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A Shear-based Adaptive Pushover Procedure for Moment-resisting Frames

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ABSTRACT: The effects of higher modes are neglected in conventional pushover analysis procedures. Among the improved pushover methods, the adaptive pushover procedures are attractive for their multi-mode capability. In such procedures, the dynamic characteristics of buildings are updated in each stage of analysis consistent with the extent of the non-linear action throughout the structure. In this paper an adaptive pushover procedure is introduced that works with inter-story shear forces. It is compared with the conventional adaptive pushover methods where story accelerations or displacements are the bases of analysis. In the proposed method, the inter-story shears are calculated and updated based on the current dynamic characteristics of structure at each analysis step. They are then converted to the equivalent lateral forces for pushover analysis. Through using a correction factor based on the fundamental period of the building, a procedure is also developed for modifying the story drifts. Comparison with the average results of exact nonlinear dynamic analysis of a number of buildings under several earthquakes shows accuracy similar to the most precise procedure within the available conventional adaptive pushover methods. For the comparative analysis, 5, 10 and 15-story buildings and seven ground motions are utilized. Moreover, the proposed method is practically more adaptable to the current commercial softwares.

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1- Introduction

The non-linear progressive static procedure which is called "pushover analysis" is an approximate method for seismic analysis of structures being popular because of its simplicity in comparison with the complicated and time-consuming nonlinear dynamic analysis.

In this procedure the structure is "pushed" using a pre-specified lateral load (force or displacement) pattern, until the structure attains a predefined or "target" design point, usually defined as a certain roof displacement or base shear. Design values of members are those generated at this design point.

The ability of this method to predict the critical response of structures is to the extent that many earthquake engineering codes, instructions, and manuals, such as ATC40 [1] and FEMA356 [2], have adopted it as the preferred analysis method.

Two of the more widely used approaches for determining the design point are those of FEMA356 and ATC40. In FEMA356 the target displacement is determined by using the displacement coefficient method. Calculation for the same purpose in ATC40 is accomplished graphically by depicting demand and capacity curves and finding their intersection, called the capacity spectrum method. Both methods basically assess a multi-degree-of-freedom (MDOF) structure through converting it to an equivalent single-degree-of-freedom (SDOF) system.

In the conventional non-adaptive pushover analysis, distributed lateral forces with an invariant pattern (triangular, uniform, etc.) are applied along the height of structure to achieve the design point. Despite possessing good capabilities to estimate seismic demands of structures, the prime disadvantage of this method is its reliance on the specified invariant pattern of lateral forces for calculating the displaced shape and associated actions. As a result, for the cases of tall or irregular buildings where the effects of higher modes are important, this method can produce large errors.

Extensive research studies have been implemented in recent years to improve the accuracy of the conventional push over. Regarding the higher mode effects, the pushover methods can be classified as single-mode and multi-mode and concerning the nonlinear behavior of structure, they can be divided into non-adaptive and adaptive methods.

As part of the results of the mentioned attempts, improved equations were published to estimate the design point (target displacement) in FEMA440 [3] and ASCE41-06 [4] documents. Among other available methods for defining the design point, the N2 [5], the Capacity Spectrum [6], the Adaptive Capacity Spectrum [7], the IRSA [8] methods can be mentioned here.

The first studies regarding the application of higher mode effects in pushover analysis were carried out by Parret et al. [9] and Sasaki et al. [10]. They proposed a multi-modal pushover

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procedure (MMP). In their method, several pushover analyses are carried out each one for one of the natural modes of the structure. The forcing vector is obtained from modal analysis of the system. The produced capacity curves are converted to the ADRS (Acceleration-Displacement Response Spectrum) format and are plotted simultaneously with the seismic response spectrum to compare the capacity and demand in a single coordinate system. The obtained results demonstrate which modes are more effective in the seismic response calculation of structure. An improved version of the multi-modal pushover procedure is the PRC (Pushover Results Combination) method which has been suggested by Tso and Moghadam [11].

Based on the mentioned methods, Chopra and Goel [12] introduced an improved method called the Modal Pushover Analysis (MPA). In their procedure, after computing the modal characteristics of the structure, a pushover analysis is conducted for each mode (usually only for the first 3 modes) using the corresponding mode shapes as the loading pattern. The desired responses for each mode are calculated and combined through standard combination rules such as SRSS or CQC, to determine the design values with a superior accuracy over the conventional pushover method. The limitation of the proposed approach is that here the elastic characteristics of structures are used to calculate the inelastic response parameters that is to retain the simplicity.

In the second approach, in addition to employing the higher modes in the procedure, the current dynamic characteristics of structure are used taking into account its inelastic behavior due to plastic hinge formations. This is called the adaptive pushover method. This approach was developed by many researchers such as Bracci et al. [13], Lefort [14], Gupta and Kunath [15], Requena and Ayala [16], and Papanikolao and Elnashai [17]. In the mentioned method, at each step of analysis, the structure is pushed by a force load pattern updated according to the current dynamic characteristics of structure.

Antoniou and Pinho [18, 19], developed two different versions of the adaptive procedure called the Force-based Adaptive Pushover (FAP) and the Displacement-based Adaptive Pushover (DAP) analyses where in the later the load pattern is obtained and updated based on the lateral displacement of structure. Because of similarity in the basis, details of FAP and DAP methods will be discussed in the next section and used as a basis for comparison in addition to the conventional method.

Turker and Irtem [20], presented an effective load increment method for multi modal adaptive procedure. In this method, both material and geometrical non-linearities (second-order effects) are included. An improved modal pushover analysis procedure was presented by Jianmeng et al. [21]. In their procedure, the computational effort was lowered by adopting a two-phase lateral force distribution.

Poursha et al. [22] introduced an improved method of modal pushover analysis for estimating the seismic demands of tall buildings called the consecutive modal pushover procedure (CMP). The higher mode effects were included by successively pushing the structure according to the consecutive mode shapes. This way, they managed to retain the signs of the modal responses. Gholipour et al. [23], proposed a new lateral load pattern for pushover analysis. Their proposed load pattern varied based on the distribution of weight and stiffness of stories in height and mode shapes of structure. In another attempt, Manoukas et al. [24] presented a multimode pushover analysis based on energy-equivalent SDOF systems associated with each higher mode contribution.

Pradip et al. [25], studied seismic response of stepped RC building frames using an improved pushover analysis. They proposed a new approach to determine the lateral load pattern considering the contributions from the higher modes, suitable for pushover analysis of stepped buildings. Xiaohui et al. [26] used the pushover procedure to assess limit state capacities for reinforced concrete frame structures considering the inherent randomness of structural parameters. However, these multi-run methods could not display the yielding effect of one mode on the other modes resulting in the interaction between different modes in the non-linear range. In addition, the modal combination rules such as square-root-of-the-sum-of-the-squares (SRSS) are valid for combining the responses of independent modes in the elastic range. Since in the inelastic domain the structural system cannot be supposed to contain independent modes of vibration, validity of using the classic modal combination rules in the inelastic range is strongly under question.

Shakeri et al. [27] presented a new adaptive method based on the story shears called the SSAP. Because of similarity of the basis, details and difference between this method and the method presented in this paper will be discussed in more depth in Section 3.

In the present study, a new adaptive multi-mode pushover procedure is presented where the lateral loads are calculated based on inter-story shear forces and are updated on the basis of the progressively reduced stiffness of structure. This method, called the shear-based adaptive pushover (SAP), is verified by obtaining the seismic demands of a number of moment-resisting example frames using the nonlinear dynamic analysis subjected to selected earthquake ground motions.

On theoretical grounds, as will be shown, the proposed method can be regarded as a force-based companion to the DAP of Antoniou and Pinho. Therefore, it seems appropriate to describe their method first, to put the proposed method within the context.

2- The Adaptive Pushover Analysis

When a structure is subjected to severe ground motions caused by large earthquakes, plastic hinges develop in members, structure's stiffness decreases gradually, and the lateral forces change consistent with the lateral stiffness. In fact, height-wise distribution of the base shear that is based on the elastic modes in linear behavior, changes according to the instantaneous stiffness of structure in non-linear behavior. In the adaptive pushover analysis (APA), the continuous change of lateral loading pattern is taken into account where the load vector is updated based on the current dynamic characteristics of structure and the higher mode effects are considered. The APA is implemented in two different ways, the force-based and the displacement-based APA, or to be concise, FAP and DAP, respectively.

2- 1- Force-based adaptive pushover analysis (FAP)

To adapt the force distribution in non-linear static analysis, several attempts have been carried out. The initial concepts were presented and developed by Bracci et al. [13] and Sasaki et al. [10]. In this regard other attempts have been carried out by Lefort [14], Gupta and Kunnath [15], Papanikolaou and Elnashai [17], and Requena and Ayala [16]. Later on, the method was developed and tested by Antoniou and Pinho [18].

In this procedure, first the lateral forces in each mode are computed using a design spectrum and the current mode shapes of structure by the following relationship:

$$F_{ij} = \Gamma_j \varphi_{ij} S_{aj} m_i \; ; \; i = 1,2,...,n \; ; \; j = 1,2,...,n \tag{1}$$

in which:

$$\Gamma_j = \sum_{i=1}^{n} m_i \varphi_{ij} \Big/ \sum_{i=1}^{n} m_i \varphi_{ij}^2 \tag{2}$$

where F_{ij} is the lateral force at the ith story in the jth mode, Γ_j is the modal participation factor of the jth mode, φ_{ij} is the mode shape value of the ith story in the jth mode, S_{aj} is the pseudo spectral acceleration in the jth mode, m_i is the mass of the ith story, and n is number of modes.

Then the total lateral force F_i on the ith story for calculating the member demands, is determined using, e.g., the SRSS rule:

$$F_i = \left(\sum_{j=1}^{n} F_{ij}^2 \right)^{1/2} \tag{3}$$

Because of non-linearity of analysis, the above force has to be applied to the ith story incrementally. On the other hand, as mentioned earlier, in the APA the load pattern is updated according to the dynamic properties of structure in each step of analysis. To achieve this, at the beginning of each analysis step, components of the load vector are calculated based on the dynamic characteristics of structure corresponding to the structure's state at the end of the previous step. The newly obtained load pattern replaces the previous one used in the last step. Then the difference between the new load vector and the loads applied to structure in the last step are applied incrementally. This procedure continues until reaching the design point or the defined failure condition. Quadratic modal combination rules (e.g. SRSS) used to combine the modal loads which, always leads to a positive value for all the story levels in the incremental load pattern (Equation 3). Consequently, the effects of the sign reversal in the higher modes forces are not reflected in the applied load pattern and thus only the amount of the modal forces are reflected.

2- 2- Displacement-based adaptive pushover (DAP)

In contrast to the force-based analysis wherein lateral forces are employed, in a displacement-based analysis the pre-calculated lateral displacements are enforced. Generally the performance of the DAP procedure is better than FAP, because this method could take reversal of sign in the story force profile. This reversal of sign can be interpreted as an effect of the sign reversal of the modal forces in the higher modes. This procedure can be implemented based on two different patterns, using the lateral displacements or using the drifts.

2- 2- 1- DAP based on the total lateral displacements

Antoniou and Pinho [19] presented an adaptive procedure where the lateral loads are applied to push the stories to certain displacements. The results of their investigation on some 8 and 12-story concrete structures indicated a considerable increase in the accuracy of response prediction over the FAP procedure, in comparison to the results of accurate nonlinear time history analysis.

The lateral displacement of the ith story in the jth mode, D_{ij}, is calculated using the following well known equation of the spectral analysis:

$$D_{ij} = \Gamma_j \varphi_{ij} S_{dj} \tag{4}$$

where S_{dj} is spectral displacement of the jth mode. Then, the target lateral displacement of the ith story, D_i, is calculated, e.g., using the SRSS rule:

$$D_i = (\sum_{j=1}^{n} D_{ij}^2)^{1/2} \; : i = 1,2,...,n \tag{5}$$

The load-equivalent of this displacement is applied to the ith story incrementally. Again, if there is a stiffness decrease in an analysis increment due to structural plasticization, the target displacement D_i is updated based on the current dynamic characteristics. Then the difference of the new target displacement of each story and its horizontal displacement until the last analysis step is applied to the story incrementally. This procedure is continued to the target displacement or failure.

2- 2- 2- DAP based on the inter-story drifts

The maximum lateral displacement of a particular story showing the value of displacement relative to foundation is unable to provide an adequate insight into the non-linear behavior of the story. In contrast, the inter-story drift can be appropriately related to the possible failures. In this context, a DAP version based on inter-story drifts was also presented by Antoniou and Pinho [19] and was shown to have a superior accuracy over using the total lateral displacements for analysis.

The ith story drift in the jth mode, Δ_{ij}, is determined as:

$$\Delta_{ij} = \Gamma_j (\varphi_{ij} - \varphi_{i-1j}) S_{dj} \; : i = 1,2,...,n \tag{6}$$

The drift response of the ith story, Δ_i, is calculated using, e.g., the SRSS rule:

$$\Delta_i = (\sum_{j=1}^{n} \Delta_{ij}^2)^{1/2} \; : i = 1,2,...,n \tag{7}$$

Finally, the target displacement of the ith story in the DAP analysis, already shown as D_i, is computed using Equation 8:

$$D_i = \sum_{k=1}^{i} \Delta_k \tag{8}$$

3- The proposed method of the Shear-Based Adaptive Pushover (SAP)

In line with the idea that the modal inter-story drifts can be combined to arrive at the lateral displacements in DAP for a better accuracy, it can be imagined that combining the modal story shears of the consecutive stories can be resulted in a better accuracy for estimation of lateral forces in FAP. It is the idea behind the current study and is called the shear-based adaptive pushover (SAP). The spectral shear forces are calculated in each mode at each story and are combined to give the total inter-story shear responses. These are then converted to the corresponding lateral forces on each story and a FAP analysis procedure similar to Section 2.1 is followed in the rest of analysis.

A step by step procedure is presented for implementation of SAP as follows:

1. Calculate the equivalent lateral forces of each mode, F_{ij}, using Equations 1 and 2.
2. Determine the modal story shears as the sum of the equivalent lateral forces of that mode applied to the stories above the one under study, as follows:

$$V_{ij} = \sum_{k=i}^{n} F_{kj} \tag{9}$$

in which V_{ij} is the spectral shear of the ith story in the jth mode.

3. Calculate the total shear of the ith story, V_i, e.g., using the SRSS rule:

$$V_i = (\sum_{j=1}^{n} V_{ij}^2)^{1/2} \; : i = 1, 2, ..., n \tag{10}$$

4. Compute the corresponding lateral force of the ith story, F_i, as the difference between the inter-story shears of stories i and i+1:

$$F_i = V_i - V_{i+1} \tag{11}$$

Conceptually, F_i's are the forces producing story shears V_i. These forces replace those of Equation 3 in the FAP analysis. The rest of the procedure is similar to FAP as explained following Equation 3.

A similar method based on the story shears has been developed by Shakeri et al. [27] called here SSAP. In their method the story shears and the corresponding lateral loads in each step are computed using the current dynamic characteristics of the structure at hand similar to Equations 9-11. The calculated lateral forces F_i are normalized to their sum, i.e. the base shear V_b, to determine the shape of the lateral loading $\overline{F_i}$. The base shear V_b is increased from small values in each step to the amount of ΔV_b. For the same purpose, the corresponding lateral forces Fi are increased in each step to the amount of $\Delta F_i = \Delta V_b \times \overline{F_i}$ to push the structure laterally to the target displacement.

There are two differences between SAP and SSAP:

1. In SSAP, a desirable constant value ΔV_b is taken as the increment of the base shear. At higher levels of lateral loading, characteristics of the structure can vary largely during the increment. In such instances, the SSAP procedure can yield large errors. In contrast, in the SAP procedure value of the load increment is decided by a response control algorithm such that whenever a small increase in the load results in a large increase in the response, the load increment is decreased consistently to keep the response increase in the range of less than two times.
2. As will be shown later, in the SAP method the final responses are modified using a response modifier calculated using the nonlinear dynamic time history analysis and a regression synthesis. Therefore, SAP is a semi-analytical pushover method.

In the following section, the SAP method is developed and its accuracy is established against the exact nonlinear time history analysis.

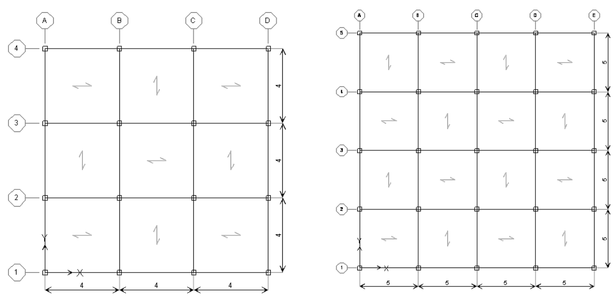
4- Numerical establishment of SAP

4- 1- The structural models

For the purposes of this study, three regular steel structures with the following properties are considered. The structural (lateral resisting) system of the buildings consists of special steel moment-resisting frames (SMRF) designed according to the AISC 2016 [28]. The buildings are regular and have symmetric plans, as shown in Figure 1. The buildings are located on a very dense soil in a very high seismicity region. The other specifications are as follows:

- Building usage: residential;
- Number of stories: 5, 10 and 15;
- Height of each floor: 3 m;
- Number and length of spans: 3 spans at 4 m for the 5-story building, and 4 spans at 5 m for 10 and 15-story buildings;
- Dead and live loads on floors: 5.5 and 2 kN/m2, respectively;
- Floor system: RC slab;
- Beam and column sections: I and square box sections, respectively.

The story plans are shown in Figure 1. Also, Table 1 summarizes the designed section dimensions.



(a) 5-story building (b) 10 and 15-story buildings

Figure 1. Floor plans of the studied buildings.

4- 2- The selected accelerograms

A set of seven accelerograms have been selected for non-linear time history analysis of the sample buildings out of the PEER database [29]. The accelerograms were selected with the aim of covering a wide range of the peak ground acceleration (PGA), having a wide frequency content, duration and number of high amplitude cycles. Some important characteristics of the earthquakes are shown in Table 2. All of the selected earthquakes have been recorded on a very dense soil, had similar magnitudes and were originated on thrust faults.

Table 1. Profile sections used for the structural members

Building	Story number	Beam profile (depth in mm)	Column profile (square dimension × thickness, mm)
5 story	1, 2	HEB-200	BOX 250X10
	3	HEB-200	BOX 250X8
	4	HEB-160	BOX 250X8
	5	HEB-140	BOX 250X8
10 story	1	HEB-240	BOX 350X15
	2	HEB-260	BOX 350X15
	3	HEB-280	BOX 350X12
	4	HEB-260	BOX 350X12
	5	HEB-260	BOX 350X10
	6, 7, 8	HEB-240	BOX 350X10
	9	HEB-180	BOX 300X10
	10	HEB-160	BOX 300X10
15 story	1	HEB-280	BOX 350X18
	2	HEB-260	BOX 350X18
	3	HEB-300	BOX 350X18
	4, 5	HEB-280	BOX 350X18
	6, 7, 8	HEB-280	BOX 350X15
	9, 10	HEB-260	BOX 350X12
	11	HEB-240	BOX 350X12
	12	HEB-240	BOX 350X10
	13, 14	HEB-200	BOX 350X10
	15	HEB-180	BOX 350X10

Table 2. The selected earthquakes for non-linear time history analysis of the structures

Record	PGA (g)	YEAR	DURATION (s)	REMARKS
El centro	0.35	1940	15	NS component
Loma Prieta	0.80	1989	16.9	Corralitos recording station
Tabas	0.93	1978	25	North eastern Iran
Artificial	0.44	-	15	Generated by Campos-Costa & Pinto [30]
Hollister	0.13	1974	15	City Hall recording station
Friulli	0.48	1976	20	Italy
Kocaeli	0.63	1999	20	Sakaria recording station

4- 3- Analysis of the structures and the results

The structural frames under study are analyzed using the SAP method (Section 3). The results are compared with those of the non-linear time history analysis (NTA). Through a regression analysis, a response modifier is calculated to improve the accuracy of the SAP procedure. The response results are then compared with the adaptive pushover methods FAP and DAP (Section 2). In addition, the conventional pushover method described in FEMA 356 is also implemented for comparison. The later method consists of different loading patterns out of which two more practical patterns of triangular and uniform load distributions are used. To have a common basis for comparison, when a specific earthquake record is used, the maximum roof displacement under the same earthquake is utilized as the target displacement for all of the pushover procedures undertaken. Moreover, some of the records are amplified beforehand in order to obtain a considerable nonlinear response. The maximum roof (target) displacement under each earthquake for each building is shown in Table 3.

Table 3. The target displacements as the maxima of roof displacements (cm)

Record	5-story	10-story	15-story
El centro	37.2	70.2	68.8
Loma Prieta	36.0	51.6	77.3
Tabas	30.3	62.1	102.2
Artificial	34.0	61.2	60.1
Hollister	38.0	52.1	40.3
Friulli	40.0	62.0	71.7
Kocaeli	30.2	72.0	111.1

For pushover analysis as well as NTA of the structures under study, the Seismostruct software freely available on the internet is used. This software was originally developed by Antoniou and Pinho for APA and NTA [31]. The distributed plasticity model is benefitted from when modeling the beams and columns of the 2-D frames under study with 1-D elements.

As the story drift is the main parameter identifying the extent of seismic response in a particular story, in this study the drift ratio (drift divided by story height) is selected as the basis for comparing the results of different methods discussed above. This is the sole response which is presented in this paper.

The distribution of maximum drifts along the height of the structures studied using SAP and NTA methods is shown in Figures 2-8 for each earthquake and in Figure 9 for the average response of earthquakes. In the latter case, the target displacement is the average of the values mentioned in Table 3 for each building.

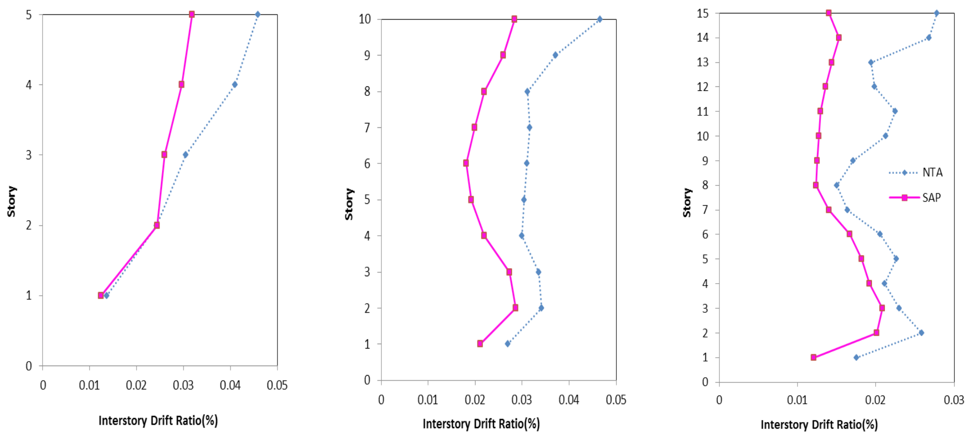


Figure 2. Maximum dift ratios under Elcentro 1940 earthquake for different buildings

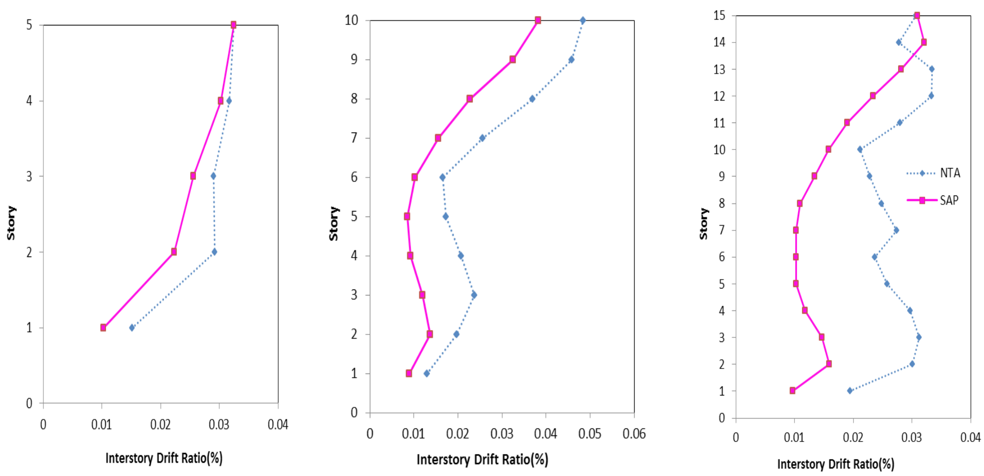


Figure 3. Maximum drift ratios under Loma Prieta 1989 earthquake for different buildings

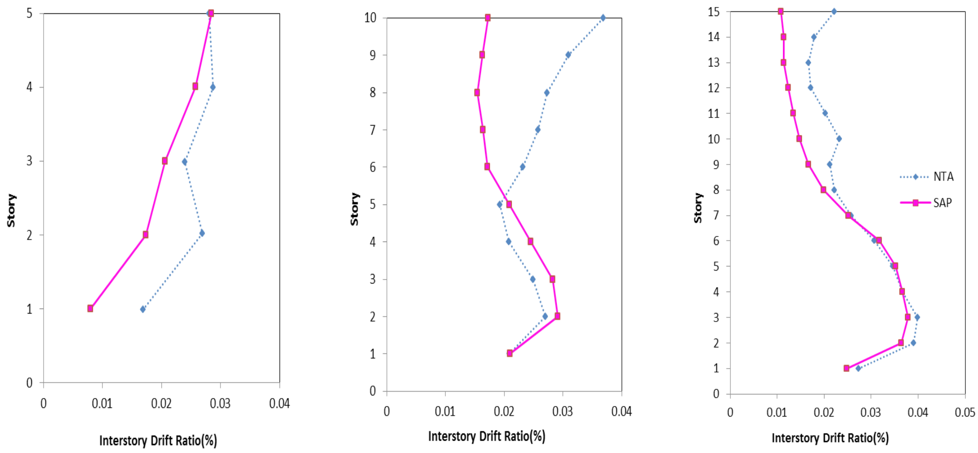


Figure 4. Maximim drift ratios under Tabas 1978 earthquake for different buildings

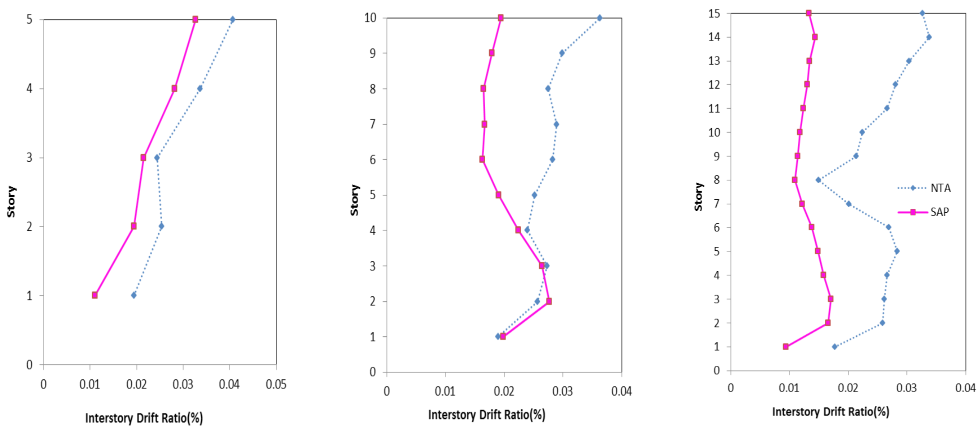


Figure 5. Maximum drift ratios under artificial record for different buildings

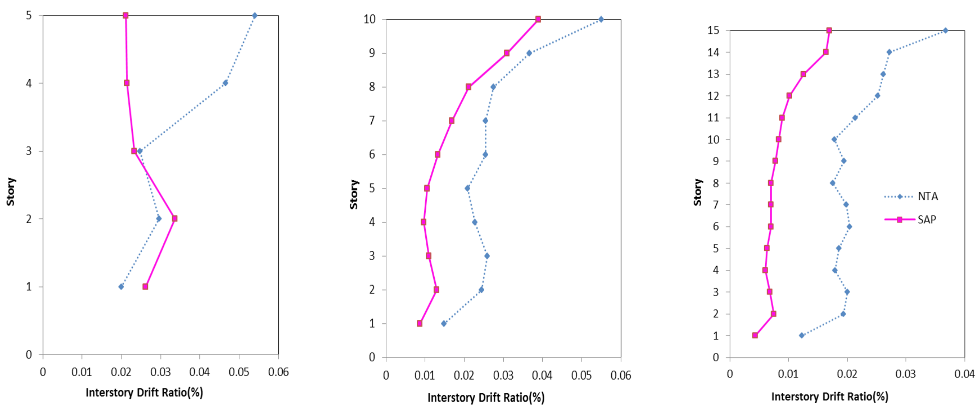


Figure 6. Maximum drift ratios under Hollister 1974 record for different buildings

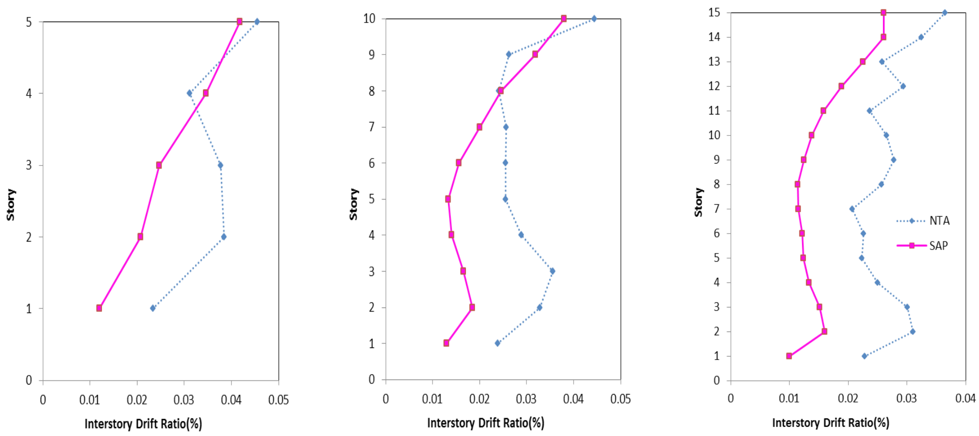


Figure 7. Maximum drift ratios under Friulli 1976 record for different buildings

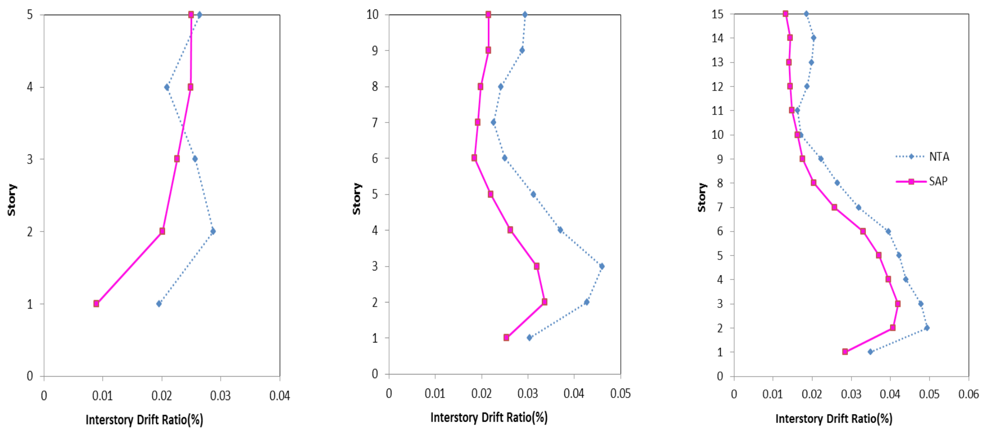


Figure 8. Maximum drift ratios under Kocaeli 1999 record for different buildings

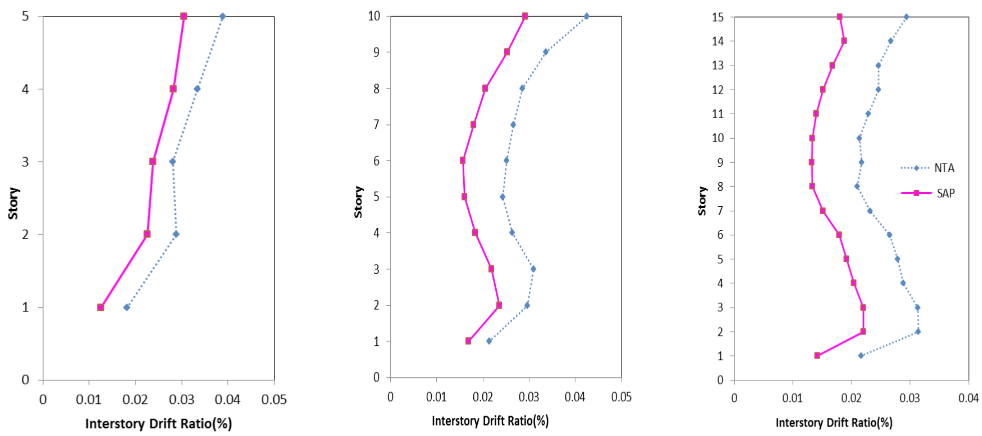


Figure 9. Averages of the drift ratios of Figures 2-8

The common trend seen in Figures 2-8 is that in most cases, the SAP method gives results that are smaller than the exact values. In many occasions, the error is larger at upper stories. It is also larger anywhere for taller buildings. The last two conclusions are more obviously seen in Figure 9 that shows the responses averaged between the earthquakes. Based on this discussion, a procedure is devised in the next section to enhance the accuracy of the SAP procedure.

4- 4- Correction factor for the drifts

As stated in the above, by examining Figures. 2-8 for each earthquake and Figure 9 for average response of the earthquakes, it is observed that in most cases the calculated drifts with SAP are smaller than the exact values. Therefore, it seems that the corrected drifts have to be determined from an equation with the following form:

$$\Delta_{iM} = \Delta_i \times (1+\beta_i) \tag{12}$$

where Δ_{iM} is the modified drift of the ith story, Δ_i is the original ith story drift calculated with SAP, and β_i is a positive correction factor for the ith story drift. According to Figures. 2-9, it is obvious that β_i must increase with height. Therefore, assuming a dimensionless power function based on relative height is likely to result in an effective modification of the response. This fact results in examining the following parametric equation for β_i:

$$\beta_i = a(h_i / H)^b \tag{13}$$

where h_i is height of the ith story from the base and H is the total height of building. The dimensionless parameters a and b have to be calculated by regression analysis for the average drifts of Figure 9.

As observed in Figure 9, the correction increases for taller buildings. It means that a and b should assume larger values for buildings having longer periods. Conducting a best fit analysis on this basis, results in the following equations for a and b:

$$a = T/5 \; , \; b = T/4 \tag{14}$$

The story drift ratios with and without the modifications represented by Equations 12-14 are shown in Figure 10 for the average of earthquakes along with the drifts calculated by NTA.

Figure 10 shows that how the performed modification has been successful in resembling the NTA drifts. The average responses of earthquakes calculated by other procedures are also shown in Figure 11.

Figure 11 shows that the response from the proposed method is closer to the exact answer.

Table 4. The drift error percentages relative to NTA averaged between the stories and earthquakes

	5 story building	10 story building	15 story building
SAP with modification	-6.6%	-9.5%	-13.0%
SAP without modification	-21.3%	-28.9%	-34.2%
DAP	-21.8%	-28.7%	-34.0%
FAP	-14.3%	-24.5%	-36.3%
Uniform	-14.2%	-24.4%	-34.8%
Triangular	-21.1%	-25.7%	-36.4%

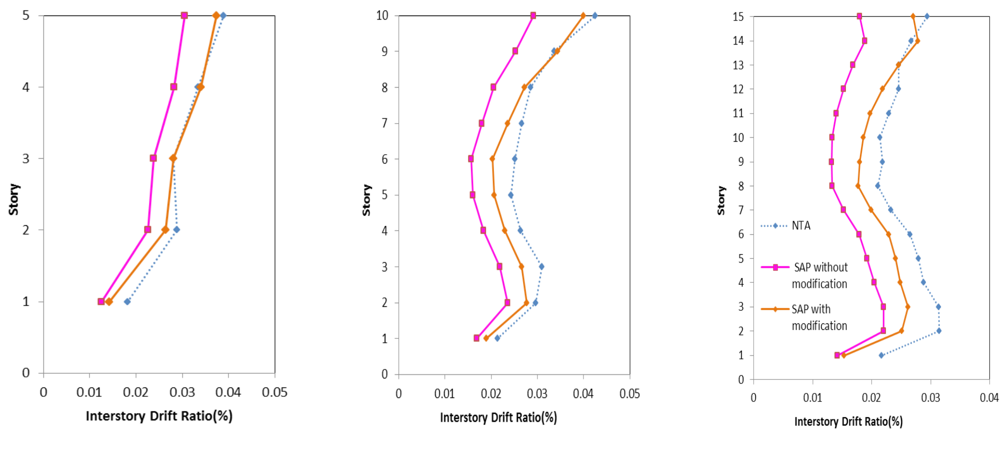


Figure 10. Maximum drift ratios averaged between the earthquakes, comparing SAP and NTA for different buildings

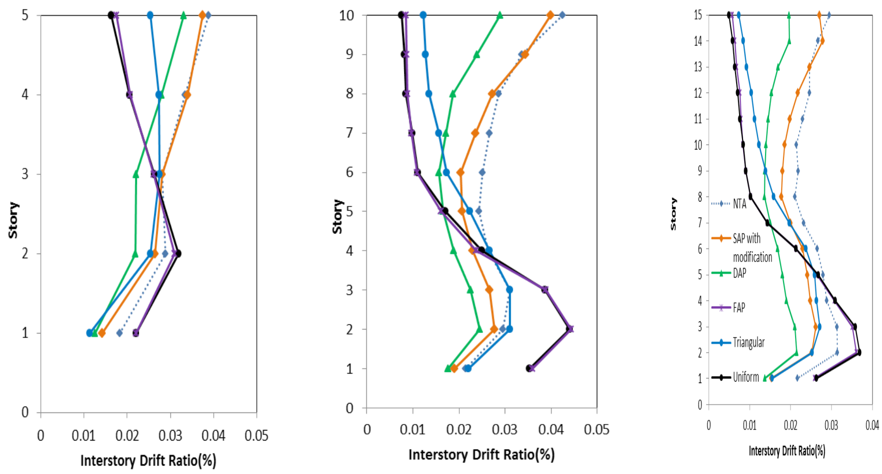


Figure 11. Maximum drift ratios averaged between the earthquakes, comparing several methods for different buildings

Numerically, this can be proved by computing and comparing the errors with respect to NTA. The percentage of error is calculated by Equation 15:

$$\text{Relative error (\%)}=\frac{\Delta_{ip}-\Delta_{iN}}{\Delta_{iN}}\times 100 \qquad (15)$$

in which Δ_{ip} is the ith story drift calculated with each of the pushover methods and is that of NTA.

The average error percentages among the earthquakes and stories are mentioned in Table 4. The Table presents also the drift responses calculated by FAP, DAP, and FEMA356 procedures for comparison

Table 4 shows that the responses calculated with the proposed SAP method with modification are much more accurate than FAP, DAP and FEMA356. The largest relative error of drift estimation by SAP is 13% compared to 34%, 36.3% and 36.4% for FAP, DAP, and Fema356, respectively. Therefore, the SAP method with modification is more accurate than the other studied methods for the cases investigated. Then, the SAP method is completed with modification for practical applications.

5- Conclusions

In this study a new adaptive pushover method was proposed. The new method, called SAP, benefits from the distribution of maximum story shears, converted to the corresponding lateral forces at floor levels. While this method can be regarded as a force-based companion to the existing displacement-based adaptive pushover methods, it is much easier to implement in earthquake engineering softwares since they generally use force-based computational algorithms. Moreover, the proposed method directly uses the familiar and easily available design acceleration spectrum. In addition, a correction factor was introduced for the drifts calculated with the proposed SAP method. The presented correction factor was shown to be effective in improving the accuracy of drift estimation. By comparing to results of nonlinear dynamic analysis, it was shown that the proposed method possesses a very good accuracy in estimating the story drifts for regular frames up to 15 stories.

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