Comparative Assessment of Enhanced Multi-mode Pushover Analysis Methods for Performance Based Design

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Summary

Performance Based Design (PBD) is a logical design process to determine the performance of such structures where normal code-based prescriptive methods may not apply. Although Non-Linear Time History Analysis (NLTHA) has proven to be the most appropriate and reliable approach to follow, it requires considerable effort, cost and skill, which may be either not practical or justified in many cases. For such cases, Non-linear Static Pushover Analysis (NSPA) has become a popular "tool" for PBD. However, NSPA has an inherent deficiency that its invariant load distribution cannot take the higher-mode effect into consideration which may have significant effects in structures, especially mid- to high-rise buildings, slender towers and unsymmetrical structures. Several attempts had been made to develop NSPA so that the higher-mode effects can be considered. This paper investigates the effectiveness of several enhanced pushover methods in predicting the response characteristic of structures in comparison with benchmark responses obtained from NLTHA solution.

Keywords: Performance based design; Enhanced pushover analysis; Seismic evaluation.

1. Introduction

Performance Based Design (PBD) is a logical design process that will give a solution to achieve a specified performance. Nowadays, Performance Based Design has entered into mainstream use. Most Codes now incorporate a performance based design option as an alternative to its prescriptive requirements. Linear analysis is far from accurate, while nonlinear analysis is more difficult but can give rational result. For practical reasons, people may choose non-linear pushover analysis than Non-Linear Time History Analysis (NLTHA). Despite of the "exact" solution which NLTHA offered, higher computational cost compared to NSPA becomes a disadvantage of NLTHA.

However, NSPA has several inherent deficiencies. One of them is that the NSPA invariant load distribution cannot take the higher-mode effect into consideration which will take important role for structures that their behavior will be affected by higher mode (e.g. tall buildings). This issue pushed engineers to develop enhanced pushover procedures that can consider higher-mode effects.

Attempts had been made to develop NSPA so that the higher-mode effects can be considered, especially for the tall building cases. A number of these procedures considered different loading vectors that might be determined form mode shape. Others use the adaptive pushover procedures where the loading vectors keep changing progressively due to the change of the structure during inelastic phase. This procedure calculates the load vector using the instantaneous mode shapes at each pushover step.

2. VARIOUS METHODS

Pushover Analysis method can be categorized into three major groups based on how they analyze the structure (lateral load vector). The groups are Single Mode Pushover Analysis Method (SMPAM), Simple Pushover Analysis Method (SPAM), and Multi-mode Pushover Analysis Method (MMPAM).

2.1. Single Mode Pushover Analysis (SMPAM)

Pushover Analysis can be done using the mode shape of the structure as the pattern of its lateral loading vector. The most common mode shape that is used as lateral loading vector for analysis is the elastic first mode shape (fundamental mode shape) of the structure.

However, these single mode load distributions are inadequate when higher-mode (mode higher than the fundamental mode) of the structure significantly contributes to the response of the structure.

2.2. Simple Pushover Analysis (SPAM)

Simple Pushover Analysis uses simple lateral load vector distribution. Two types of this loading vector are uniform distribution and equivalent lateral force. FEMA-273 determined the uniform distribution as $s^*_i = m_i$, in which m_i is the mass at *i*-th floor, and s^*_i is the lateral force at *i*-th floor.

The second type is the equivalent lateral force (ELF) distribution. Based on FEMA-273, ELF can be obtained as $s_i^* = \left(m_x h_x^k\right) / \left(\sum_{i=1}^{N} m_i h_i^k\right)$, where the exponent $k=1$ for $T_1 < 0.5$ sec (fundamental period), $k=2$ for $T_1 > 2.5$ sec and linear interpolation shall be used for values in between, h_i and h_x are heights from the base to *i*-level floor and *x*, respectively.

2.3. Multi-mode Pushover Analysis (MMPAM)

In order to solve the problem of the structure which higher-mode effects are important, a number of enhanced procedures which account for the higher-mode effects have been proposed. Most of the current proposed methods have similarity with each other. They can be categorized into four groups based on how they determine the lateral loading vector and also how they obtain the seismic demands of the structures (results). The groupings are as follows:

1. Modal Combination for Loading (MCL)
2. Modal Combination for Response (MCR)
3. Consecutive Modal Pushover Analysis (CMPA)
4. Adaptive Modal Pushover Analysis. (AMPA)

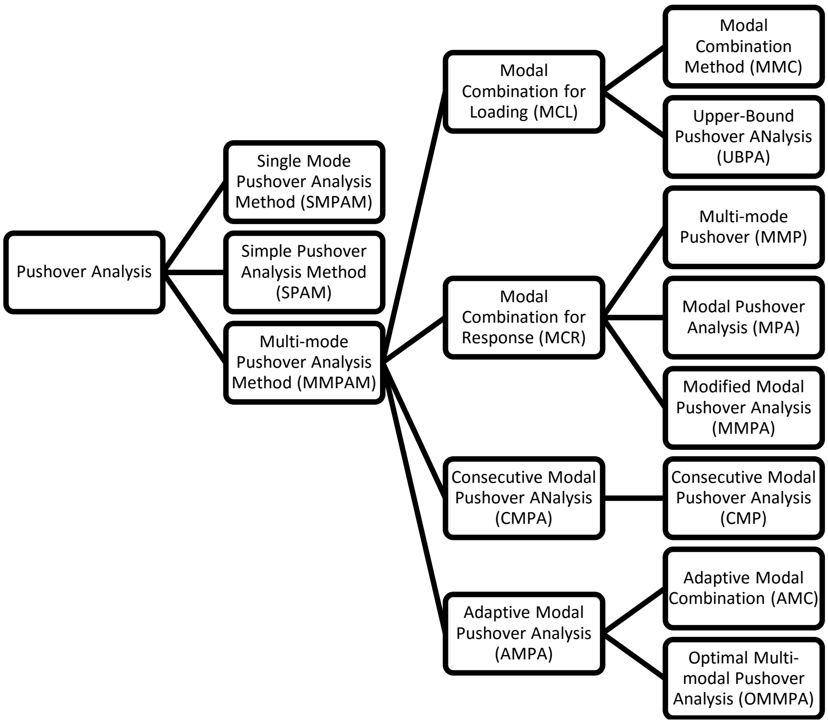


Figure 1: Category of Pushover Analysis Method

3. Methodology

This study will explore the ability of the current enhanced pushover procedure to simulate the structure's performance and seismic demands. A set of RC structures will be analyzed. The effectiveness of each method in the particular type of structure will be investigated in this study.

The methods that will be compared are Modal Pushover Analysis (MPA), Consecutive Modal Pushover (CMP), Upper-bound Pushover Analysis (UBPA) and also Simple Pushover Analysis (SPA) Method. All of those methods will be compared with the "benchmark" solution from NLTHA.

3.1 Modal Pushover Analysis (MPA)

Modal Pushover Analysis (MPA) that has been recently developed by Goel and Chopra, 2001 [1], is an improved pushover procedure which take into account higher-mode effect in analyzing seismic demand while retaining the simplicity of the loading pattern in pushover analysis. MPA utilizes the concept of modal combination through several pushover analyses using invariant loading distribution vector based on the elastic modes of the structure. The response of each pushover analysis is being combined use SRSS or CQC combination rule to get the total response of the structure.

3.2 Consecutive Modal Pushover (CMP)

Consecutive Modal Pushover (CMP) has been proposed by Poursha et.al., 2009 [2]. This method uses a single-stage and multi-stage pushover analysis. The multi-stage pushover analysis is conducted using an advantage of the consecutive implementation of MPA procedure. When one stage of the modal pushover analysis has been performed, then the next stage (another modal pushover analysis) begins with an initial state (stresses and deformations) from the end state condition of the previous stage.

CMP procedure is carried out with the various loading pattern based on the modal properties of the linearly elastic structure. The changing in the modal properties of the structure in the inelastic phase during the pushover analysis is ignored. The number of the mode that has to be considered in this method depends on the fundamental period of the structure. If the fundamental period of the building (using moment-resisting frame system) is less than 2.2 second, then two stages of the multi-stage pushover analysis has to be carried out. If the fundamental period is 2.2 second or more, then both two and three-stages pushover analysis has to be performed.

It is notable that the response (nonlinear behavior) of the structure depends on the loading path, the loading input and the structural response cannot be separated. Consequently, the Modal Pushover procedure must be carried out consecutively in the CMP procedure for each stage from first mode to higher mode.

3.3 Upper-bound Pushover Analysis (UBPA)

Upper-bound Pushover Analysis (UBPA) first proposed by Jan et.al, 2004 [3] determined the distribution vector of the lateral loads over the height of the building by combining effects of the first and second mode.

4. Structural System and Analytical Model

The structural systems that will be used in this study is a 20- building. The floor plan and elevation view of the structural systems in this study are shown in Figure 2. Nonlinearity in the frame section will be carried out by defining hinge properties of each member. Fiber modeling will be used in modeling nonlinearity of the shear wall section.

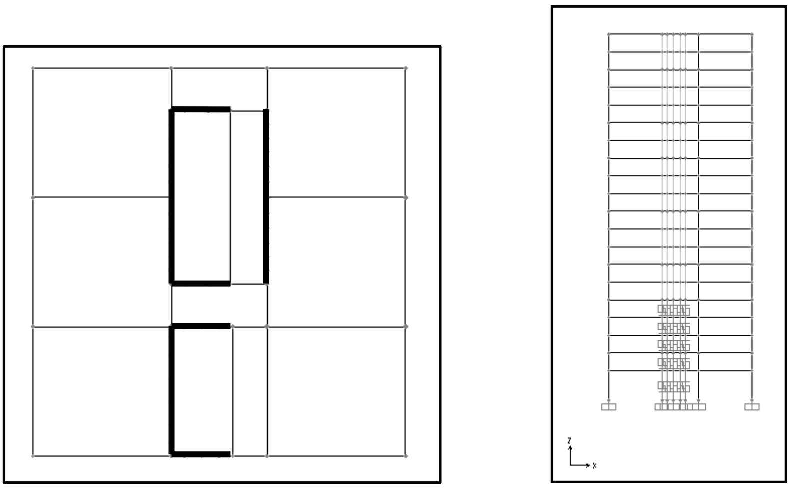
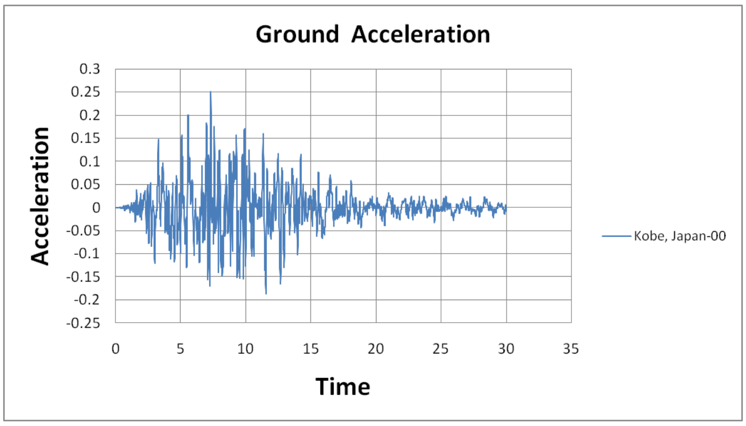


Figure 2: Floor plan and elevation view of the structures

The computer program that will be used in this study is SAP2000 v.14.1.0 program [4]. This computer program will be used for all the analysis that will be done in this study.

In order to obtain the “benchmark” result, Nonlinear Time History Analysis was conducted. Kobe Earthquake ground motion was selected for the analysis. To facilitate a rational basis for comparing different method’s procedure, the ground motion records were scaled so that it will be matched the UBC’97 response spectrum (Z=2.00, Soil Profile D). Figure 3 shows the modified ground motion.



Earthquake Name	Kobe, Japan
YEAR	1995
Earthquake Magnitude	6.90
EpiD (km)	24.20
Preferred NEHRP Based on	D
Preferred Vs30 (m/s)	312.0
PGA (g)	0.2668
PGV (cm/sec)	21.66
PGD (cm)	7.60

Figure 3: Modified Kobe Earthquake Ground Motion Detail

5. Evaluation of nonlinear static procedures

To compare all methods that will be observed in this study (NLTHA included), a number of parameter will be selected. The results from NLTHA analysis will be presented in two values, minimum and maximum. The response evaluation parameters which were selected to analyze the structural system are as follows:

(1) **Story drift of the structure**. Story drift is the lateral displacement that occurs in a single story of multistory building. Story drift can be obtained as the relative drift between two consecutive stories normalized by corresponding story height.

The results from NLTHA analysis will be presented in two different values, minimum in negative (-) and maximum in (+) value. Minimum (-) value that presented is the absolute value so that it can be compared with other methods. UBPA method can give quite similar response compared to NLTHA (+). CMP method seems to over-estimate upper story and under-estimate bottom story drift profile. MPA method gives good results for the bottom story drift profile compared with NLTHA (-) but overestimates it at the upper storey. Figure 4 shows the inter story drift ratio obtained with each methods.

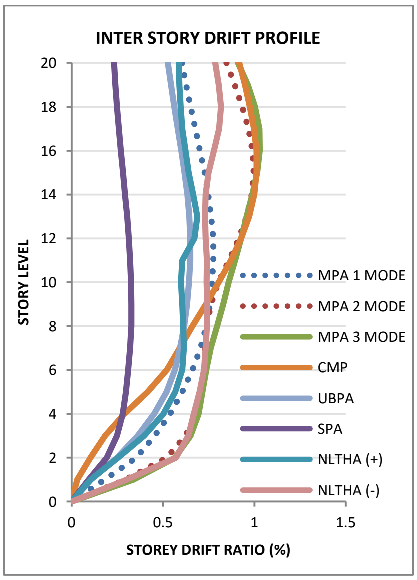


Figure 4 : Inter story drift profile

(2) **Lateral displacement of the structure**. To find the behavior of the structure when it is subjected to the lateral loading can be observed from its lateral displacement.

All methods can give reliable estimation for displacement profile. MPA, UBPA give close results to the NLTHA. Only SPA underestimates displacement value of the structure. Figure 5 shows the peak displacement profile of the structure obtained with each procedure.

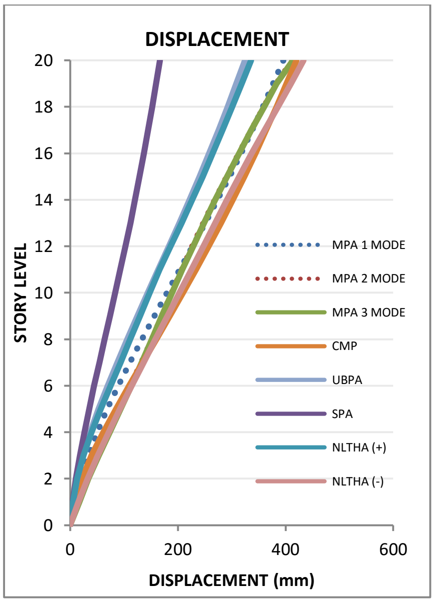


Figure 5 : Displacement profile

(3) **Member hinge plastic rotation**. Member hinge plastic rotation of the analyzed frame members can determine the structure failure mechanism. Hinge properties of the members are calculated based on the design of the structure.

From the results shows in Figure 7, UBPA underestimates column hinge plastic rotation, in the other hand, CMP overestimates it. Beam hinge plastic rotation was estimated closely by UBPA and CMP method at the bottom floor, but for the top floor, CMP overestimated it while UBPA underestimated it. MPA can predict closest results among other methods for both column and beam plastic hinge rotation value. Figure 6 shows the location of the investigated beams and columns.

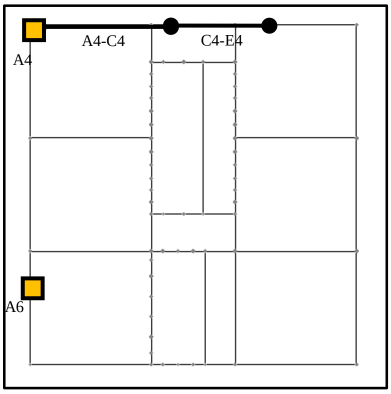


Figure 7 : Location of investigated beams and columns

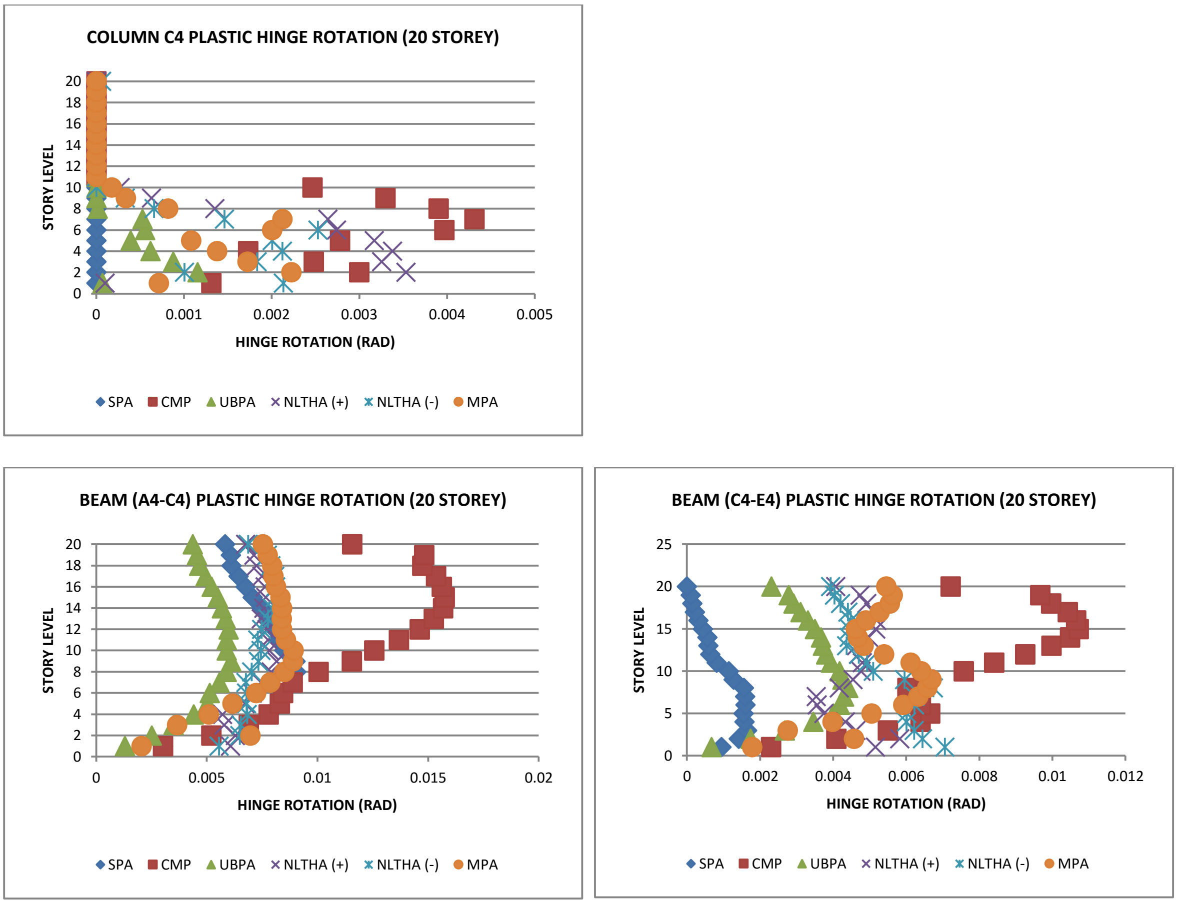


Figure 7 : Beam and column plastic hinge rotation

(4) **Base Shear**. Total Base Shear of the structure is compared to verify the accuracy of each method. Pushover methods cannot estimate total base shear of the structure well because NLTHA includes all modes of the structure with its complexity while Pushover Analysis method has limitation in including higher-mode effect because of many difficulties. CMP and MPA give considerable estimation of the total base shear of the structure. Figure 8 shows total base shear of the 20-storey building.

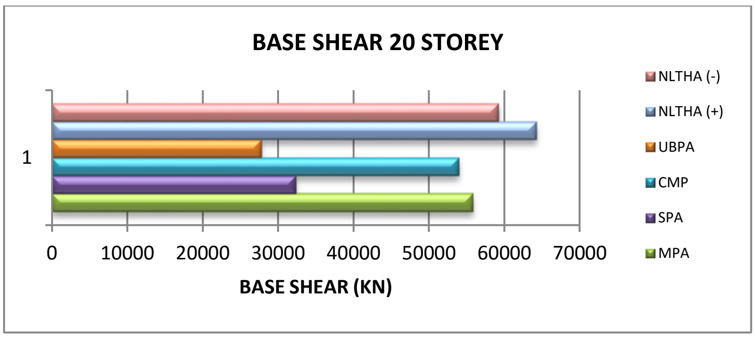
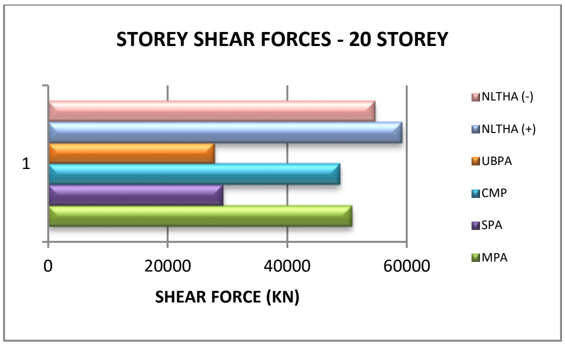


Figure 8 : Total Base Shear of 20- and 50-storey Building

(5) **Story Shear Force and Shear Wall Shear Force**. To find out how much shear wall takes part in resisting the lateral forces when the structure is analyzed, shear force in shear wall must be estimated and compared to the story shear force. In this study the results below was taken for the 2nd level of the structure. Only CMP and MPA method seem can give reliable

estimation while the others cannot predict well. Figure 9 shows comparison of Story shear forces and Shear wall forces of 20-storey building.



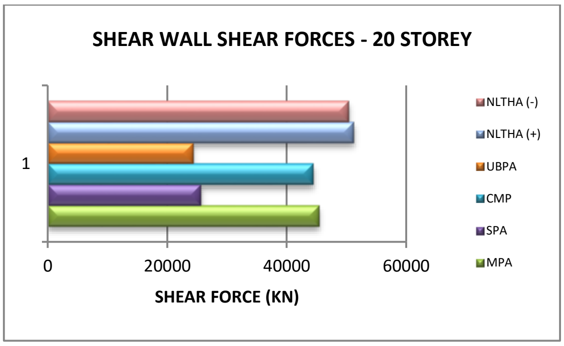


Figure 9 : Story Shear and Shear Wall Shear Force

(6) **Shear Wall Stress-Strain.** In this study, shear wall in the structure was modeled using fiber-modeling technique (Location of the nonlinear-links is shown at Figure 10). To find out whether it already yielded or not, stress and strain of the fiber should be investigated. The stress-strain yield point of concrete ((-) sign) is 49(MPa)-0.002, and the stress-strain yield point of concrete ((+) sign) is 400(MPa)-0.0047. No shearwall has reach yield point for all methods. Only CMP method can predict close value of stress and strain of shearwall compared to NLTHA. MPA results cannot be obtained because the results for each mode cannot be combined. Different loading direction (+ or -) will affect which fiber will take compression/tension side, concrete will take main part in compression force while tension force will be taken by steel. If *n*th-mode analysis has opposite loading direction, then stress and strain result cannot be combined with the other mode result in MPA. Figure 11 shows shearwall stress and strain value for different methods.

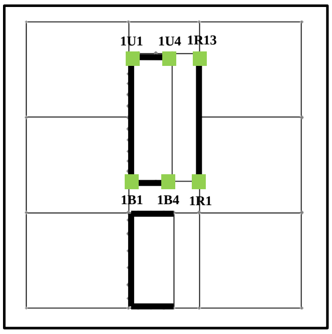
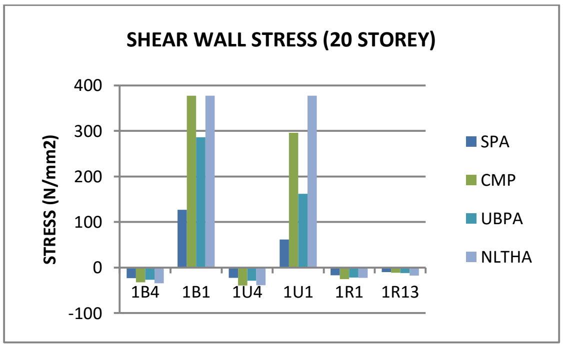


Figure 10 : Location of Nonlinear- links



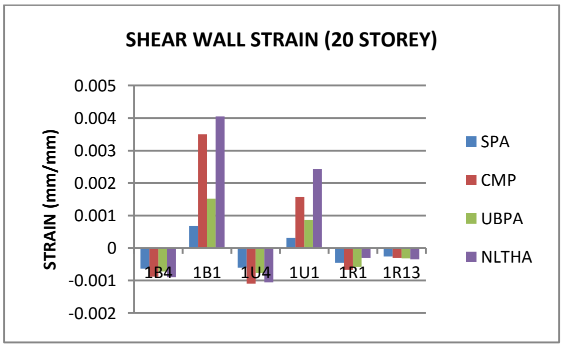


Figure 11 : Shear Wall Stress and Strain

6. Conclusions

Attempts have been made to include higher-mode effect to the Pushover Analysis method so that it can obtain reliable results. This study compared all 3 methods (CMP, MPA and UBPA) that include higher-mode effects to the analysis and compared to the Simple Pushover Analysis (SPA) and also “benchmark” result from NLTHA. Research has been conducted and led to the following conclusions:

(1) Enhanced Pushover Analysis methods that have been studied in this research tend to be conservative in giving displacement value and story drift ratio of the structure compared to the NLTHA.
(2) To predict frame hinge plastic rotation value of the structure, the best overall methods is MPA. CMP tends to overestimate it, while UBPA underestimate it.
(3) To obtain total base shear, story shear force, and shearwall shear force, only MPA and CMP can give reasonable results compared with NLTHA. Other methods underestimate total base shear value, story shear force and shearwall shear force.
(4) The Pushover methods tend to give reasonable results for overall structural response and deformations, but are less reliable for determining the local response of members.

Based on the results and analysis of the investigated methods, it can be concluded that enhanced pushover analysis methods can be used to evaluate particular response (displacement, drift, base shear, story shear force, shearwall shear force) of the structure although some of the results cannot give conservative results compared to NLTHA.

7. References

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