EVALUATION OF ADAPTIVE PUSHOVER METHODS IN STRUCTURES WITH VERTICAL STRENGTH IRREGULARITIES

Arian KHANEDANI
Msc Student, Department of Structural Engineering, Science and Research Branch, Islamic Azad university Tehran, Iran
ariankhanedani@gmail.com

Armin AZIMINEJAD
Assitant Professor, Department of Structural Engineering, Science and Research Branch, Islamic Azad university, Tehran, Iran
armin.aziminejad@gmail.com

Abdolreza SARVGHAD MOGHADAM
Assitant Professor, International institute of earthquake engineering and seismology, Tehran, Iran
Moghadam.research@gmail.com

Keywords: Adaptive Pushover, Irregular in Height, Weak Storey, Nonlinear Analysis, Moment Frame

ABSTRACT

In recent years, many studies have been performed to develop and improve various methods for performance evaluation of structures. One of the most practical tools for this purpose is nonlinear static analysis procedure or so called pushover analysis. Nonlinear static procedures (Push Over) have attracted special attention of researchers due to simplicity of implementation (Chopra, 2002) and ease of results interpretation. The main disadvantage of the common nonlinear static procedures in the current Codes and regulations is that a constant lateral load pattern is applied during the analysis and the changes in the modal characteristics of the structure due nonlinear behavior cannot be applied. Another dis advantage of these method is their weakness in performance evaluation of irregular structures. In these structures the estimation of nonlinear static procedures experiences meaningful errors and diverge from the result of more exact procedures such as nonlinear dynamic analysis. To overcome such a disadvantage, Adaptive Push over Procedure has been introduced by a number of researchers in recent years. In this procedure, lateral load pattern is changed in accordance with the instant stiffness matrix (Gupta and Kunnath, 2000).

In this study the ability of this method on performance evaluation of irregular building in height was examined. Different nonlinear static procedures are evaluated by applying constant and adaptive loading patterns on 20-story steel moment frames irregular in height. Seismic demands obtained from nonlinear static procedures were compared with exact results obtained from the nonlinear time history dynamic analysis. The results indicated that among chosen method, Shear-based Adaptive Procedure (SAP) has the best performance in predicting the seismic demands among other Adaptive Procedures in performance evaluation of irregular buildings.

INTRODUCTION

Irregular structures are generally divided into two groups of structures irregular in plan and elevation. Irregularity in plan is due to non-compliance of the centers of mass and stiffness. While irregularity in height, is due to the change in dynamic specifications of the structure in vertical direction. This will cause significantly different values of mass, stiffness and strength at different stories if the structure. This type of irregularity is attributed to different occupancies of different stories, different lateral load bearing systems of the structure, and changes of plan dimensions in different stories of the structure. Therefore, given that the irregularities in height may be imposed to the designers due to the above reasons, further knowledge of the seismic performance of such structures and appropriate design and analysis methods of the structures irregular in height seems necessary for the engineers. In this study, high-rise structures with irregular strength distributions in height have been studied and analyzed.

The design procedures of most current regulations are based on the strength criteria. While researches on structural behavior during recent earthquakes showed that the strength alone cannot be considered a suitable design criterion and increasing the strength does not necessarily mean a developed safety. Therefore, the strength design criterion has been replaced by the behavior design criterion in new regulations. Application of the behavior design criterion of a structure highlights the importance of strength and deformation distribution patterns in the structural members besides the strengths itself. This behavior-based design procedure is also called performance-based design procedure. For the practical development of the performance-based design procedures, reliable seismic analysis methods that besides the simplicity would be of high accuracy are highly needed.

PUSH-OVER PROCEDURES WITH ADAPTIVE LOAD PATTERN

Nonlinear Static Analysis (Push-Over) is among the structural analysis procedures which has developed significantly due to advances in performance-based design procedure. The main problem with the conventional Push-Over procedures included in the current regulations and codes is that, they are limited to a fixed given modal shape and do not consider the effects of higher modes and changes of the modal specifications of the structure during the nonlinear dynamic analysis. Therefore, several Push-Over methods using Adaptive load pattern have been developed in recent years in order to solve this problem [1]. A group of Push-Over procedures in which during the analysis, lateral load pattern is changed based on instantaneous stiffness matrix is called Adaptive Push-Over procedure. In these procedures, applied load pattern is changed and adapted at each loading step relative to the modal specifications of the structure. Adaptation of the load pattern at different steps of a Push-Over analysis is shown in Figure (1) as an example.

Push Over methods in this study were classified into two groups of constant load pattern and adaptive load pattern. In the first group, the lateral load patterns corresponding to the Mode 1, Rectangular, Inverted Triangular and Code lateral load distributions were used (Equation 1).

$$c_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k} \tag{1}$$

Where i is number of the floors, Wi and Wx are weights of the ith and xth floors, hi and hx are heights of ith and xth floors, and n is number of the floors. The value of k was obtained using equation (2):

$$K=0.5T+ 0.75 \tag{2}$$

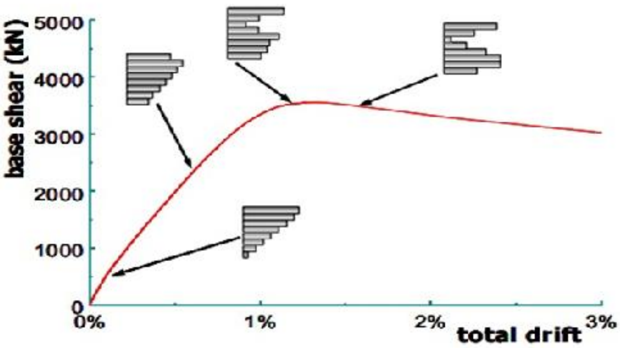


Figure 1:Adaptive pushover: shape of loding vector is updated at each analysis step

For periods less than 0.5 seconds and more than 2.5 seconds, k is equal to 1 and 2, respectively (FEMA 2005).

In the second group, Push Over methods with Adaptive load pattern based on the force(FAP), drift of the floors(DRAP), Mode 1 of the structure(A-Mode1), and also floor shear were used(SAP).

FORCE-BASED ADAPTIVE PUSH-OVER PROCEDURE (FAP)

To determine the load vector shape at each stage of the analysis, the normalized modal vector,   which is calculated at the beginning of each loading stage, is used(Antoniou and Pinho, 2004a).

The lateral load due to j-th vibration mode at i-th story is given according to Equation (3), and SRSS method (Equation 4) was used to combine the modal forces in this study. Since the relative values of the story forces are important in determination of the load vector shape, thus normalized modal vector of at each loading stage was obtained using Equation (5).

$$F_{ij} = \Gamma_j \text{¤}_{ij} M_i S_a(j) \tag{3}$$

$$F_i = \sqrt{\sum_{j=1}^{n} F_{ij}^{\ 2}} \tag{4}$$

$$\overline{F_i} = \frac{F_i}{\sum F_i} \tag{5}$$

In Equation (3), i is story number, j is mode number, Γ_j is participation factor of j-th mode, $S_a(j)$ is spectral acceleration at j-th mode, ¤_{ij} is the vector shape component of the j-th mode at i-th story and M_i is the mass of the i-th story.

Finally, calculated load pattern at each stage was added to the load pattern of the previous stage and the obtained new load pattern was applied to the structure.

STORY DRIFT-BASED ADAPTIVE PUSH-OVER PROCEDURE (DRAP)

To determine the lateral load pattern at each stage of the analysis, the scaled modal vector of is used. Therefore, before each loading stage, eigenvalues analysis was performed according to the stiffness characteristics of the structure, and modal loads were calculated considering the modal shapes and participation coefficients of the modes as well as spectral displacement. Story drift is used to adapt the load pattern in this procedure. Therefore, maximum drifts of the stories were directly calculated at each mode and combined using the square root of the sum of squares (SRSS) method. Displacement of each story was obtained by adding the drift of the story to the drifts of the lower stories (Equations 6 and 7) (Antoniou and pinho,2004b).

$$\Delta_i = \sqrt{\sum_{j=1}^{N} \Delta_{ij}^2} = \sqrt{\sum_{j=1}^{N} \left[\Gamma_j \left(\text{¤}_{ij} - \text{¤}_{i-1,j}\right) S_d(j)\right]^2} \tag{6}$$

$$D_i = \sum_{k=1}^{i} \Delta_k \tag{7}$$

In Equations 6 and 7, i is the story number, j is the mode number, Γ_j is participation factor of j-th mode, ¤_{ij} is the vector shape component of the j-th mode at i-th story, Sd(j) is spectral displacement at j-th mode, Δ_i is drift of the i-th story and D_i is displacement of the i-th story.

Given that, the aim is to determine the load vector shape rather than its magnitude, so vector is transformed into normal scaled vector of using Equation (8).

$$\overline{D_i} = \frac{D_i}{\max D_i} \tag{8}$$

MODE 1-BASED ADAPTIVE PUSH-OVER PROCEDURE (A-M1)

Lateral load pattern in this procedure is proportional to the first mode of the structure and is adapted at each stage. This procedure takes into account the softening of the capacity curve due to reduced structural stiffness. This will change the shape of the modes (FEMA440 , 2005).

STORY SHEAR-BASED ADAPTIVE PUSH-OVER PROCEDURE (SAP)

In order to determine the lateral load distribution pattern at each stage, $\overline{f_i}$ vector is used in this procedure. First, modal force at each story was obtained according to Equation (9) and using the mass of the stories, modal shapes and spectral acceleration.

$$\mathrm{F_{ij}} = \mathrm{M_i} \varphi_{\mathrm{ij}} \mathrm{S_a}\left(\mathrm{j}\right) \tag{9}$$

Then, these forces were added together at each mode to yield the modal shears of the stories (Equation 10).

$$V_{ij} = \sum_{k=i}^{k=n} F_{kj} \tag{10}$$

Modal shear forces of each story were combined using SRSS method to obtain a structural shear profile (Equation 11).

$$V_i = \sqrt{\sum_{j=1}^{n} \left(V_{ij}\right)^2} \tag{11}$$

Then, the applied force on each story was achieved as the absolute value of the difference between the shear force of the story and the shear of the upper story (Equation 12).

$$f_i = \left|V_i - V_{i+1}\right| \tag{12}$$

Finally, f_i vector was transformed into normalized force vector of $\overline{f_i}$ by using Equation (13)(Zare and Aziminejad 2013) .

$$\overline{f_i} = \frac{f_i}{\sum_{i=1}^{n} f_i} \tag{13}$$

EARTHQUAKE CHARACTERISTICS

In this study, eleven earthquake records introduced in FEMA 440 were used for the nonlinear dynamic analyses. Characteristics of these earthquakes are listed in Table (1). Coordination of the accelerograms was performed using ASCE7-10 Code specifications (ASCE7-10, 2010).

Table 1: 11-Graund Motions characteristics

#	Identifier	Earthquake	Date	Magnitude	Station Location (Number)	Component	PGA (g)	PGV (cm/sec)
1	ICC000	Superstitn	11-24-87	Ms=6.6	El Centro Imp. Co.Cent(01335)	000	0.358	46.4
2	LOS000	Northridge	1-17-94	Ms=6.7	Canyon Country-W Lost Cany(90057)	000	0.41	43
3	G02090	Loma Prieta	10-18-89	Ms=7.1	Gilroy Array #2 (47380)	090	0.322	39.1
4	TCU122N	Chi-Chi,Taiwan	9-20-99	Ms=7.6	(TCU122)	N	0.261	34
5	G03090	Loma Prieta	10-18-89	Ms=7.1	Gilroy Array #3 (47381)	090	0.367	44.7
6	CNP196	Northridge	1-17-94	Ms=6.7	Canoga Park-Topanga Can(90053)	196	0.42	60.8
7	CHY101W	Chi-Chi,Taiwan	9-20-99	Ms=7.6	(CHY101)	w	0.353	70.6
8	ICC090	Superstitn	11-24-87	Ms=6.6	El Centro Imp. Co.Cent(01335)	090	0.258	40.9
9	CNP106	Northridge	1-17-94	Ms=6.7	Canoga Park-Topanga Can(90053)	106	0.356	32.1
10	E02140	Imperial Valley	10-15-79	Ms=6.9	El Centro Array #2 (5115)	140	0.315	31.5
11	E11230	Imperial Valley	10-15-79	Ms=6.9	El Centro Array #11 (5058)	230	0.38	42.1

CALCULATION OF THE TARGET DISPLACEMENT

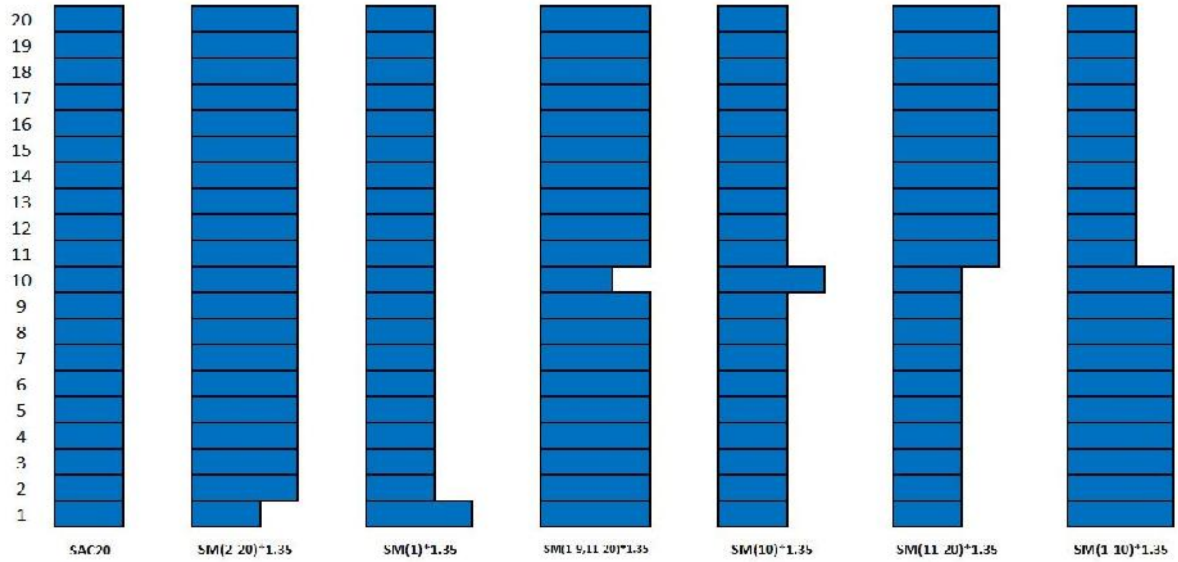
In order accurately assess the performance and efficiency of Adaptive Push-Over procedures, target displacement parameter was directly calculated from the results of nonlinear time history dynamic analyses (NTHA). In this way, nonlinear dynamic analysis of all the earthquake records were first performed for each structural model, then maximum displacement of the roof center of mass (control point of the structure) was calculated for each of the 11 nonlinear dynamic analyses. Finally, the average of these values was used as the target displacement in the nonlinear static analysis techniques.

INTRODUCTION TO THE STRUCTURAL MODELS

Structural models studied in this paper were divided into two groups of the reference model and models with asymmetric strength distribution in height. The structural 20-story model by SAC group was used as the reference model, which is called SAC20 here after in the paper. SAC buildings had peripheral steel moment-frames designed by consulting engineers for the second phase of the SAC group research project. In designing these structures, seismic specifications of 1994UBC Regulations for Los Angeles area have been considered (Ohtori, Christenson, Spencer & Dyke, 2003).

In this study, two-dimensional models were used and only one of the peripheral moment-frames with the north-south direction of the building was modeled. The second group of the assessed models were structures with irregular distribution of the strength in height that were developed by applying some changes to the structural components of the reference model (SAC20). For this purpose, six models including irregular strength distribution patterns in height have been considered (Figure 2).

Irregular models were named using SM(X-Y)×Z term, in which (X-Y) indicates the stories whose strength has been increased (If only the number of a story has been used indicates that the strength of only one story has been modified). Z parameter indicates the value of the strength correction coefficient. This coefficient shows the strength of the stories in the irregular model to the strength of the same stories at the reference model ratio. According to ASCE 7 Code regulations, this coefficient indicates the strength irregularity of the structure in height so that the weak story is located where the lateral strength of the story would be less than 80% of the corresponding value for the upper story. The lateral strength of the story is the sum of lateral strengths of all seismic resistant elements that resist the story shear in the desired direction. Figure 4 shows a schematic view of the story strength in models with irregular strength distribution in height in comparison to SAC20 model values.



Figure

Figure 2: schematic view of the story strength in models with irregular strength distribution in height in comparison to SAC20 model values

ANALYSIS RESULTS

To evaluate the accuracy of the studied Push-Over procedures in this study, analysis results for displacement and story drift parameters were compared with the exact values of these parameters obtained from averaging the maximum responses of the nonlinear dynamic analyses. Equation (12) was used to calculate the induced error by different methods.

$$Error\ (\%) = 100 \times \left| \frac{R_{NTHA} - R_{PUSH}}{R_{NTHA}} \right|$$

EVALUATION OF THE STORY DISPLACEMENT

Figure 3 shows the average story displacement error values for 20-story structures. As it can be seen, SAP procedure yields the lowest error in estimating the story displacement in all the models except SM (1-9, 2-20)×1/35 model. The maximum error was obtained equal to 11.56% using this procedure for SM (2-20) × 1/35 model, and the lowest error was equal to 5.37% using in this procedure for SM (2-20) × 1/35 model. Rectangular procedure provided the highest error in estimation of the story displacement, and the lowest error of this procedure was equal to 29.48% for SM (10) ×1.35 model. The story displacement error in SM (1-9, 2-20) × 1/35 model was more than the corresponding error in the reference model for all the procedures except Code procedure. In SM (10) × 1/35 model, the story displacement error was less than the corresponding error in the reference model. It should be noted that the two models had different story strength distribution patterns. This was also the case for SM (1-10) × 1/35 and SM (11-20) × 1/35 models with the difference that the story displacement difference between SM (10) × 1/35 and SM (1-9,11-20) × 1/35 models were more than the differences between SM (1-10) × 1/35 and SM (11-20) × 1/35 models.

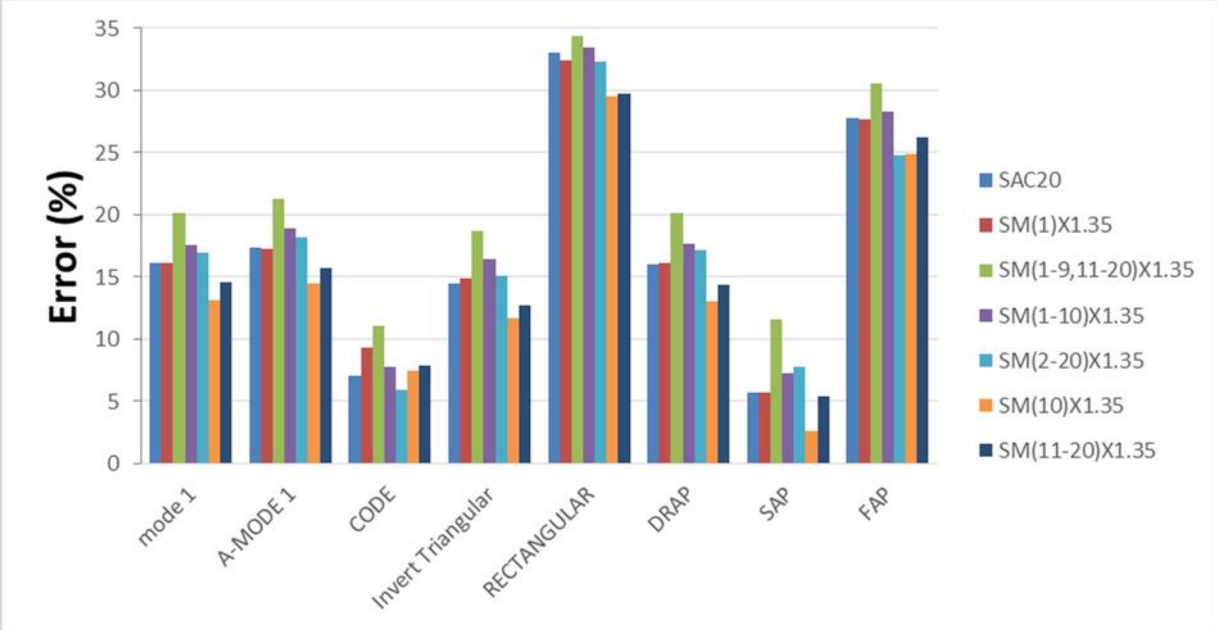


Figure 3. Average displacement error of the stories for the studied nonlinear static methods (%)

EVALUATION OF THE STORY DRIFT

Figure 4 shows the average drift error for the studied structures. As it can be seen from the figure, Code method is the most accurate method. In SM (1) * 1.35 and SM (10) * 1.35 models, all the methods except Code method estimated the drift of the floors with less error in comparison to Base model. In SM (1-9.11-20) * 1.35 model, all the methods estimated the drift of the floors with a higher error value than Base method. But in SM (2-20) * 1.35 model, with a weak first floor, all the methods except FAP and Code methods estimated the drift of the floors with higher error values than Base method. Among all the adaptive methods, SAP method has the best performance for all the structures, with a maximum error of 37.81%. Rectangular method has the worst performance with a maximum error of 52.26% for SM (1-9.11-20) * 1.35 model.

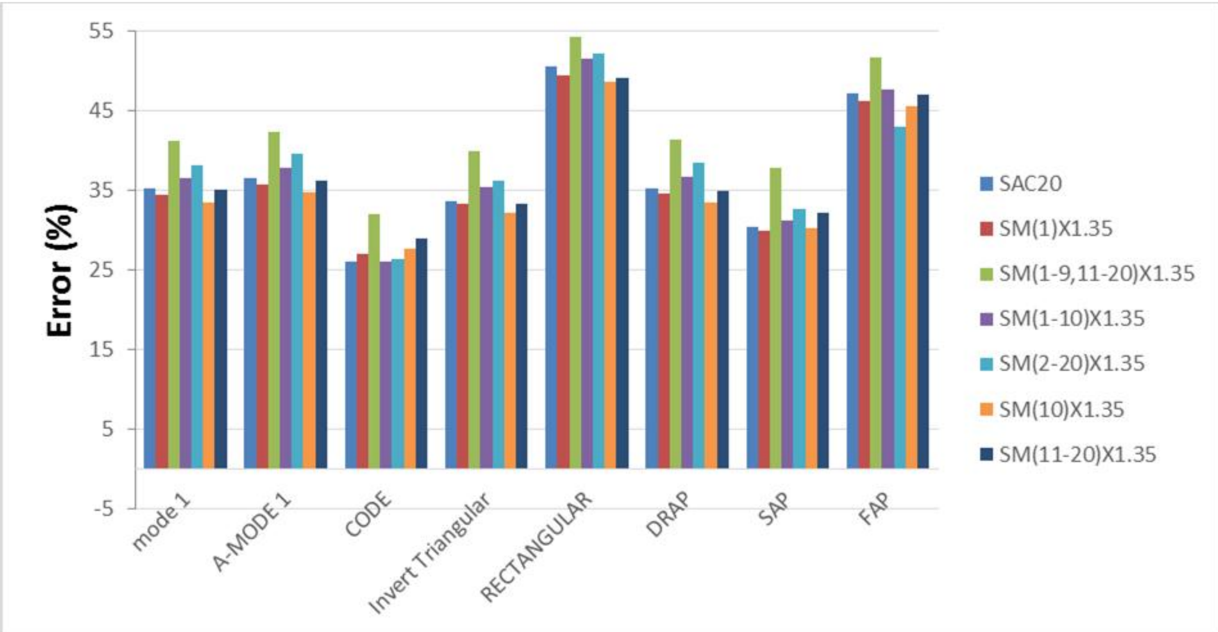


Figure 4. Average interstorey drift error of the stories for the studied nonlinear static methods (%)

EVALUATION OF THE STORY SHEAR FORCE

As can be seen from figure 5 , Rectangular procedure provided the highest error in estimation of the story shear force. Again, adaptation of the load pattern according to Mode 1 of the structure in A-Model procedure had no significant effect compared to Model procedure and even caused a slight increase in error calculation for all the models. All of the studied procedures except Code procedure evaluated the story shear in SM (1-9, 11-20) × 1/35, SM (10) × 1/35 and SM (11-20) × 1/35 models with higher errors than in the reference model. In case of SM (1) × 1/35 and SM (1-10) × 1/35 models, story shear error for all the procedures except Code procedure was less than the reference model. Evaluation of Diagram 1 showed that in all the models, except for SM (1) × 1/35 and SM (1-10) × 1/35 models, Code procedure was the most accurate one. Minimum error of this procedure was equal to 24.04% in SM (1-9, 11-20) × 1/35 model. In other models, SAP procedure was the superior one with the minimum error of 25.4% in SM (1-10) × 1/35 model.

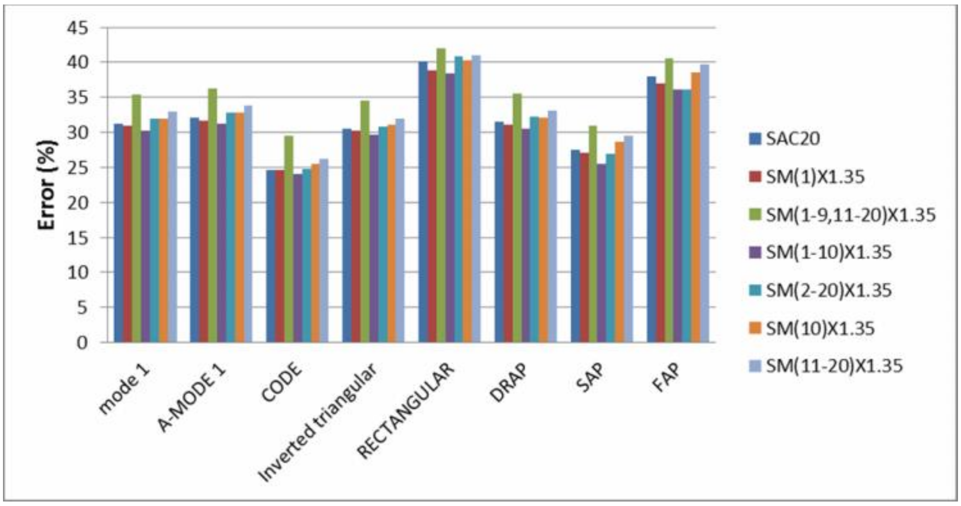


Figure 5. Average interstorey shear error of the stories for the studied nonlinear static methods (%)

EVALUATION OF THE STORY MOMENT

Figure 6 shows the average errors of the story overturning moment in the studied models. Code procedure provided better results for all the models except for SM (1) × 1/35 and SM (1-10) × 1/35 models with the minimum error of 27.97% in SM (1-9, 11-20) × 1/35 model. In other models, SAP procedure provided better results. In all the procedures except FAP and Code, models including weak story, i. e. SM (2-20) × 1/35, SM (1-9,11-20) × 1/35 and SM (11-20) × 1/35, had increased errors as compared to the counterpart models with strong story. This was the case in FAP procedure for SM (1-9,11-20) × 1/35 and SM (11-20) × 1/35 models.

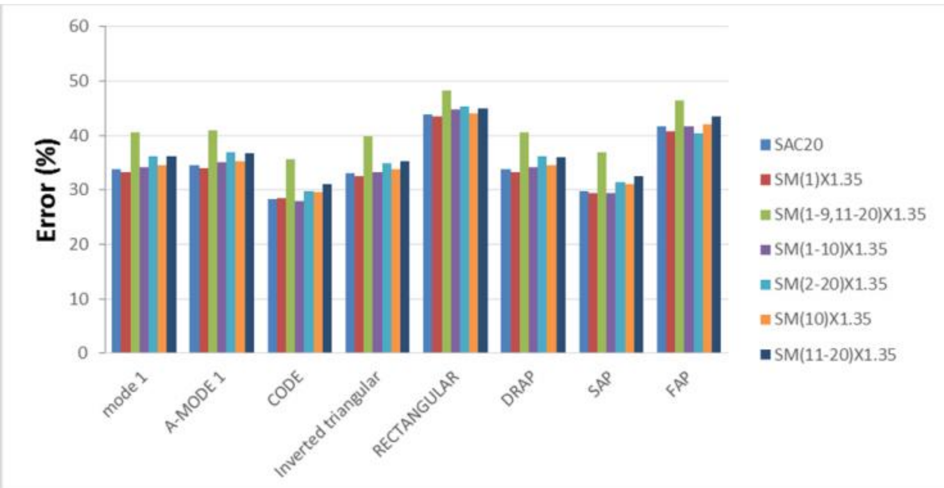


Figure 6. Average interstorey moment error of the stories for the studied nonlinear static methods (%)

CONCLUSIONS

1. Shear-based Adaptive Push-Over procedure (SAP) had the best performance in estimating the studied parameters among Adaptive load pattern Push-Over procedures.
2. Adaptation of the load pattern proportional to the structure Mode-1 in A-Mode 1 procedure did not improve the results in comparison to Mode 1 procedure.
3. Rectangular procedure provided the lowest performance in the estimation of displacement, drift, shear and overturning moment than other procedures.
4. Code procedure had the highest accuracy in evaluation of story drift than all other procedures.
5. SAP procedure had the lowest error among other methods in estimating the story displacement for all the models except for SM (1-9, 2-20) × 1/35 model.
6. In evaluation of the story shear and overturning moment parameters, Code procedure provided better results for all the models except for SM (1) × 1/35 and SM (1-10) × 1/35 models.

REFERENCES

Al-Ali AAK and Krawinkler H (1998) Effects of vertical irregularities on seismic behavior of building structures, John A.Blume *Earthquake Engineering Center*, Stanford Calif, 130:198

Antoniou S and Pinho R (2004a) Advantages and; imitations of adaptive and non-adaptive force-based pushover procedures. *Journal of Earthquake Engineering*, 8(4), pp. 497-522

Antoniou S and Pinho R (2004b) Develoment and verification of a dispiacement-based adaptive pushover procedure, *Journal of Earthquake Engineering*, Vol. 8, No.5, pp. 643-661

ASCE, 2010, Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-10, American Society of Civil Engineers, Reston, Virginia

Chopra AK and Goel RK (2002) A modal pushover analysis procedure for estimating seismic. Demands for buildings. *Earthquake Engineering and Structural Dynamics*, Vol. 31, pp. 561-582

FEMA (2005) Improvement of Nonlinear Static Seismic Analysis Procedures, (ATC-55 Project) FEMA 440. Federal Emergency Management Agency, Washlngton, DC

Gupta B and Kunnath SK (2000) Adaptive spectra-based pushover procedure for seismic evaluatlon of Structures. *Earthquake Spectra*, 16(2). Pp. 367-391

Ohtori Y, Christenson RE, Spencer BF and Dyke SJ (2003) Benchmark problems in seismically excited nonlinear buildings, Journal of Engineering Mechanics, ASCE, 129, to appear, http://cee.uiuc.edu/sstl/

Zare M and Aziminejad A (2013) Evaluation of Adaptive Pushover Procedure in Steel Moment Resisting Frames, Department of Structural Engineering Science and Research Branch, Islamic Azad university, Tehran, Iran, 2013