load Patterns for Pushover Analysis of Building

Mohsen Ali Shayanfar[1] · Mehrollah Rakhshanimehr[2] · Mansoor Ashoory[1]

Received: 10 September 2016 / Accepted: 16 May 2018 / Published online: 8 October 2018

Abstract

Nowadays, concepts of the performance-based design engineering constitute the main basis for compilation of most of the seismic analysis and design codes. During the past 2 decades, broad attempts have been made by the researchers to narrow the gap between the nonlinear static procedures (NSP), and the nonlinear time-history analysis (NTHA) as the most exact method for structural analysis. It is well known, ignoring the higher-mode effects and dynamic characteristics alterations, are the main shortcomings of the NSPs. In this regard, procedures with adaptive load pattern have been addressed by many researchers and consider the effects of changes in modal characteristics of structures during monotonically increasing load process. In this paper, two advanced adaptive modal pushovers, namely SSAP and FAP, have been investigated versus their non-adaptive load pattern counterparts. In order to evaluate the efficiency of the procedures, three moment-resistant steel frames of SAC group, SAC-3, SAC-9 and SAC-20, are chosen. The NTHA is performed for the typical far-fault ground motion records, LA01–LA40, consisting of both 10 and 2% probability of exceedance in 50 years. Although adaptive load pattern seems plausible, the results show it cannot improve the accuracy of the responses significantly, especially in low-rise structures. Moreover, its efficiency depends on basic source of the lateral load pattern.

Keywords Seismic demand · Nonlinear analysis · Modal pushover · Adaptive load pattern

1 Introduction

Nowadays, the performance-based engineering concepts constitute the main basis for compilation of most of the seismic analysis and design codes of the day (FEMA-356 2000; FEMA-440 2005; ATC40 1996; FEMA-P695 2009; ATC-58 2009). In low performance levels, Life Safety and Collapse Prevention, and under the effect of high intensity quakes, structures enter into the nonlinear phase, so that the structural damage index is generally controlled by the non-elastic deformation capacity of the structural and non-structural elements. Hence, displacement-based nonlinear analysis would be necessary to control and design the performance-based structures. Regarding the nature of the seismic loads, categorized as base excitation and imposed as accelerations to the upper masses, the dynamic nonlinear time-history analysis, NTHA has been widely welcomed as the most accurate method of analysis for the structures. However, the method entails complexities and application problems as follows:

(a) Earthquake record selection procedures, appropriate for each region and their scaling, for which currently extensive researches are being accomplished;
(b) Lack of reliable commercial software and time-consuming nature of the NTHA;
(c) Abundant data output of such analyses, requiring too much time for analyzing and post-processing the results;
(d) Problem associated with the construction of damping matrix (Aydinoğlu and Onem 2010).

Taking notice of the above issues, different researchers around the world have tried to propose simple and

✉ Mehrollah Rakhshanimehr
m.rakhshanimehr@alzahra.ac.ir

[1] Center of Excellence for Fundamental Studies in Structural Engineering, School of Civil Engineering, Iran University of Science and Technology, P.O. Box 16846-13114, Tehran, Iran

[2] Department of Civil Engineering, University of Alzahra, Tehran, Iran

applicable methods for seismic evaluation of structures based on the deformation. The outcome of such studies has been the "Nonlinear Static Procedure using the pushover concept."

In this regard, adaptive load pattern was first used by Reinhorn (1997). In this method, the initial load distribution pattern was often triangular. The load pattern is adapted at each step based on the story's internal resisting force. The eigen values and spectral analysis are used only as rudimentary and to provide the demand spectrum. Satyarno et al. (1998), presented a pushover method with adaptive load pattern based on the modal changes of structure in each step of loading in which the Rayleigh method is used to modify, based on incremental displacement of floors. Requena and Ayala (2000) proposed two different methods of adaptive pushover analysis called 2-A and 2-B method. According to the method 2-A, the imposed forces in different floor levels in each step of loading is gained from a combination of modal forces using the square root of sum of squares (SRSS) method. On the other hand, the presence of an equivalent fundamental mode shape has been accepted in the 2-B method. This equivalent mode is a combination of the mode shapes using the SRSS method in each step of loading.

A method which was conceptually similar to the 2-A method was presented by Elnashai (2001), with the difference that in his new method, the fiber model analysis was used instead of using discrete model; also load pattern is updated continually. Albanesi et al. (2002), proposed an adaptive energy-based pushover analysis method (AEPOA) in which the natural attributes of the structure, such as the kinetic energy resulting from the seismic effect, are considered in the adaptive load pattern.

Antoniou and Pinho (2004) proposed a force-based adaptive pushover (FAP) analysis method. The proposed method was multi-modal, and the decrease in the structural stiffness, period elongation and modification of inertial forces based on the spectral values are considered. The load vector in each step of the analysis is determined from the structure's stiffness at the end of the previous step. Then the lateral forces resulting from each vibration mode are combined using the SRSS method or complete quadratic combination method (CQC), depending on the interdependency of the modes. The load vector can be updated in each step of the analysis, using any of the two, total or incremental adaptive methods.

Shakeri et al. (2010) presented an advanced story shear-based adaptive pushover (SSAP) analysis method in which the following three key concepts have been used: (A) adapting the employed load pattern based on the modal story shear in each step. (B) Exploiting the assumed fundamental mode shape of the structure from the load profile employed during loading. (C) Converting the pushover curve coordinates of MDOF structure into the coordinates of the equivalent SDOF system capacity curve, using assumed fundamental mode shape of the structure and the energy concept (Hernandez-Montes et al. 2004). This method attempts to consider the higher-mode effects and the structural stiffness changes during the analysis, as well as interaction between the modes. The method exploits the target displacement utilizing the energy concept. In this line, Shakeri et al. (2012) suggested the story-shear-and-torque-based adaptive for asymmetric-plan buildings. In this method, the single modal load pattern with regard to effects of the higher modes and the interaction between the modes was considered. Abbasnia et al. (2013) proposed a displacement-based adaptive modal pushover procedure based on effective modal mass combination rule for considering the sign reversals in the load vectors. This combination rule was defined in order to obtain a modification factor associated to each mode and this modified factor applied to the corresponding load vector. Finally, these modified load vectors are algebraically subtracted and added and result in a range of load pattern.

Also some other researchers used the adaptive load application as displacement instead of force (Kalkan and Kunnath 2006; Ferracuti et al. 2009; Pinho et al. 2006).

2 Producing an Adaptive Load Pattern

Single-run modal pushover analysis is a method in which the modal shape vectors are combined using modal combination rules and are applied as force vector to the structure through a pushover process, and then, the results are extracted in a target displacement. In fact, such methods use modal combination rules to determine the load pattern for considering the higher-mode effects.

Also, some single-run methods utilize variable load pattern to consider the effects resulted from structural nonlinearity (yielding) during the analysis.

In the SSAP, in each analysis step, based on the instantaneous dynamic parameters, the story shear associated with each mode is calculated by Eqs. (1) and (2) (Fig. 1a, b). The story shears associated with each of the modes considered, are combined using the SRSS rule (Eq. (3), Fig. 1c). In calculation of the story shears for each mode, the sign reversal of the modal forces is also considered.

$$F_{ij} = \Gamma_j \emptyset_{ij} m_i Sa_j \quad (1)$$

$$\mathrm{SS}_{ij} = \sum_{k=i}^{n} F_{kj} \quad (2)$$

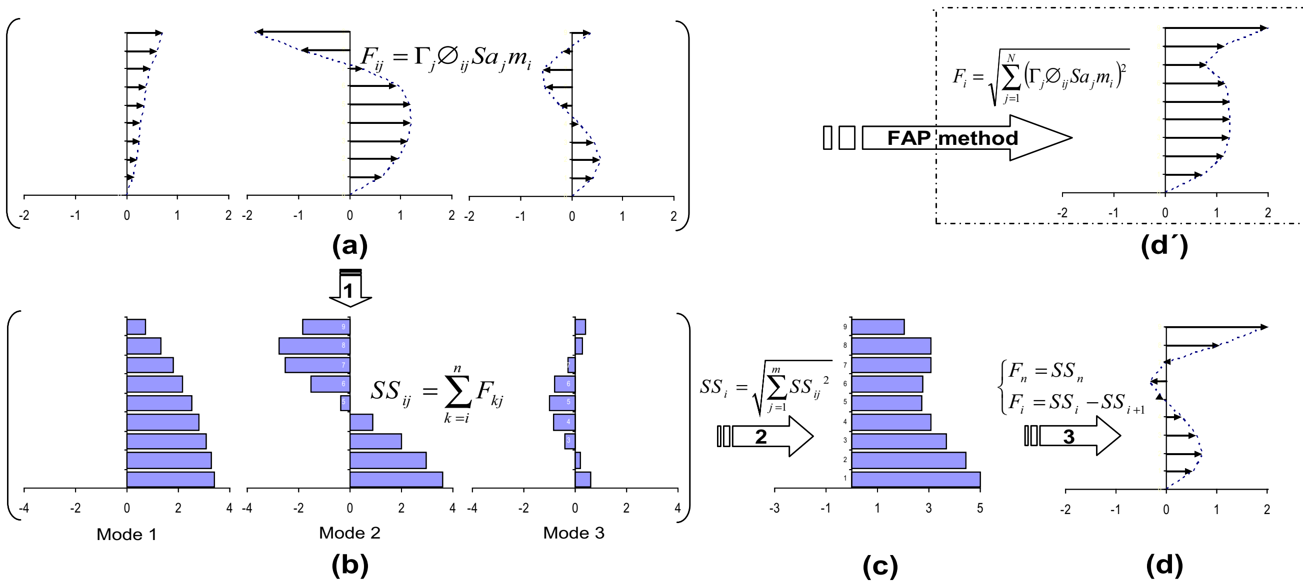


Fig. 1 The process of defining the applied load pattern at one step of the proposed SSAP and FAP procedures. **a** Modal story forces, **b** story shears profiles for each mode, **c** combined modal story shears profiles, **d** load pattern in the SSAP method, **d′** load pattern in the FAP method

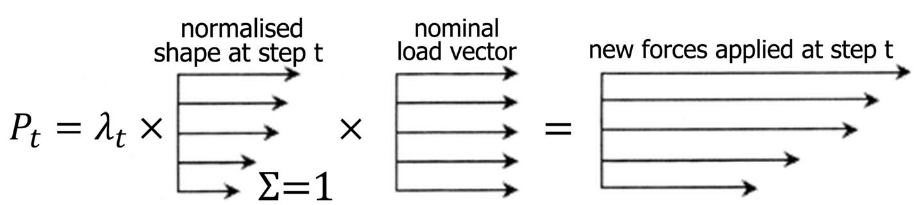


Fig. 2 Process for defining total adaptive load pattern

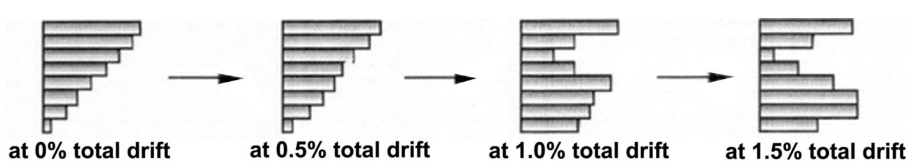


Fig. 3 Lateral load pattern in different stage of total updating load pattern

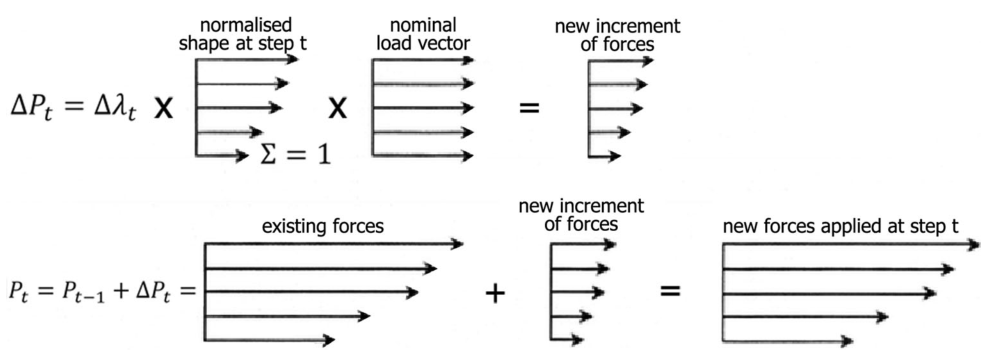
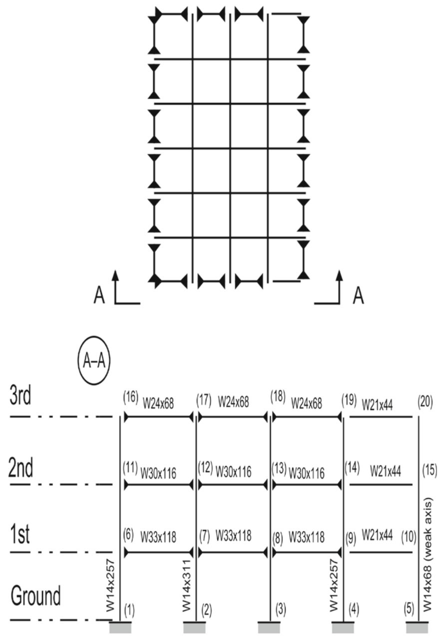


Fig. 4 Process for defining incremental adaptive load pattern

$$SS_i = \sqrt{\sum_{j=1}^{m} SS_{ij}^2} \tag{3}$$

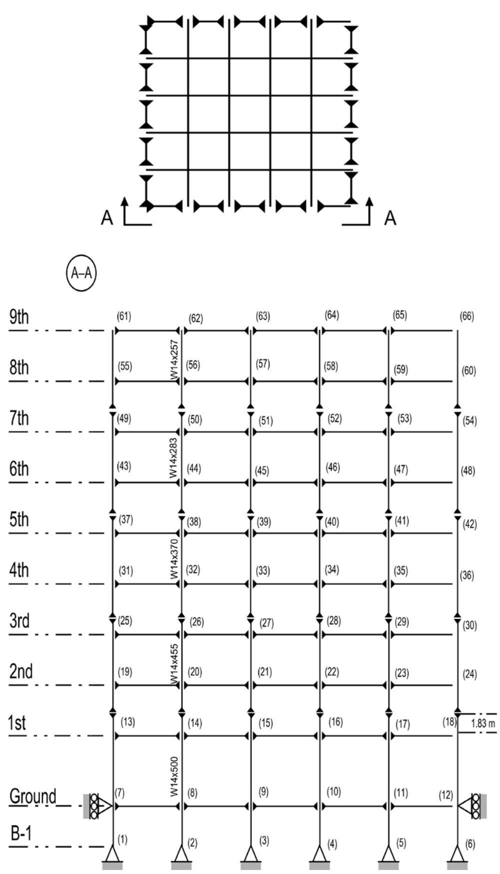
where i is the story number, j—the mode number, $\emptyset_{ij}$—the ith component of the jth eigenvector (mode shape), m_i—the mass of the ith story, Sa_j—the spectral acceleration corresponding to the jth mode, Γ_j—modal participation factor for the jth mode, SS_{ij}—the story shear in level i associated with mode j, SS_i—the modal story shear in level i associated with all the considered modes.

Fig. 5 3-Story building



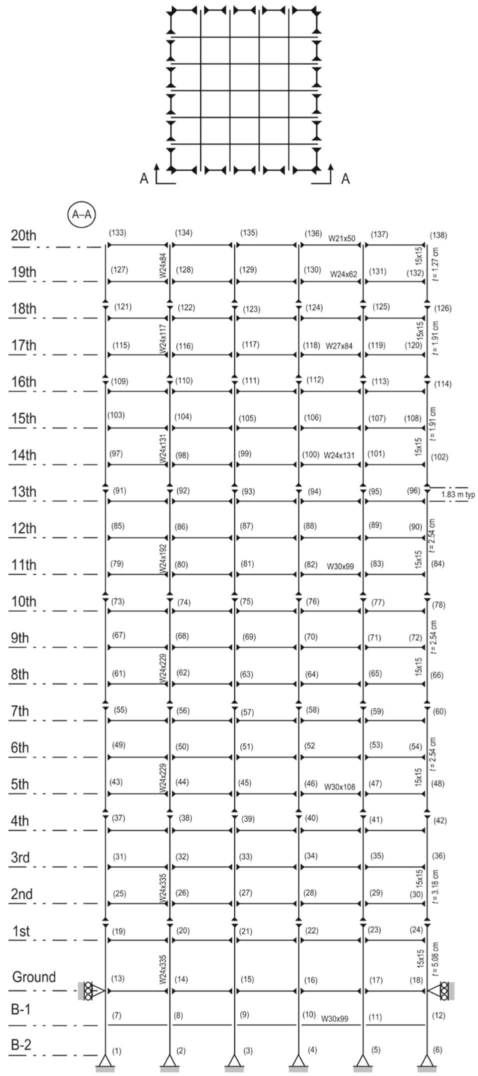
NOTES
Beams (248 MPa):
Beam sizes as indicated in figure.
Columns (345 MPa):
Column sizes same throughout elevation
Restraints:
Column fixed at base
Connections:
⊣ ⊢ indicates a moment resisting connection
– – indicates a simple (hinged) connection.
Dimension:
All measurments are center line;
floor-to-floor heights 3.96 m (13′ -0″);
bay widths (all) 9.15 m (30′ -0″).
Seismic Mass:
Including steel framing, for both N-S MRFs;
1st-2nd levels 9.57×10^5 kg;
3rd level 1.04×10^6 kg;
entire structure 2.95×10^6 kg.

Fig. 6 9-Story building



NOTES
Beams (248 MPa):
Ground- 2nd level W36×160;
3rd- 6th level W36×135;
7th level W30×99;
8th level W27×84;
9th level W24×68.
Columns (345 MPa):
column sizes change at splices
corner columns and interior columns the same, respectively, throughout elevation;
Restraints:
columns pinned at base;
structure laterally restrained at 1st level
Splices:
denoted with ∓;
are at 1.83 m (6 ft) w.r.t. beam-to-column joint
Connections:
⊣ ⊢ indicates a moment resisting connection
– – indicates a simple (hinged) connection.
Dimension:
All measurments are center line;
basement level height 3.65 m (12′ -0″);
Ground level height 5.49 m (18′ -0″);
1st – 8th level heights 3.96 m (13′ -0″);
bay widths (all) 9.15 m (30′ -0″).
Seismic Mass:
Including steel framing, for both N-S MRFs;
Ground level 9.65×10^5 kg;
1st level 1.01×10^6 kg;
2nd – 8th level 9.89×10^5 kg;
9th level 1.07×10^6 kg;
entire structure (above ground) 9.00×10^6 kg.

Fig. 7 20-Story building



NOTES

Beams (248 MPa):

B-2 – 4th level	W30×99;
5th – 10th level	W30×108;
11th – 16th level	W30×99;
17th – 18th level	W27×84;
19th level	W24×62;
20th level	W21×50.

Columns (345 MPa):
column sizes change at splices
corner columns and interior columns the same, respectively, throughout elevation;
box columns are ASTM A500 (15×15 indicates a 0.38 m (15 in) square box column with wall thickness of t).

Restraints:
columns pinned at base;
structure laterally restrained at Ground level.

Splices:
denoted with ╪;
are at 1.83 m (6 ft) w.r.t. beam-to-column joint

Connections:
⤙ ⤚ indicates a moment resisting connection
– – indicates a simple (hinged) connection.

Dimension:
All measurments are center line;

basement level height	3.65 m (12′ -0″);
Ground level height	5.49 m (18′ -0″);
1st – 19th level heights	3.96 m (13′ -0″);
bay widths (all)	6.10 m (20′ -0″).

Seismic Mass:
Including steel framing, for both N-S MRFs;

Ground level	5.32×10^5 kg;
1st level	5.63×10^5 kg;
2nd – 19th level	5.52×10^5 kg;
20th level	5.84×10^5 kg;
entire structure (above ground)	1.11×10^7 kg.

Table 1 Modal frequency (Hz)

	3-Story	9-Story	20-Story
Mode 1	0.99	0.443	0.261
Mode 2	3.06	1.18	0.753
Mode 3	5.83	2.05	1.3

Table 2 Modal mass % age

	3-Story	9-Story	20-Story
Mode 1	82.9	82.1	80.1
Mode 2	13.7	11.1	11.3
Mode 3	3.4	4.1	3.5

2.1 Different Methods for Producing Adaptive Load Pattern

There are two main procedures for adapting load patterns in each step of loading, namely total adaptive method and incremental adaptive method. In the former method, after each step of loading, modal forces are extracted based on the current stiffness of structure, and then, modal forces are combined and the load pattern is provided. Finally, previous load pattern will totally be replaced by the provided new load pattern (Fig. 2).

where λ_t is the base shear at step t, P_t is lateral load distribution at step t in total adaptive load pattern. The total adaptive method is more conceptual, because the force is distributed based on the structural stiffness; in spite of that, usually there would be some convergence problem in the analysis due to sudden changes in load pattern in the inelastic phase and also sometimes there would be reversal

Table 3 Specifications of the earthquake records

EQ code	Description	EQ Mag	Dist (km)	Scale factor	No. of points	Time Step (s)	PGA (cm/ s^2)	PGA (g's)
LA 10 in 50 (DBE)								
la01	fn Imperial Valley, 1940, El Centro	6.9	10.0	2.01	2674	0.020	452.03	0.46
la02	fp Imperial Valley, 1940, El Centro	6.9	10.0	2.01	2674	0.020	662.88	0.68
la03	fn Imperial Valley, 1979, Array #05	6.5	4.1	1.01	3939	0.010	386.04	0.39
la04	fp Imperial Valley, 1979, Array #05	6.5	4.1	1.01	3939	0.010	478.65	0.49
la05	fn Imperial Valley, 1979, Array #06	6.5	1.2	0.84	3909	0.010	295.69	0.30
la06	fp Imperial Valley, 1979, Array #06	6.5	1.2	0.84	3909	0.010	230.08	0.23
la07	fn Landers, 1992, Barstow	7.3	36.0	3.20	4000	0.020	412.98	0.42
la08	fp Landers, 1992, Barstow	7.3	36.0	3.20	4000	0.020	417.49	0.43
la09	fn Landers, 1992, Yermo	7.3	25.0	2.17	4000	0.020	509.70	0.52
la10	fp Landers, 1992, Yermo	7.3	25.0	2.17	4000	0.020	353.35	0.36
la11	fn Loma Prieta, 1989, Gilroy	7.0	12.0	1.79	2000	0.020	652.49	0.67
la12	fp Loma Prieta, 1989, Gilroy	7.0	12.0	1.79	2000	0.020	950.93	0.97
la13	fn Northridge, 1994, Newhall	6.7	6.7	1.03	3000	0.020	664.93	0.68
la14	fp Northridge, 1994, Newhall	6.7	6.7	1.03	3000	0.020	644.49	0.66
la15	fn Northridge, 1994, Rinaldi RS	6.7	7.5	0.79	2990	0.005	523.30	0.53
la16	fp Northridge, 1994, Rinaldi RS	6.7	7.5	0.79	2990	0.005	568.58	0.58
la17	fn Northridge, 1994, Sylmar	6.7	6.4	0.99	3000	0.020	558.43	0.57
la18	fp Northridge, 1994, Sylmar	6.7	6.4	0.99	3000	0.020	801.44	0.82
la19	fn North Palm Springs, 1986	6.0	6.7	2.97	3000	0.020	999.43	1.02
la20	fp North Palm Springs, 1986	6.0	6.7	2.97	3000	0.020	967.61	0.99
LA 2 in 50 (MCE)								
la21	fn 1995 Kobe	6.9	3.4	1.15	3000	0.020	1258.00	1.28
la22	fp 1995 Kobe	6.9	3.4	1.15	3000	0.020	902.75	0.92
la23	fn 1989 Loma Prieta	7.0	3.5	0.82	2500	0.010	409.95	0.42
la24	fp 1989 Loma Prieta	7.0	3.5	0.82	2500	0.010	463.76	0.47
la25	fn 1994 Northridge	6.7	7.5	1.29	2990	0.005	851.62	0.87
la26	fp 1994 Northridge	6.7	7.5	1.29	2990	0.005	925.29	0.94
la27	fn 1994 Northridge	6.7	6.4	1.61	3000	0.020	908.70	0.93
la28	fp 1994 Northridge	6.7	6.4	1.61	3000	0.020	1304.10	1.33
la29	fn 1974 Tabas	7.4	1.2	1.08	2500	0.020	793.45	0.81
la30	fp 1974 Tabas	7.4	1.2	1.08	2500	0.020	972.58	0.99
la31	fn Elysian Park (simulated)	7.1	17.5	1.43	3000	0.010	1271.20	1.30
la32	fp Elysian Park (simulated)	7.1	17.5	1.43	3000	0.010	1163.50	1.19
la33	fn Elysian Park (simulated)	7.1	10.7	0.97	3000	0.010	767.26	0.78
la34	fp Elysian Park (simulated)	7.1	10.7	0.97	3000	0.010	667.59	0.68
la35	fn Elysian Park (simulated)	7.1	11.2	1.10	3000	0.010	973.16	0.99
la36	fp Elysian Park (simulated)	7.1	11.2	1.10	3000	0.010	1079.30	1.10
la37	fn Palos Verdes (simulated)	7.1	1.5	0.90	3000	0.020	697.84	0.71
la38	fp Palos Verdes (simulated)	7.1	1.5	0.90	3000	0.020	761.31	0.78
la39	fn Palos Verdes (simulated)	7.1	1.5	0.88	3000	0.020	490.58	0.50
la40	fp Palos Verdes (simulated)	7.1	1.5	0.88	3000	0.020	613.28	0.63

displacement of roof story because of the variable load distribution (Fig. 3).

Hence, the incremental adaptive load patterns, which are conceptually a better procedure for displacement-based methods, were emerged. In this method, the normalized lateral load pattern is amplified by incremental base shear and so provide incremental lateral load for each floor. Then at this step incremental load will be added to the previous

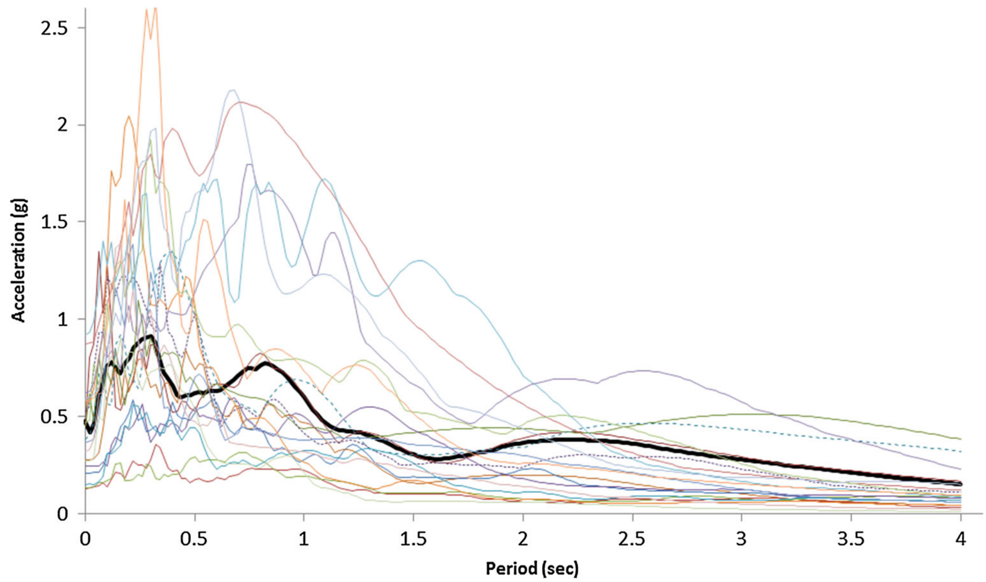


Fig. 8 Pseudo-acceleration spectra of the DBE records of ground motions, damping ratio = 5%. The mean spectra are shown by a thicker line

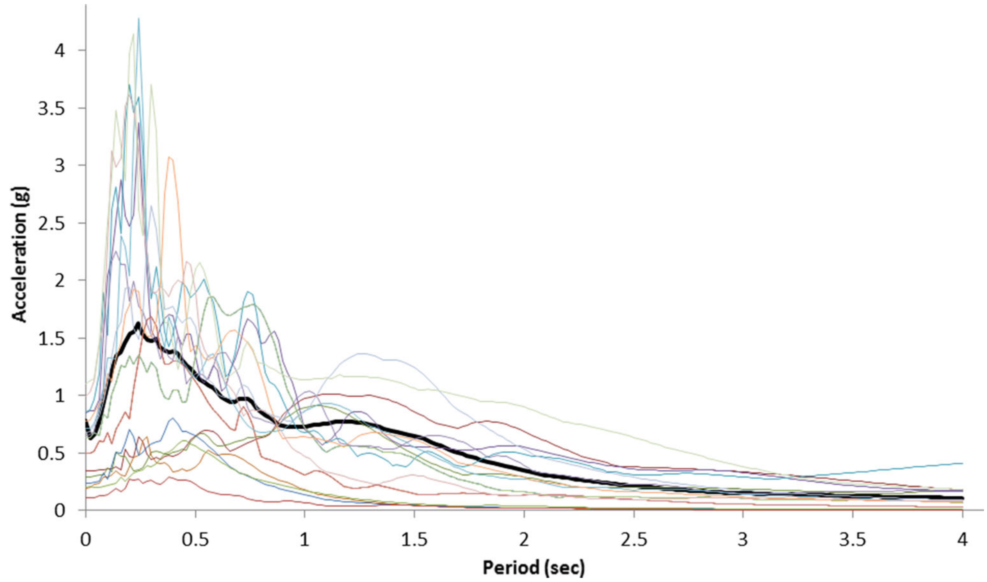


Fig. 9 Pseudo-acceleration spectra of the MCE records of ground motions, damping ratio = 5%. The mean spectra are shown by a thicker line

lateral load pattern and after normalizing, it would be implemented as the new load pattern. So there would not be a big sudden change in incremental adaptive load patterns (Antoniou and Pinho 2004, Fig. 4).

3 Validation of the Adaptive Modal Pushover Procedure

In this study, in order to evaluate the efficiency of adaptive load patterns, the equivalent non-adaptive load patterns of SSAP and FAP methods, namely story shear-based pushover, "SSP", and force-based pushover, "FP", are introduced.

FAP method utilizes the maximum roof displacement resulted from NTHA, as the target displacement and does not calculate the target displacement by itself. Because the main concern of this study is to evaluate the efficiency of adaptive load patterns, assumed fundamental mode shape of the structure was calculated instantaneously based on the load profile. Then energy concept was implemented to convert pushover curve of multi degree of freedom system "MDOF", into capacity curve of single degree of freedom system "SDOF". In this stage, first the SDOF capacity curve is idealized to a bilinear graph, and then for each ground motion record, a NTHA was carried out to achieve the target displacement. Incremental adaptive load pattern has been used in both SSAP and FAP methods in this

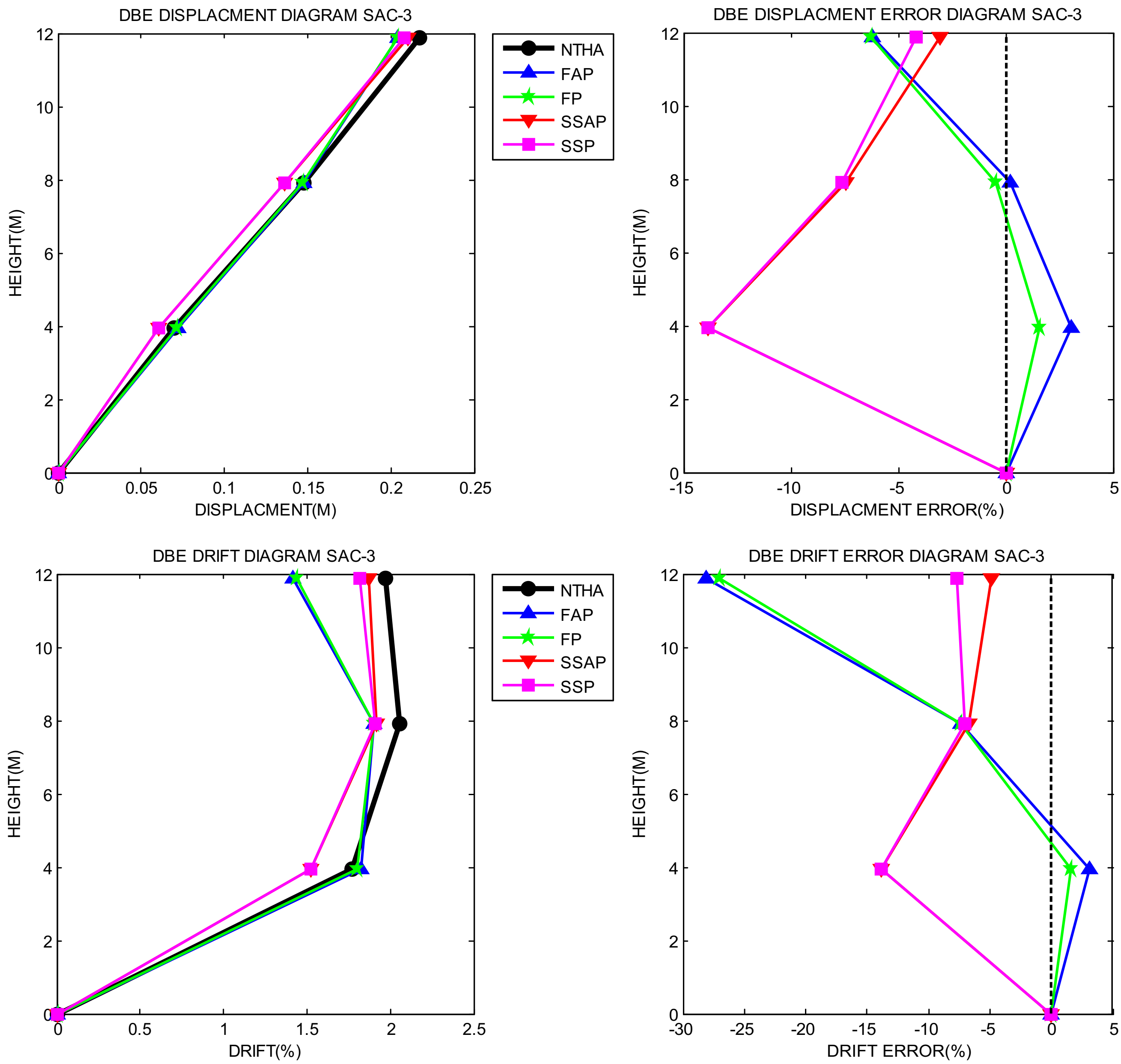


Fig. 10 Average displacement and inter-story drift profile and their corresponding error diagram resulted from NTHA, FAP, FP, SSAP and SP method, subjected to twenty 10% probability of exceedance ground motions of Los Angeles region for 3-story building

study. For more information about the process of SSAP and FAP methods, refer to the original papers.

3.1 Structural Model

In this paper, three steel moment-resistant frame (SMRF) of the Phase II of SAC group buildings has been observed (FEMA-355 2000). Accordingly, SAC-3, a 3 story building as low-rise structure, SAC-9, a ten-story construction as the representative of mid-rise constructions and SAC-20, a twenty-two-story construction as a high-rise structure, have been used to evaluate efficiency and precision of the mentioned method in comparison with NTHA. These structures have been specially designed according to the UBC1994 code for Los Angeles region, the USA. Given that in each direction only two moment frames resist against the lateral forces, only one of the northward–southward moment frames has been modeled in two-dimensional state. A half of each story mass is considered as its seismic lumped mass. The gravity load has been ignored

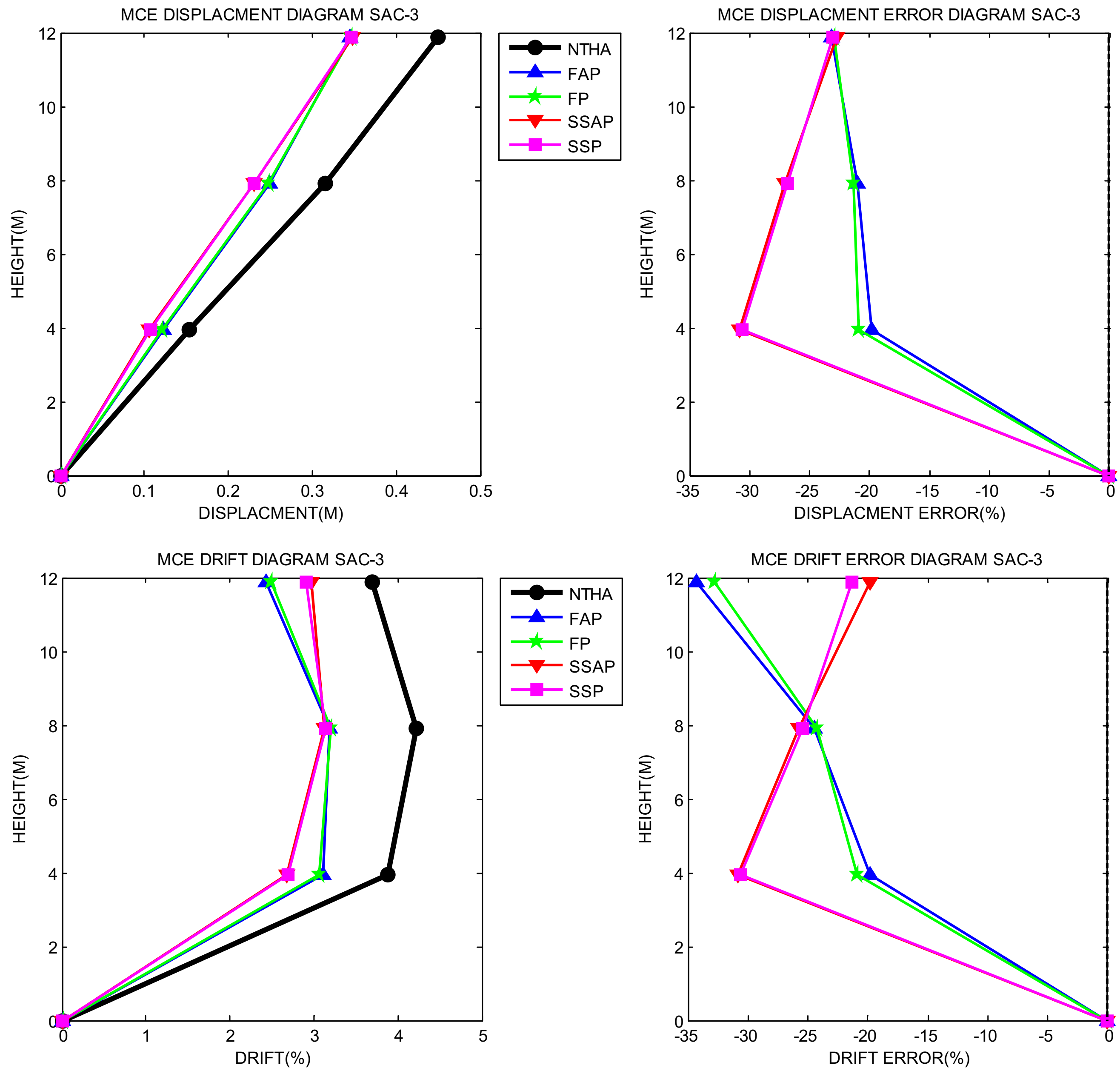


Fig. 11 Average displacement and inter-story drift profile and their corresponding error diagram resulted from NTHA, FAP, FP, SSAP and SP method, subjected to twenty 2% probability of exceedance ground motions of Los Angeles region for 3-story building

in modeling. In this study, in order to define the Rayleigh damping matrix, a damping ratio of 5% was considered for the first and third modes of vibration. The details related to the 3-, 9- and 20- story buildings are shown in Figs. 5, 6 and 7. The levels of the 3-, 9- and 20-story building are numbered with respect to the ground level (see Fig. 5, 6, 7). Further details of these buildings are presented in Gupta and Krawinkler (1999).

The first three modal frequencies of the 3-, 9- and 20-story buildings are presented in Table 1. Also, the first three modal masses of the buildings are presented in Table 2.

3.2 Software

Open System for Earthquake Engineering Simulation, OpenSEES, has been used to model and perform nonlinear static and dynamic analyses. Using the software capabilities, the material specifications have been modeled considering nonlinearity using "uniaxialMaterial Steel02"

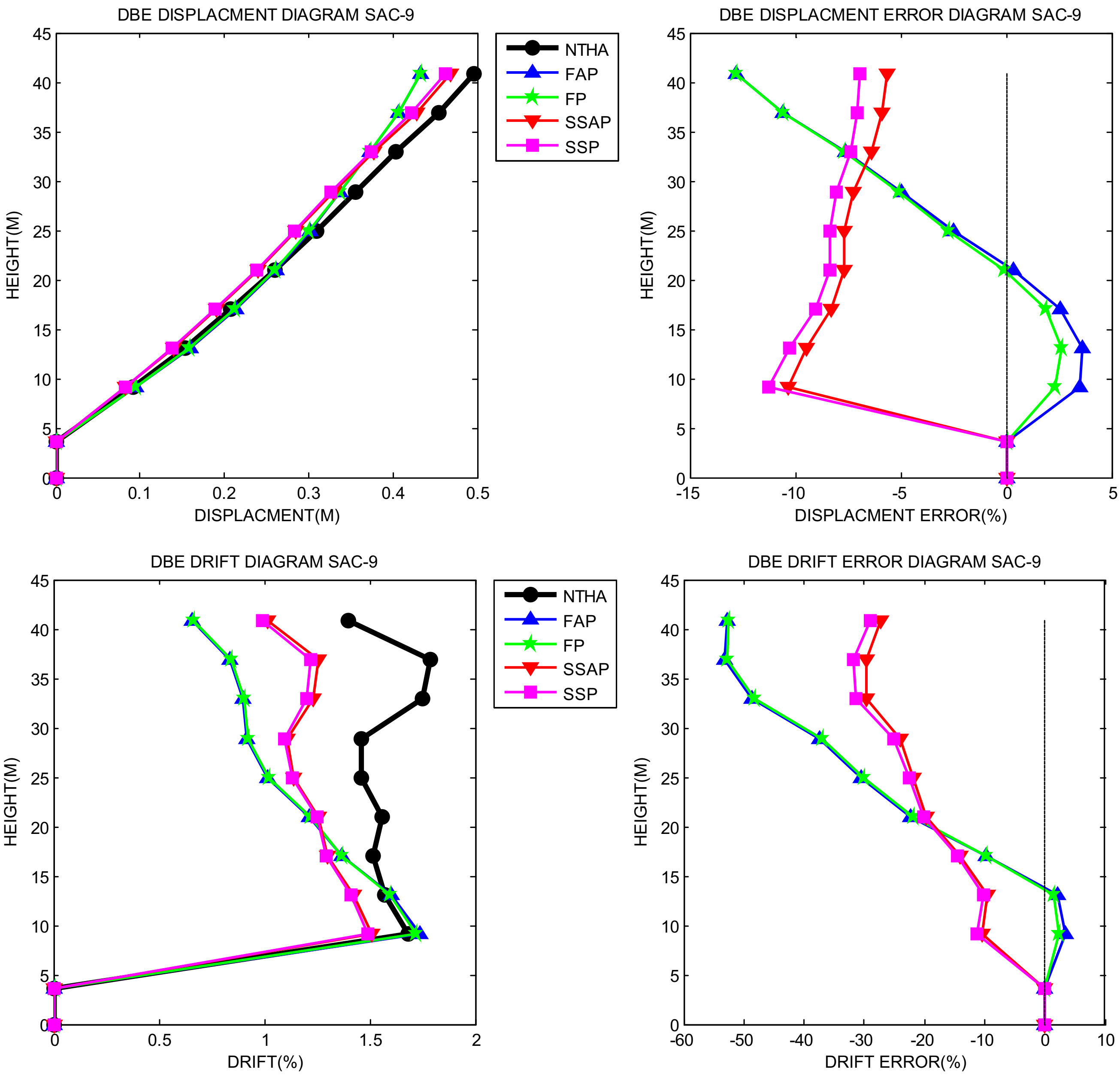


Fig. 12 Average displacement and inter-story drift profile and their corresponding error diagram resulted from NTHA, FAP, FP, SSAP and SP method, subjected to twenty 10% probability of exceedance ground motions of Los Angeles region for 9-story building

command. Element sections are modeled in fiber state. The structural elements have been modeled in the "Force-Based Beam-Column Element" command, which consider distributed plasticity along the element length (Mazzoni et al. 2007). The first three modes of vibration were considered to extract modal forces in all of the NSP methods.

3.3 Ground Motions

For performing nonlinear dynamic analyses of MDOF and SDOF systems, forty SAC Los Angeles region ground motions records (Somerville et al. 1997), twenty at 10% (design basis earthquake "DBE") and twenty at 2% (maximum considered earthquake "MCE") probability of exceedance in 50 years, were used. The characteristics of the selected SAC ground motions are given in Table 3. In order to achieve modal spectral accelerations, the elastic spectrum with 5% of damping was calculated. The elastic pseudo-acceleration for DBE and MCE records, together with the corresponding the mean spectra, is presented, for 5% damping ratio in Figs. 8 and 9.

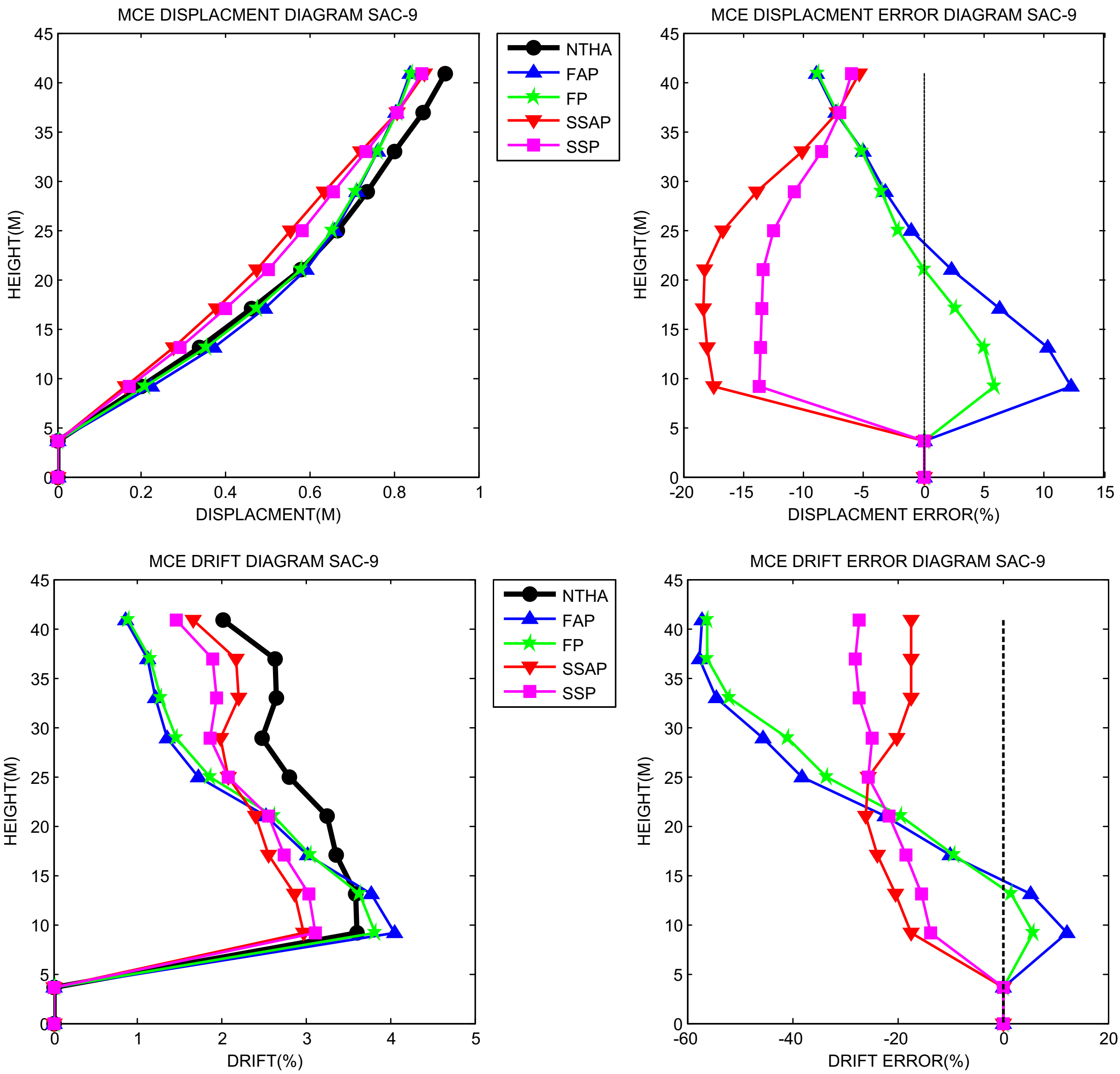


Fig. 13 Average displacement and inter-story drift profile and their corresponding error diagram resulted from NTHA, FAP, FP, SSAP and SP method, subjected to twenty 2% probability of exceedance ground motions of Los Angeles region for 9-story building

3.4 Surveyed Pushover Methods

The following advanced pushover procedures have been investigated:

1. Force-based adaptive pushover (FAP) analysis method, presented by Antoniou and Pinho (2004);
2. Force-based pushover (FP) method, equivalent non-adaptive load pattern procedure of FAP methodology;
3. Story shear-based adaptive pushover (SSAP) analysis method, presented by Shakeri et al. (2010);
4. Story shear-based pushover (SSP), equivalent non-adaptive load pattern procedure of SSAP methodology;

3.5 Comparison Criteria

Since the structural damage is mainly controlled first by the story drift and then by the displacements, it will be evaluated and compared with NTHA counterpart.

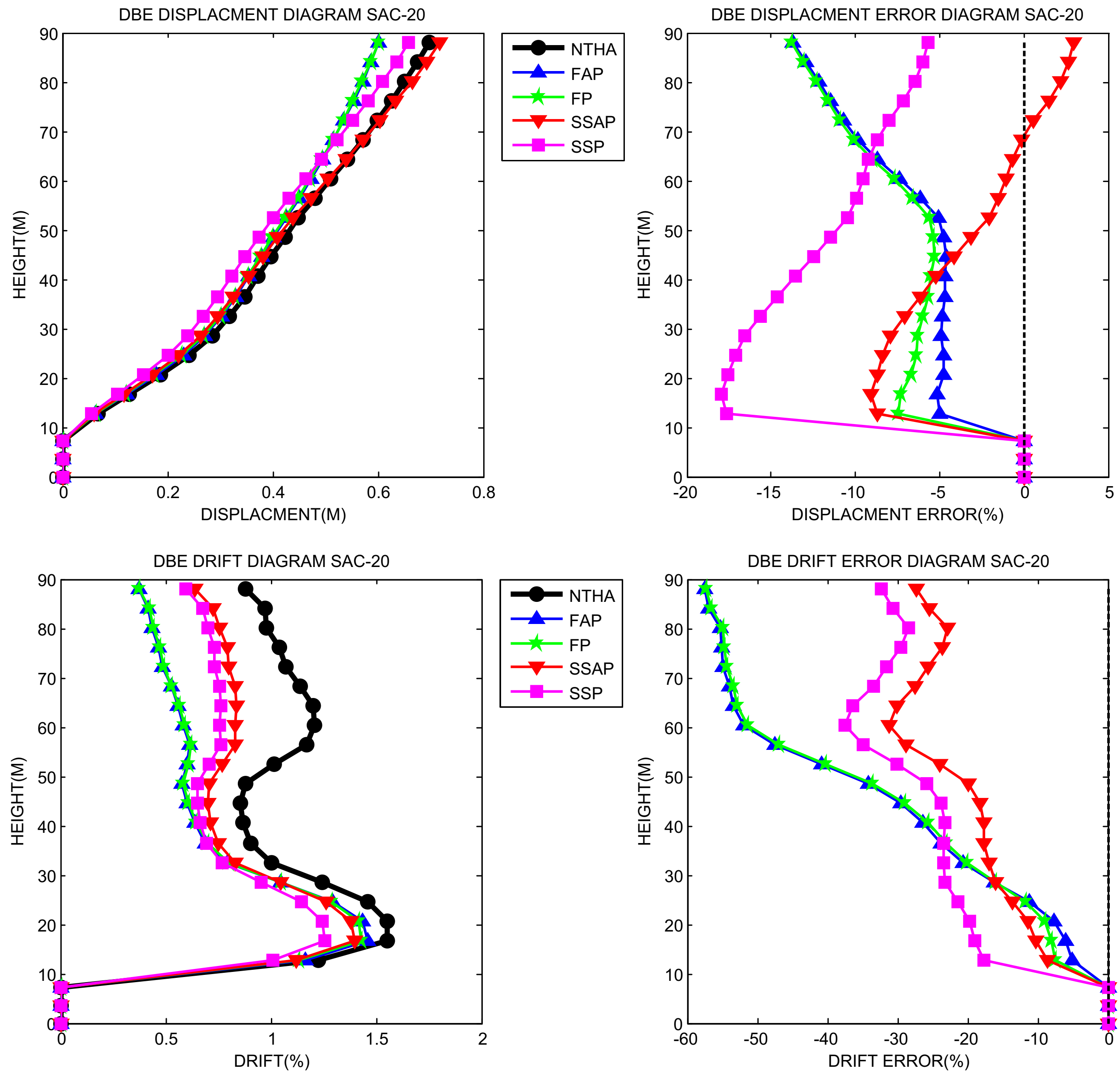


Fig. 14 Average displacement and inter-story drift profile and their corresponding error diagram resulted from NTHA, FAP, FP, SSAP and SP method, subjected to twenty 10% probability of exceedance ground motions of Los Angeles region for 20-story building

Maximum responses gained from NTHA have been considered as benchmark. The error index is defined by Eq. (4):

$$\mathrm{Error}_{\Delta}(\%) = 100 \times \left(\frac{\Delta_{i-\mathrm{NSP}} - \Delta_{i-\mathrm{NTHA}}}{\Delta_{i-\mathrm{NTHA}}}\right) \quad (4)$$

where $\Delta_{i-\mathrm{NTHA}}$ is the peak inter-story drift or displacement at a given level *i*, resulting from the NTHA and $\Delta_{i-\mathrm{NSP}}$ is the corresponding inter-story drift or displacement from the nonlinear static procedure.

4 Analyses Results

The average inter-story drift and displacement profiles resulted from the NTHAs are plotted in Figs. 10, 11, 12, 13, 14 and 15.

Average seismic demand predicted by pushover methods and NTHA for SAC-3 can be observed in Figs. 10 and 11. It can be seen that the average of FAP and FP seismic demands is more accurate. On the other hand, the average of SSAP and SSP responses indicates that these two

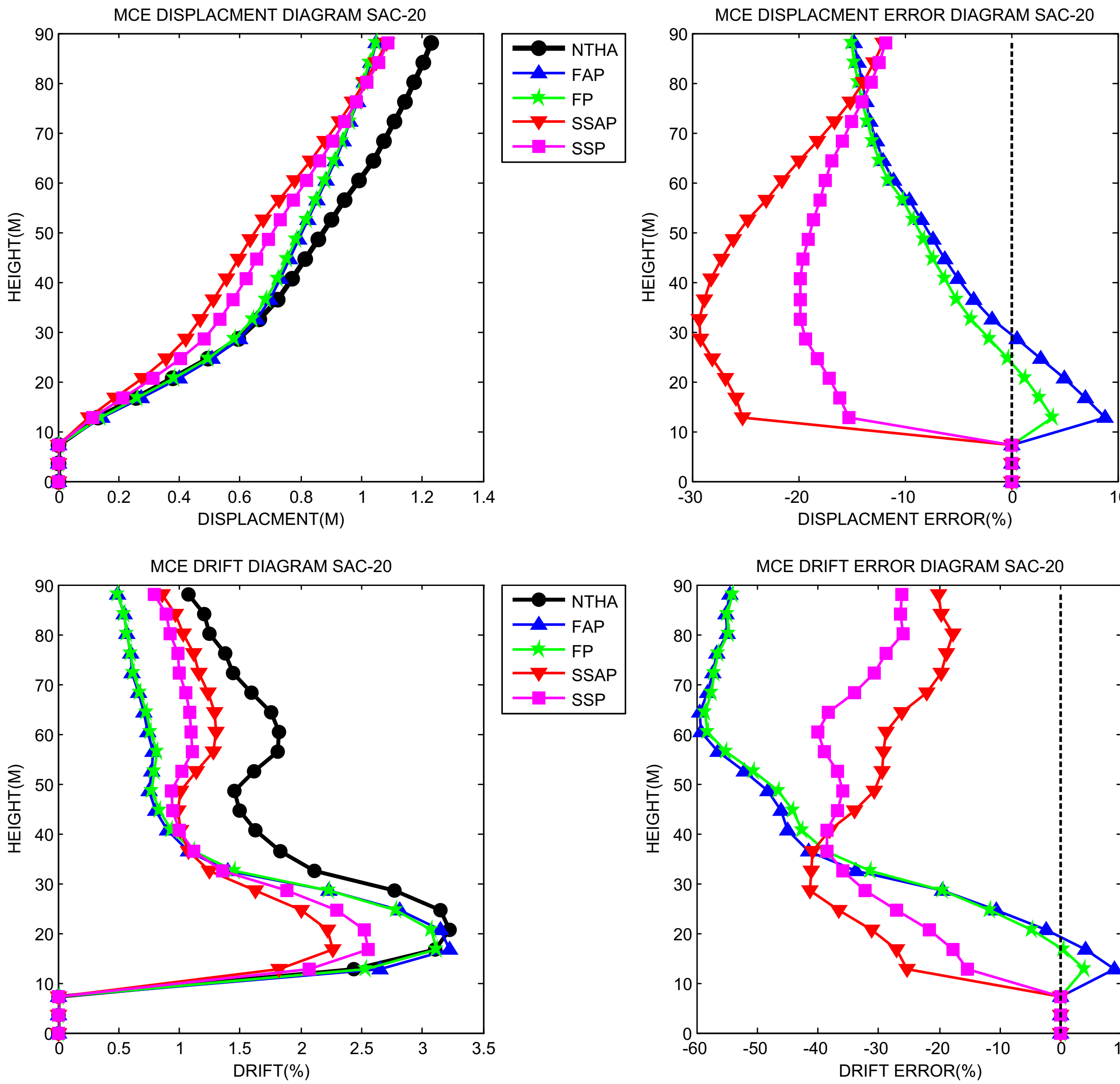


Fig. 15 Average displacement and inter-story drift profile and their corresponding error diagram resulted from NTHA, FAP, FP, SSAP and SP method, subjected to twenty 2% probability of exceedance ground motions of Los Angeles region for 20-story building

methods predict upper stories drift and displacement values better. In addition, there is no remarkable difference in the responses of FAP and SSAP in comparison with their equivalent non-adaptive procedures, FP and SSP, respectively. It means adaptive load patterns cannot significantly increase the accuracy of NSP methods in low-rise buildings.

Regarding Fig. 12, responses of the FAP and the FP procedures seem closer to NTHA than SSAP and SSP in lower stories for DBE records. Conversely, for the upper stories the average of SSAP and SSP responses is achieved better for the SAC-9. Similar to the SAC-3 model, the difference between adaptive and non-adaptive procedures is not considerable for DBE records.

Figure 13 illustrates the results for MCE set of records. Interpretations are approximately the same as they were for DBE set of records. It is noticeable here to state that for MCE records, the gap between adaptive and non-adaptive procedures is clearer than it for DBE. SSAP led to better result in upper stories than SP, while FAP led to better responses in lower stories than its non-adaptive counterpart.

Referring Fig. 14, the SSAP is much more accurate than all other procedures in DBE set of records.

It can be inferred from Fig. 15 that when SAC-20 is subjected to MCE records, SSAP is better for upper stories than all other procedures and FAP and FP are better for lower stories.

5 Conclusion

The equivalent non-adaptive load patterns of story shear-based adaptive pushover "SSAP", and force-based adaptive pushover "FAP" methodologies are introduced: story shear-based pushover, "SSP", and force-based pushover, "FP". In order to evaluate the efficiency of adaptive load patterns, three well-known steel frames that are SAC groups, covering wide range of periods, have been subjected to two sets of earthquake records, including twenty design basis earthquakes and twenty maximum considered earthquake records. The inter-story drift and displacement have been extracted to compare the efficiency of the methods.

However, the improvement due to the adaptive characteristic is not very considerable. In this respect, SSAP led to more precise drift responses in comparison with SSP in all structures, especially in SAC-20's upper stories. On the other hand, there is just a very negligible difference between FAP and FP drift responses. It can be said that FAP predicts drift demand more in lower stories, and less in upper stories, than FP. Furthermore, adaptive load patterns are more efficient under the effects of high intensity records, the MCE set.

All in all it can be inferred that adaptive load patterns' efficiency and accuracy are higher for intense earthquakes and also in high-rise buildings. Furthermore, results showed that the SSAP and SSP procedures result in more accurate drift responses than FAP and FP procedures.

References

Abbasnia R, Tajik Davoudi AR, Maddah MM (2013) An adaptive pushover procedure based on effective modal mass combination rule. Eng Struct 52(1):654–666

Albanesi T, Biondi S, Petranegli M (2002) Pushover analysis: an energy based approach. In: Proceedings of the 12th European on earthquake engineering. Barbican Center, London

Antoniou S, Pinho R (2004) Advantages and limitations of adaptive and non-adaptive force-based pushover procedures. J Earthq Eng 8(4):497–522

Applied Technology Council (1996) Seismic evaluation and retrofit of concrete building. Report ATC-40, Redwood City, CA

Applied Technology Council (2009) Guidelines for seismic performance assessment of buildings. ATC-58 50% Draft, Redwood City

Aydinoğlu MN, Onem G (2010) Evaluation of analysis procedures for seismic assessment and retrofit design. In: Garevski M, Ansal A (eds) Earthquake engineering in Europe. Springer, New York, pp 171–198

Elnashai AS (2001) Advanced inelastic static (pushover) analysis for earthquake applications. Struct Eng Mech 12(1):51–69

FEMA (2005) "Improvement of nonlinear static seismic analysis procedures", FEMA 440. Federal Emergency Management Agency, Washington, DC

FEMA (2009) Quantification of Building Seismic Performance Factors. FEMA-P-695 Prepared by Applied Technology Council for the Federal Emergency Management Agency, Washington, DC

FEMA-355C (2000) State of the art report on systems performance of steel moment frames subject to earthquake ground shaking. SAC Joint Venture, Sacramento

FEMA-356 (2000) Prestandard and commentary for the seismic rehabilitation of buildings. Prepared by American Society of Civil Engineers for the Federal Emergency Management Agency, Washington, DC

Ferracuti B, Pinho R, Savoia M, Francia R (2009) Verification of displacement-based adaptive pushover through multi-ground motion incremental dynamic analyses. J Eng Struct 31(8):1789–1799

Gupta A, Krawinkler H (1999) Seismic demands for performance evaluation of steel moment resisting frame structures (SAC Task 5.4.3). Report No. 132. Palo Alto, CA: John A. Blume Earthquake Engineering Center, Stanford University

Hernandez-Montes E, Kwon O-S, Aschheim MA (2004) An energy-based formulation for first-and multiple-mode nonlinear static (pushover) analyses. J Earthq Eng 8(1):69–88

Kalkan E, Kunnath SK (2006) Adaptive modal combination procedure for nonlinear static analysis of building structures. J Struct Eng 132(11):1721–1731

Mazzoni S, Mckenna F, Scott MH, Fenves GL (2007) Open System for Earthquake Engineering Simulation (OpenSees) Command Language Manual. Pacific Earthquake Engineering Center, University of California, Berkeley. http://opensees.berkeley.edu. Accessed 1 Sept 2016

Pinho R, Antoniou S, Pietra D (2006) A displacement-based adaptive pushover for seismic assessment of steel and reinforced concrete buildings. In: Proceedings of the 8th US national conference on earthquake engineering

Reinhorn AM (1997) Inelastic analysis techniques in seismic evaluations. In: Proceedings of the international workshop on seismic design methodologies for the next generation of codes

Requena M, Ayala G (2000) Evaluation of a simplified method for the determination of the non-linear seismic response of RC frames. In: Proceedings of the twelfth world conference on earthquake engineering

Satyarno I, Carr AJ, Restrepo J (1998) Refined pushover analysis for the assessment of older reinforced concrete buildings. In: Proceedings of NZSEE technology conference

Shakeri K, Shayanfar MA, Kabeyasawa T (2010) A storey shear-based adaptive pushover procedure for estimating seismic demands of buildings. Eng Struct 32(1):174–183

Shakeri K, Tarbali K, Mohebbi M (2012) An adaptive modal pushover procedure for asymmetric-plan buildings. Eng Struct 36(1):160–172

Somerville PG, Smith M, Punyamurthula S, Sun J (1997) Development of ground motion time histories for phase 2 of the FEMA/SAC Steel Project. Report No. SAC/BD-97/04, SAC Joint Venture, Sacramento, California