A Comparative View on the Enhancements of Pushover Analysis Methods for Estimating Seismic Demands

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Abstract - *Developing simple and practical methods to estimate the seismic demands is one of the most important subjects. In this paper, we review several pushover analysis methods to illustrate the enhancements and refinements of the pushover analysis. In addition, how researcher could develop new procedures to overcome the drawbacks of the conventional pushover procedure. The modal pushover analysis (MPA) was developed to enhance the accuracy of the static pushover analysis. The consecutive pushover analysis (CMP) takes into account the higher modes effect. The displacement-based adaptive pushover analysis (DAP) provides more accurate structural responses and consider the higher modes effect. Spectrum-based pushover analysis (SPA) developed to provide a better estimation for the seismic demands for mid and high rise-buildings. The results were compared with the values from exact nonlinear methods such as nonlinear response time history analysis method (RHA) to illustrate the differences between the methods and development of the pushover methods.*

Key Words: Pushover analysis, Modal pushover analysis, Consecutive pushover procedure, Adaptive pushover procedure, Spectrum pushover analysis, Seismic demands, Higher-mode effects, Tall Buildings.

1. INTRODUCTION

Nowadays, the static pushover analysis is becoming a popular tool for seismic performance evaluation of existing and new structures. Buildings are usually designed for seismic resistance using elastic analysis, most of which experiences significant inelastic deformations under large seismic actions. Modern performance based design methods require ways to determine the real behavior of structures under such conditions. As such, non-linear analysis can play an important role in the design of new and existing buildings.

This paper presents the enhancements and the refinements of the pushover methods. In addition, it presents comparisons of the results of seismic demands. **(Chopra and Goel 2002)**introduced an improved pushover analysis procedure based on structural dynamics theory. He developed a modal pushover analysis (MPA) that is equivalent to response spectrum analysis. He investigated the MPA method on response of the 9-storey building and compared the results of floor displacements and the inter-storey drift with the ‘exact’ values from nonlinear response history analysis (RHA). **(Mao, Zhai, and Xie 2008)** had studied the improved modal pushover analysis (IMPA) which is based on MPA method. This method uses the deformed shape of the structure responding in elastically to the earthquake. They applied this method to a 3-storey reinforced concrete building and a 9-storey steel building and compared the results with the MPA and the extended N2 method.

Conventional pushover methods are not very accurate for tall buildings, in which higher mode response effects are significant. As a result, **(Poursha, Khoshnoudian, and Moghadam 2009)** investigated the consecutive pushover method to take the higher mode effects into consideration on four steel frame buildings and compared the results with RHA and MPA methods. **(Belejo and Bento 2016)**studied an improved consecutive pushover analysis (ICMP) procedure, which is proposed to enhance the accuracy of the conventional CMP procedure. The ICMP procedure can accurately evaluate the seismic demands of tall building taking into account the inelastic properties of the structure. Three frames with different number of storeys were studied to verify the accuracy of the ICMP and the results were compared with the results from CMP and the nonlinear time history analysis (NTHA).

In order to overcome the drawbacks of the conventional pushover methods, researchers developed adaptive pushover procedure, which consider the effect of higher modes and the progressive damage accumulation. **(Shetha, Sonib, and Shahc 2017)**studied the displacement-based adaptive pushover analysis on RC moment resisting frames

The aim of adaptive pushover analysis is to evaluate the seismic performance of the structure by predicting seismic demands and capacity of a building and considering its dynamic response characteristics includes the effect of the frequency content and deformation of input motion. **(Jalilkhani, Ghasemi, and Danesh 2020)**extended the adaptive pushover analysis by combining the advantage of ‘multi-modal’ with the adaptive pushover procedure and produced multi-mode adaptive pushover procedure (MADP). The case study was RC frames with different heights. It was found that this method enhance the value of the target displacement of the first mode and provide a better estimation for the target displacement of the structure. The results were compared with the results from nonlinear RHA, MPA and CMP. The results showed that the MADP is able to estimate the seismic demands correctly with minimum computational effort.

The pushover methods could provide acceptable results for frame structures, but these methods did not study different structure systems. **(Liu et al. 2020)**used spectrum-based pushover analysis (SPA) to estimate the seismic demands for shear wall structures.**(Liu and Kuang 2017)**studied the spectrum-based pushover analysis for estimating the seismic demands. The results of the floor displacements and inter-storey drift ratio were compared with the values from nonlinear RHA, MPA and CMP. The results of SPA were very close to the exact values.

2. A modal pushover analysis (MPA)

The pushover method has gained great popularity and become a standard tool for seismic assessment in many codes of practice. Nevertheless, for tall buildings, where the high-mode effect is so significant that the conventional pushover method does not estimate the seismic demand of tall buildings reasonably.

To achieve better estimation of seismic demand of tall buildings, while keeping the efficiency of the pushover method, many modified pushover methods of analysis were proposed**. (Chopra and Goel 2002), (Chopra and Goel 2004)** introduced the modal pushover analysis procedure (MPA) and the modified modal pushover analysis procedure (MMPA) are two of the most widely used modified pushover methods in which the contribution of higher modes to the seismic response is considered. In MPA and MMPA procedures, the seismic demand of each modal pushover procedure is determined separately and combined by the appropriate combination rules, such as square root of the sum of the squares (SRSS) method to get the final seismic demand. The MPA provides more accurate evaluation for seismic demands than the conventional pushover method. In addition, the seismic response of different modes in this method is considered separately, which is not the true for the nonlinear seismic performance of buildings due to the significant coupling effect of different modes. Neglecting the coupling effect in the calculation will induce noticeable errors to the analysis. As a result, these methods are not capable of estimating the local seismic demand of tall buildings very well.

(Chopra and Goel 2002)investigated the response of 9-storey building by the two modified methods, UMRHA and MPA, and compared the results with the 'exact' values of the non-linear RHA. The maximum values of floor displacements and storey drifts including one, two, and three modes are compared with the 'exact' values in Fig. 1.

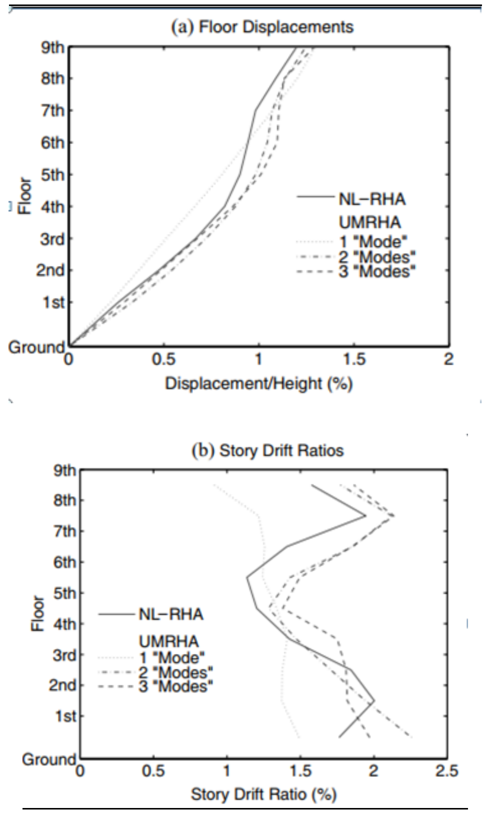

Fig. 1. Height-wise variation of floor displacements and storey drift ratios from UMRHA and non-linear RHA.

By comparing the peak response of a 9-storey SAC steel building estimated by the approximate MPA procedure with nonlinear RHA explains that the approximate procedure provided good estimates of floor displacements and store drifts, and the location of the developed plastic hinges; however, the values of plastic hinge rotations were less accurate.

3. A consecutive modal pushover analysis (CMP)

(Poursha, Khoshnoudian, and Moghadam 2009)introduced new pushover procedure, which consider the higher-mode contributions. This method is the consecutive modal pushover (CMP) method, merges the multi-stage and single-stage pushover analysis procedures. The final structure responses are the envelop of the responses of multi-stage and single-stage pushover analysis. The method was applied to four steel moment-resisting frames with different floor levels.

The main aim of this method is subsequently to propose a new procedure, which can consider the higher-mode contributions in the pushover analysis of high-rise buildings, and can perform a better estimation of seismic demands, especially of the inelastic hinge rotations.
Consecutive modal pushover analysis (CMP) were performed by distributing the lateral force using mode-

shapes calculated from Eigen-analysis of the structure at the linear elastic range. All the changes occurred in the modal properties of the structure were neglected when the structure were under nonlinear deformation because of the increased seismic loads through pushover analysis. The number of modes of the structure can be calculated using the natural time period (T), of the building structure. When the natural period of the building (with a moment-resisting frame system) was below2.2 s, the multi-stage pushover analysis was performed in two stages, the first stage was for buildings with natural periods of 2.2 s or high, both the second and the third stage pushover analysis were used. In each stage of multi-stage analysis, the roof displacement increment was obtained, by the multiplication of a factor and the total target roof displacement. This factor can be obtained from the initial modal properties of the structure.

The comparison shown in Fig. 2between the inter-storey drift ratios calculated by the MPA and CMP procedures, together and nonlinear NL-RHA, for the mid-rise(10- and 15-storey) frames structures. The figures shows that the MPA and CMP methods providing the values of inter-storey drifts ratios with a satisfactory accuracy. At the upper storeys, the CMP provides better estimates than the MPA, Meanwhile, At some lower storeys the errors from the MPA are less than those from the CMP.

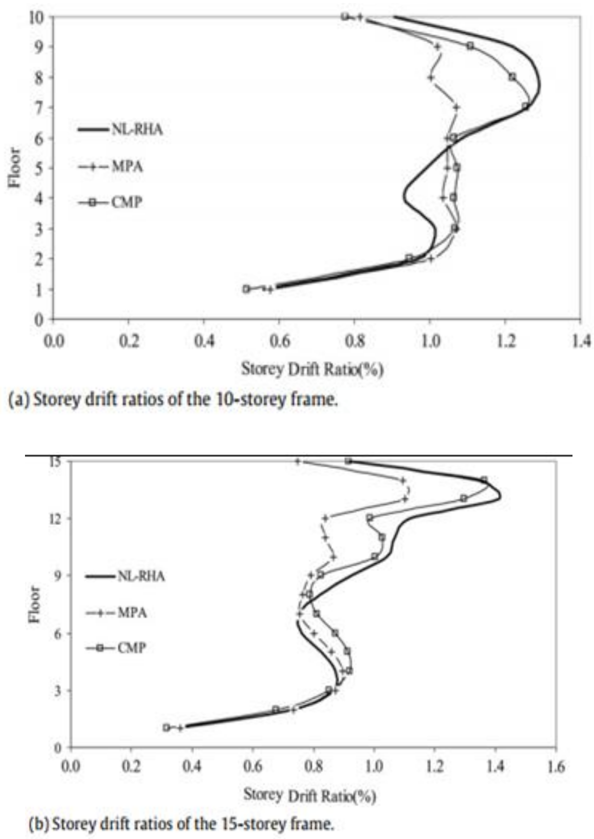

Fig. 2. Height-wise variation of the storey drifts for the 10- and 15-storey frames.

The inter-storey drift ratio can be calculated using the CMP procedure with acceptable accuracy. The inter-storey drift ratio obtained from CMP At some (upper) storeys,are more accurate than the results estimated by than by the MPA, whereas the MPA provides better estimates of storey drift than the CMP at some other (lower) storeys of the analyzed tall structures. A significant improvement has been developed in evaluating the hinge plastic rotations by the CMP procedure. The CMP procedure can provide better estimates of the plastic rotations than those estimated by the MPA procedure, especially at the mid and upper floor levels.

4. Displacement-based adaptive pushover analysis (DAP)

(Antoniou and Pinho 2004) introduced a displacement-based adaptive pushover analysis (DAP) in2004 to take into consideration the incremental load vector at each analysis step based on the initial dynamic properties of the structure. Evaluating the seismic demands of a structure and its capacity is the main objective of adaptive pushover analysis and considering the structure dynamic response characteristics includes the contribution of the frequency values and the deformation results from the motion.

The distribution of the lateral load is continuously modified along the analysis in the adaptive pushover procedure, depending on modal shapes and participation factors calculated from applying eigenvalue analysis at each step of analysis. DAP is completely multi-modal method which consider the updated inertia forces, the structural stiffness yielding, and its period variation due to spectral dilatation.

(Shetha, Sonib, and Shahc 2017) have used the adaptive pushover method to estimate the response of RC frame subjected to earthquake excitation. They compared the results with the conventional pushover analysis. They found that pushover analysis shows less capacity and higher inter-storey drift ratio. The DAP analysis procedure can take into account the higher mode effects which produce a better performance.

DAP can update and change the lateral load distributions based on the constantly changing modal characteristics of the structure. As a result, DAP provides a more accurate process for evaluating the structural dynamic performance and accurate response procedure than the conventional pushover procedures.

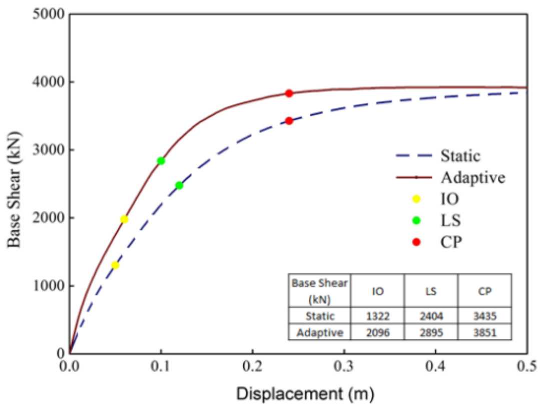

Fig. 3. Capacity curve for 5 storey frame

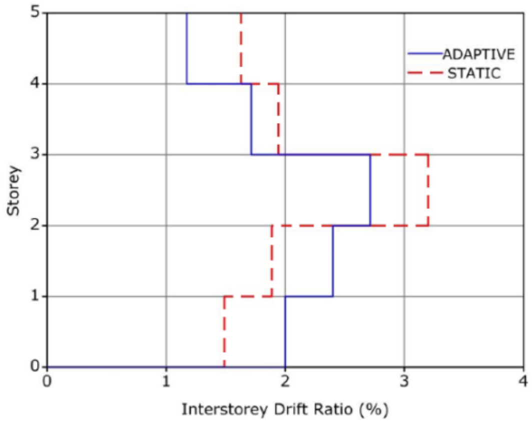

Fig. 4. Inter-storey drift ratio profile for 5 storey frame

The capacity curve for static pushover and adaptive pushover analysis is shown in **Fig. 3**. The adaptive pushover analysis shows higher capacity compared to static pushover analysis. The inter-storey drift ratio profile for 2% total target drift are shown in **Fig. 4**. The peak inter-storey drift value estimated from adaptive pushover analysis is 2.75% and static pushover analysis is 3.23%.

5. A multi-mode adaptive pushover analysis (MADP)

(Jalilkhani, Ghasemi, and Danesh 2020) presented a new method estimating the seismic demands for RC frame buildings, this method called multi-mode adaptive pushover analysis. The MADP method use the upsides of 'multi-modal' and 'adaptive' pushover procedure to come up with more accurate structural response.

The multi-mode adaptive displacement-based pushover (MADP) method utilizes serval 'multi-stage' modal pushover analysis. Every multi-stage involves a consecutive execution of pushover analysis. Once one stage is fully accomplished, the following stage starts with initial structural conditions that are the same condition at the end of the previous stage. In MADP procedure, each multistage pushover analysis begins with the horizontal load pattern comparable to the mode-shape vector in the elastic range($\mathbf{s}n= \mathbf{m}\Phi n$). The pushover analysis is then continued with a new horizontal load pattern established based on the storey displacements acquired from the prior stage. The horizontal load pattern is changed when the structure exposed to a recent inelastic event(i.e. plastic hinge).In MADP method, the multi-stage pushover analysis is carried on until the target-displacements equivalent to the displacement of theroof storey. The target-displacement for every mode is calculated using the nonlinear RHA of the correlating within elastic modal SDOF system, established based on a bilinearidealized pushover curve of the structure in that mode. although, because this research seeks to compare the seismic demands acquired from the MADP method with those given by the conventional and two developed NSPs (i.e. MPA and CMP), the target displacement at the roof storey are precisely estimated using the nonlinear RHA for the MADP and other approximate pushover methods.

The main upsides of the introduced MADP method in a comparison with other existing pushover methods are: (1) the MADP method can overcome the shortages and retractions of the conventional NSPs. The procedure takes into account the higher mode contributions and the advanced changes in the modal properties of the structure by merging the response of several single multi-mode adaptive pushover analysis (2) the MADP procedure calculates the seismic demands of structures by applying diverse(MADP). Therefore, it involves the upsides of the 'multi-modal' along with'adaptive' pushover methods; at the same time (3), a simple bilinear idealization method to estimate the target-displacement of the building is employed by the MADP method. This techniques easy to use and can help the engineer to compute the value of the target-displacement for every mode with the least computational efforts (4) the MADP method compute the seismic demands of a frame structure by the results acquired from diverse modal pushover analysis and the idea of seismic performance point.

Fig. 5presents the IDRs acquired by MADP, MPA, and CMP method. These methods can compute the IDRs of the example frames with satisfactory accuracy. The MADP can come up with finer estimates than MPA and CMPat the low and upper storeys, whereas the errors from the MPA and CMPare lowerthan those from the MADP at some midst storeys.

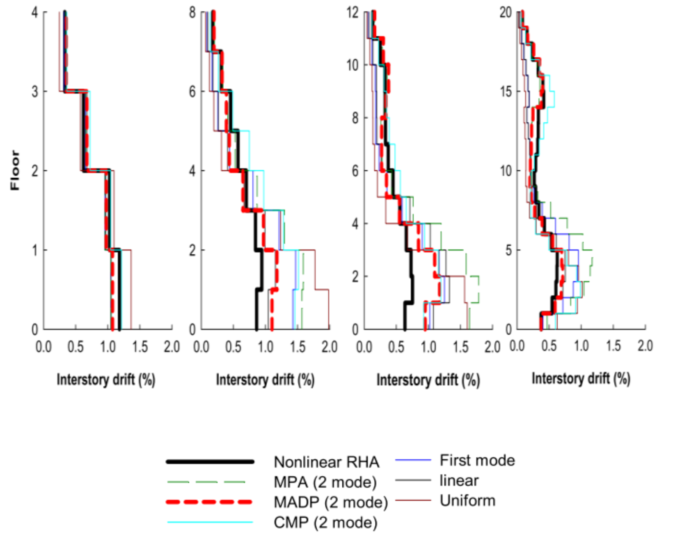

Fig. 5. The inter-storey drift ratios acquired by the MADP, MPA, CMP, and conventional pushover procedures with the RHA.

6. Spectrum-based pushover analysis (SPA)

One of the top methods used in estimating the seismic demands is multi-mode pushover analysis procedure, this assertion because of the balance of computation effort and the accuracy in computing the seismic demands. A lot of multi-modal pushover procedures were enhanced over the recent years and these procedures demonstrated its efficiency in estimating the seismic demands for frame structures. Although, the response of shear wall and frame structures are not similar when subjecting to horizontal loads. As a result, the multi-mode pushover procedures cannot be applied on different structures systems.

(Liu et al. 2020)revised the equations used for computing the roof storey displacement for shear wall structures. He studied two models of shear wall structures consists of 8 and 20 storeys. He studied the effect of choosing different target spectrums to the modal responses. After comparing the results he found that, the spectrum-based pushover analysis (SPA) of shear wall structures is able to calculate the seismic demands with good accuracy.

(Liu et al. 2020)estimated the seismic demands using SPA, MPA, CMP methods in addition to the NLRHA, and he used the results computed by the NLRHA as a reference for the accuracy of pushover analysis methods. Fig. 6 illustrates the comparison results of the roof displacement and the inter-storey drift ratio, he found that CMP method provide the best estimate of roof displacement. On the other hand, the MPA overestimate the roof displacement. The SPA has small differences between the estimated results and NLRHA results.

Fig. 7 presents the results of inter-storey drift ratio. The drift ratio computed using MPA is over-estimated and conservative comparing to the NLRHA results. CMP can calculate the drift ratio accurately for the lower levels of the structure but over-estimate the higher levels. The SPA method has the best accuracy of the drift distribution comparing to the NLRHA.

When taking into account the reasonability of the computed floor displacement, it is shown from Fig. 6 that all the computed floor displacements fall into the one standard deviation range, implying that all the pushover analysis procedures could acquire a satisfactory estimation of the floor displacement. At the same time, all the IDRs estimated by SPA are still in the one standard deviation range. Meanwhile, some IDRs estimated by the CMP and MPA procedures are further on the one standard deviation range, noting that the CPM and MPA procedures are not applicable on estimating the IDR of shear wall structures accurately.

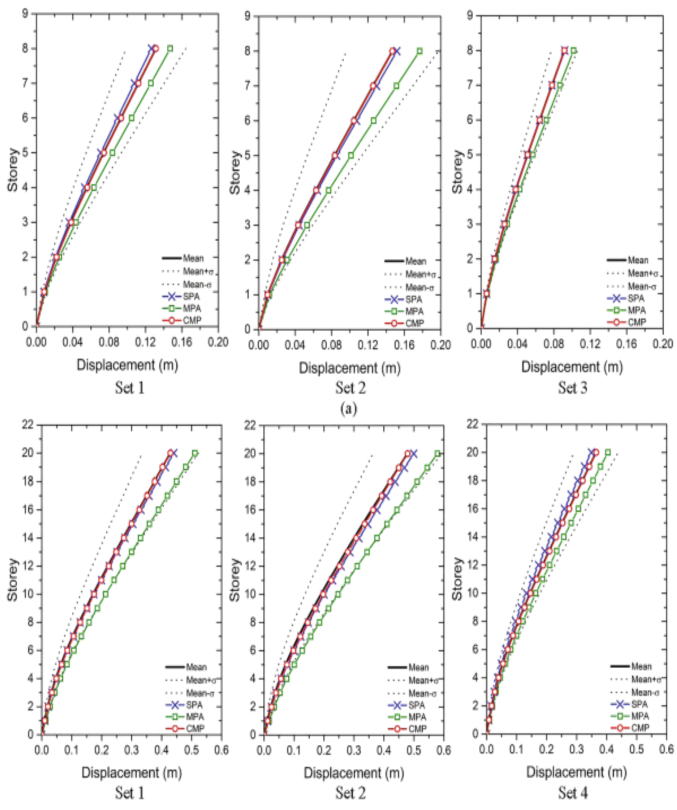

Fig. 6. Comparison of the floor displacement results

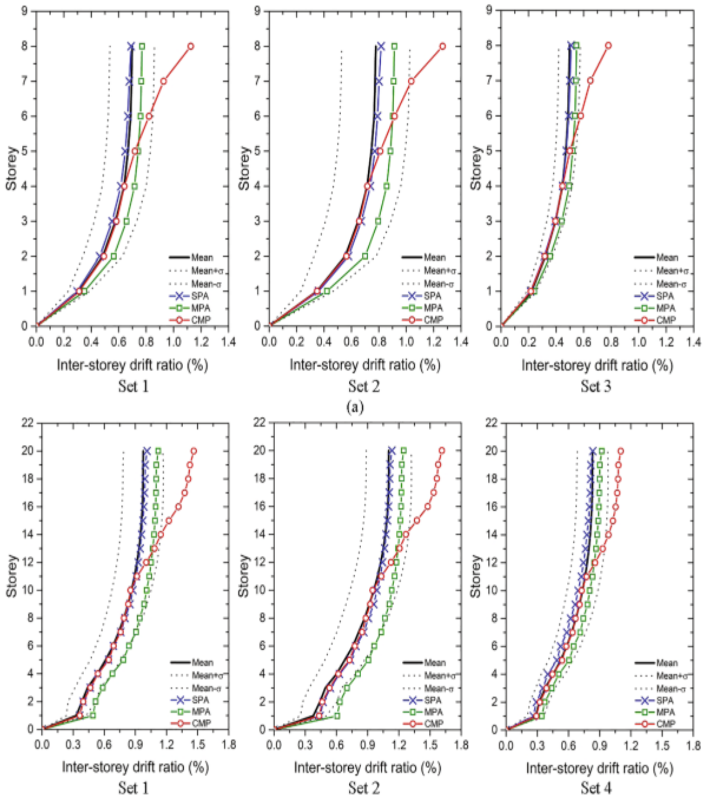

Fig. 7. Comparison of the inter-storey drift ratio results.

7. Conclusions

The pushover analysis is a very well-known tool to compute seismic demands, but it has some drawbacks when it used to compute the seismic demands for some cases and some structure systems. As a result, many methods have been developed to enhance the accuracy and the process of pushover analysis. This paper reviewed different pushover analysis methods, and made comparison of the results between them and the exact value for seismic demands such as floor displacements and inter-storey drift. A modal pushover analysis (MPA) method can provide accurate results for low-level buildings. A consecutive pushover analysis (CMP) method is more efficient for mid and high-level buildings. Displacement-based adaptive pushover (DAP) procedure, takes in consideration the contributions of higher modes. Spectrum-based pushover analysis (SPA) can overcome the drawbacks of the conventional pushover procedures and can be used for different structural systems such as RC shear wall structures. The advantage of the pushover methods is it is simple to estimate the seismic demands with satisfactory accuracy and minimum computational effort.

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9. BIOGRAPHIES

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