TheEffects ofMultimode Load Pattern on Pushover Analysis to EstimateThe Seismic Demandsfor Symmetric Steel Building Frames

Rahmita Sari R[1]
Sumargo[2]

[1, 2] Staff Pengajar Jurusan Teknik Sipil, Politeknik Negeri Bandung,
Jln. Gegerkalong Hilir, Ds Ciwaruga, Bandung, Telp dan fax (022) 2013789 dan 2013788
E-mail[1]: rahmitasari@yahoo.com
E-mail[2]: sumargo2004@yahoo.com

Abstract

To take into account higher-mode effects in pushover analysis for estimating the seismic demands of high-rise building structures, the multimode load pattern (MLP) procedure has been proposed. The multimode load pattern analyses were carried out with the force distributions using mode-shapes obtained from Eigen-analysis of linearly elastic structure and the pushover analysis were done consecutively, such that first mode pushover analysis has performed, the next mode begins with the initial structural stage (stress and deformation) which is the same as the condition at the end of previous stage. Predictions based on single mode and response spectrum analysis procedures were also presented for the sake of comparison to those obtained by the MLP procedure. The implication of using multimode and single mode in MLP analysis, the higher modes in the MLP analysis strongly affect the responses at the mid and upper storey of tall building structures, contrary to the lower storey thus gives better prediction of storey drift and plastic hinge for mid and upper storey. From the comparison to each capacity curves in term of analysis procedure performance, MLP gives better results to describe the structure performance in handling earthquake force.

Keywords : multimode load pattern, pushover analysis, seismic demands.

I.INTRODUCTION

Both structural damage and nonstructural damage sustained during earthquake ground motions are primarily produced by lateral displacement demands. While nonlinear response history analysis (NL-RHA) is the most rigorous procedure to compute seismic demands, current civil engineering practice prefers to use nonlinear static procedures (NSP) based on pushover analysis (POA). POA essentially developed from response spectrum analysis (RSA). POA is controlled by the fundamental vibration mode of the structure, and the mode shape remains unchanged after the structure yields. Obviously, the POA does not account for the contribution of higher modes to the structural response; therefore it is difficult to apply to high-rise buildings in which higher-mode contributions to the response are important. The main objective of the present study is therefore to propose and investigate the multimode load pattern (MLP) which can take into account higher-mode effects in the POA of tall buildings and can improve estimates of seismic demands mainly storey drift ratio, plastic hinge rotation and displacement.

1.METHODOLOGY

To demonstrate applicability and effectiveness of the MLP, the procedure has been applied to symmetric multistory three-dimensional steel building frames. The structures considered were three-bay frames with four different heights of 10, 15, 20, and 30 storey, covering a wide range of fundamental periods. The frame structures were 5 m bays and a storey height of 3.2 m. The structures were assumed to be founded on type `IV' soft soil of the Indonesian seismic code (SNI 03-1726-2002), and located in the region of highest seismicity. The MLP analyses are carried out using force distributions according to the mode-shapes obtained from Eigen-analysis of linearly elastic structure and the POA were done consecutively in the order of modes, from the first to the higher ones. Changes in the modal properties of the structure are ignored when the structure experiences nonlinear yielding under increasing lateral loads during POA. Predictions based on RSA and single mode (SM) procedure are also presented for the sake of comparison to those obtained by the MLP procedure.

The MLP procedure can be used to estimate the peak response of inelastic structure subjected to earthquake excitation. The MLP analysis benefits from consecutive implementation of modal pushover analyses, including a limited number of modes, such that first mode POA has been completely performed, the next mode POA begins with the initial structural stage (stress and deformation) which is the same as the condition at the end of previous stage. It is noted that the nonlinear version of the computer program ETABS was used to perform these analyses.

1.MODAL RESPONSE ANALYSIS

To develop a pushover analysis procedure consistent with RSA, we observe that static analysis of the structure subjected to lateral forces:

$$\mathbf{f}_{no} = \Gamma_n \mathbf{m} \phi_n A_n \qquad (3.1)$$

will provide the same value of r_{no}, the peak n*th*-mode response, where can be obtained from the earthquake response spectrum or design spectrum.

$$r_{no} = r_n^{st} A_n \qquad (3.2)$$

wherein $A_n = \omega_n^2 D_n$

Alternatively, this response value can be obtained by static analysis of the structure subjected to lateral forces distributed over the building height according to:

$$\mathbf{s}_n^* = \mathbf{m}\phi_n \qquad (3.3)$$

with the structure pushed to the roof displacement, u_{rno}, the peak value of the roof displacement due to the n*th*-mode.

$$u_{rno} = \Gamma_n \phi_{rn} D_n(t) \qquad (3.4)$$

In MLP procedure, the dynamic response due to next modes (next fundamental mode) under the assumption that the roof displacement for the next mode is equal to $u_{r1}+u_{rg}$ and for the next mode roof displacement is assume equal to $u_{r1}+u_{r2}+u_{rg}$. It is noted that the initial condition at each stage of the analysis is the same as the state at the end of the analysis in the previous stage. The peak modal responses r_{no}, each determined by one pushover analysis, can be combined according to the square-root-of-sum-of-squares (SRSS) to obtain an estimate of the peak value r_o of the total response:

$$r_o \approx \left(\sum_{n=1}^{N} r_{no}^2 \right)^{1/2} \qquad (3.5)$$

The peak response in each mode is squared, the squared modal peaks are summed, and the square root of the sum provides an estimate of the peak total response.

2.PUSHOVER LOAD PATTERN

For *n*th mode, develop the base shear-roof displacement, $V_{bn} - u_{rn}$, and pushover curve for force distribution, $\mathbf{s}_n^* = \mathbf{m}\phi_n$, where **m** is the mass matrix of the structure. These lateral force distributions for the first three-modes are shown schematically in **Figure 1** for 10 and 15 storey and **Figure 2** for 20 and 30 storey.

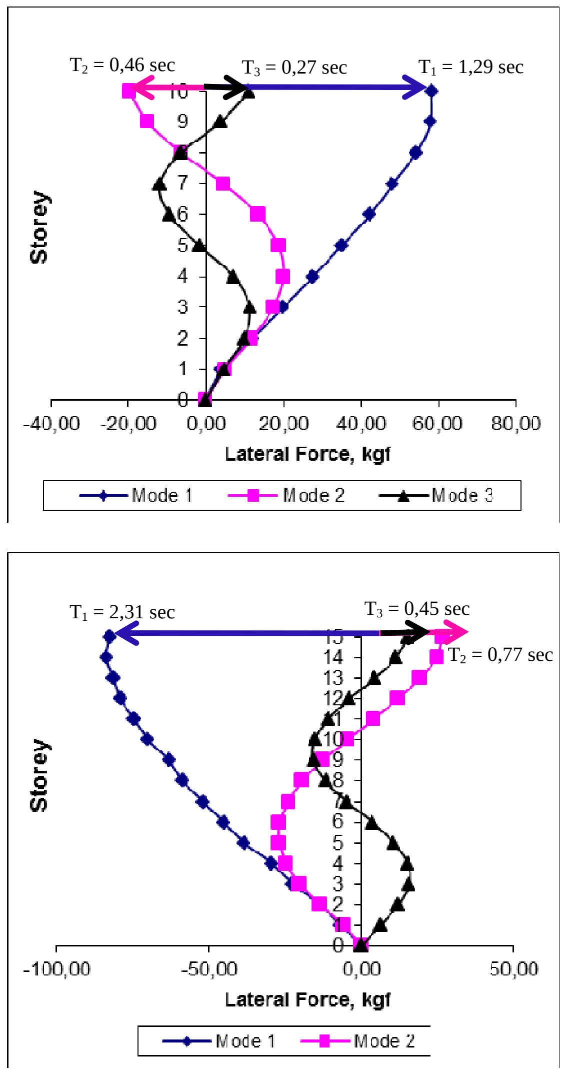


Figure 1. Distribution of lateral forces $\mathbf{s}_n^* = \mathbf{m}\phi_n$ of10 and 15 storey for the first three natural-vibration periods

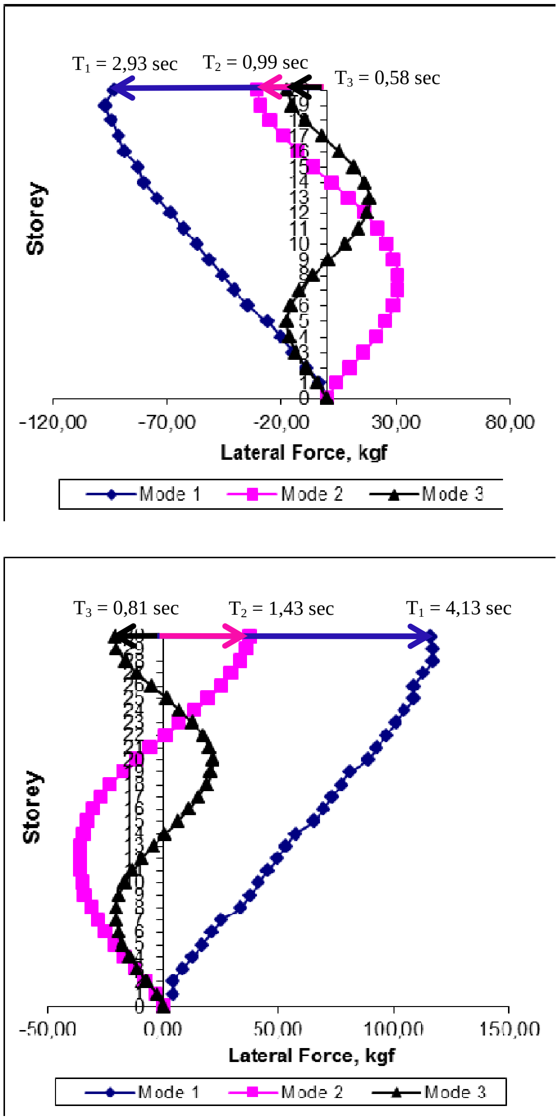


Figure 2. Distribution of lateral forces $s_n = m\phi_n$ of 20 and 30 storey for the first three natural-vibration periods

1.RESULTS AND DISCUSSIONS

As explained earlier, the seismic demands such as storey drift ratio, plastic hinge rotation and displacement in the MLP procedure are obtained by enveloping the peak responses from the multi-mode pushover analyses.

1.1 Storey Drift Ratio

For a yielding structure, the occurrence of structural damage is closely related to storey drift. The reduction of drift protects the structural components and elements, as well as non-structural components which are sensitive to drift-induced damage.Drift (also known as storey drift), as one of seismic demands, is the lateral displacement (deflection) of one floor relative to the floor below and the story drift ratio is the story drift divided by the height (floor to florr) of the story. Excessive drift can be accompanied by large secondary bending moments and inelastic behavior.

The distributions of storey drifts over the height of a multistory frame depend on plastic hinge mechanism and on how far the frame deforms into the inelastic range. In inelastic behavior, the storey drift increase at the upper stories of elastic frame, where the response contributions from higher vibration modes are known to be significant. It's demonstrated in **Figure 3** and **Figure 4** as well.

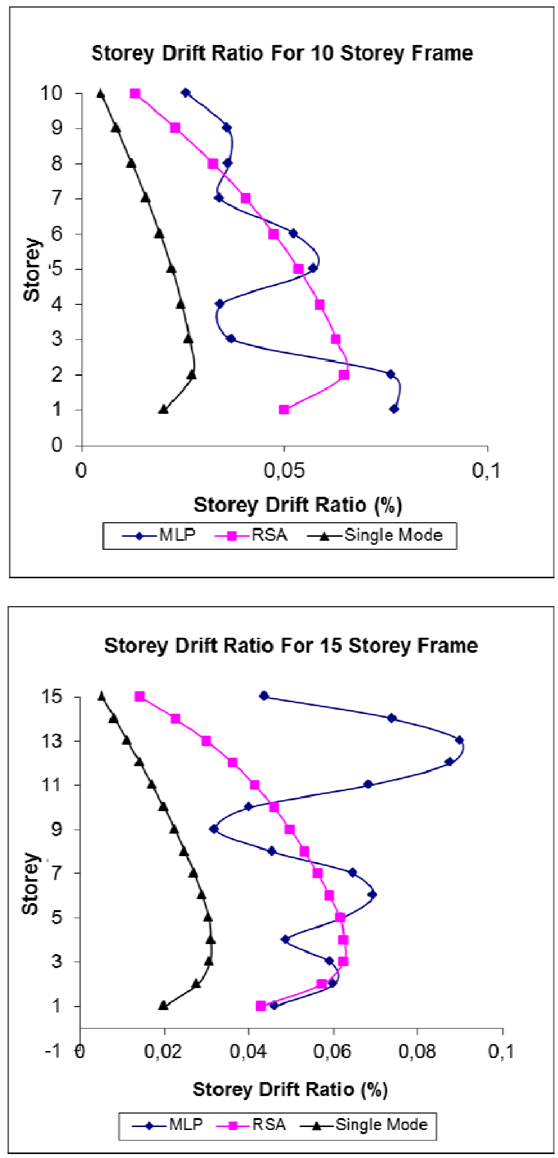


Figure 3. Height-wise variation of the storey drifts ratio for 10 and 15 storey

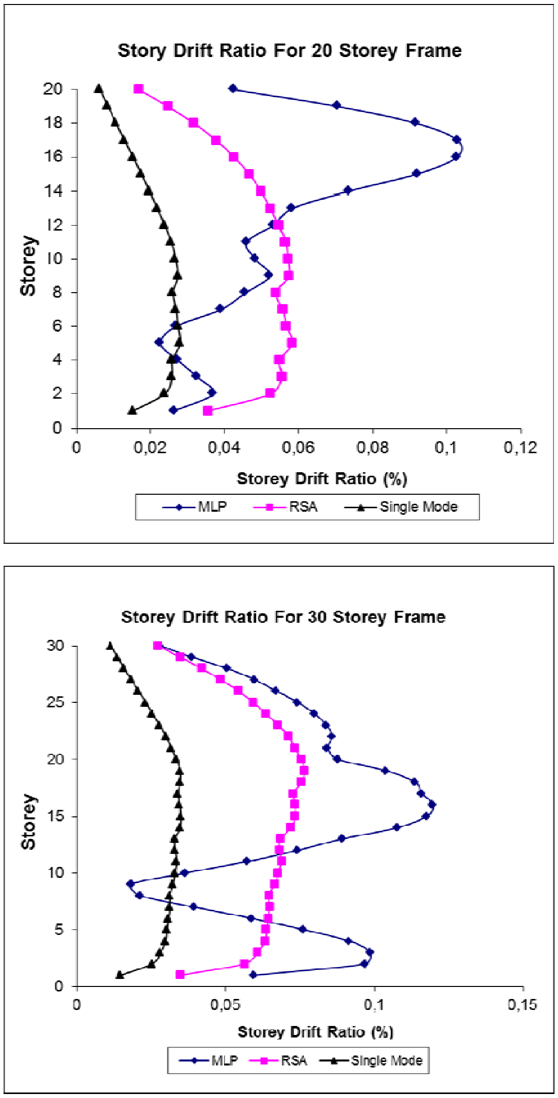


Figure 4. Height-wise variation of the storey drifts ratio for 20 and 30 storey

The implication of using multi-mode and single-mode in MLP analysis, as could be expected; the single mode (SM) pushover analysis and response spectrum analysis (RSA) control the storey drift demands only at the lower storey. The storey drift at the mid and upper storey in the other hand are controlled by two and three stage modal pushover analyses because the higher modes in the MLP analysis strongly affect the responses at the mid and upper storey, contrary to the lower storey.

The distributions of storey drifts over the height of a multistory frame depend on plastic hinge mechanism and on how far the frame deforms into the inelastic range. In inelastic behavior, the storey drift increase at the upper storey of elastic frame, where the response contributions from higher vibration modes are known to be significant.

1.2 Plastic Hinge Rotations

A plastic hinge is a type of energy damping device allowing plastic rotation (deformation) of an otherwise rigid column connection. In structural engineering beam theory, the term of plastic hinge, is used to describe the deformation of a section of a beam where plastic bending occurs.

It is necessary to calculate the end moments of every structure member, like beam segment, to check whether or not a plastic hinge has formed. The calculation is done using the element incremental moment-displacement relationship. The plastic hinge is free to rotate in one direction only, and in the other direction the section returns to an elastic behavior.

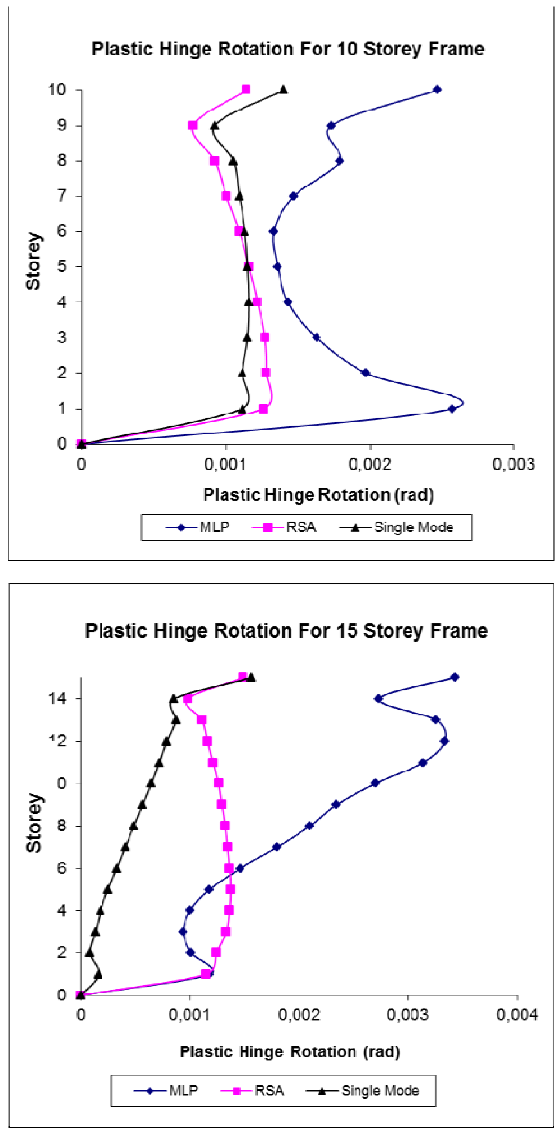
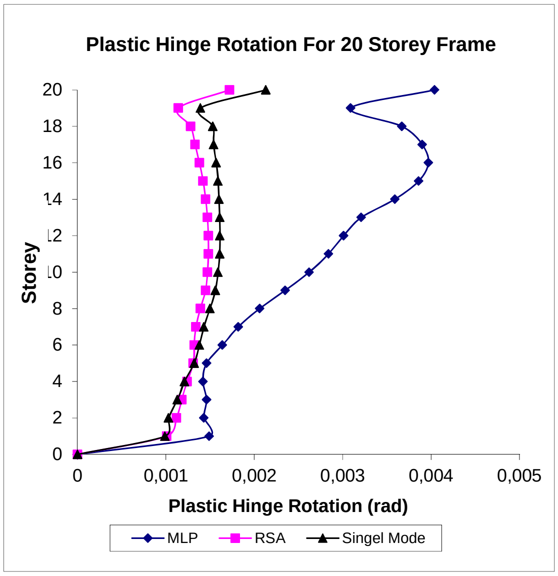


Figure 5. Plastic hinge rotation for 10 and 15 storey frame



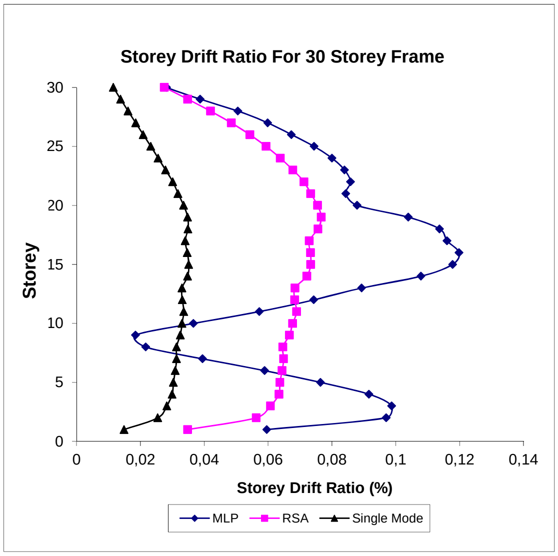


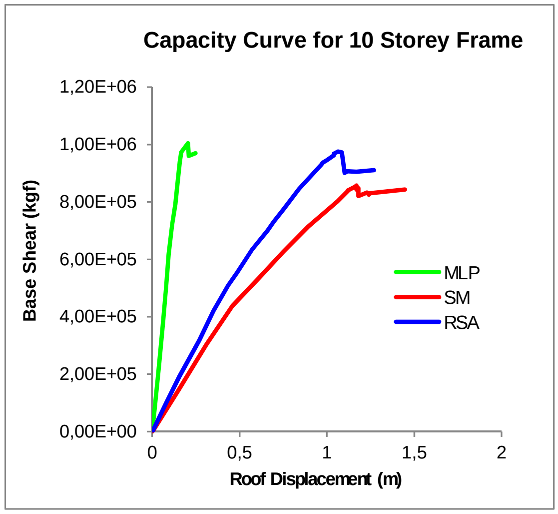
Figure 6. Plastic hinge rotation for 20 and 30 storey frame

Figure 5 and **Figure 6** show the plastic hinge rotation resulting from pushover analyses in MLP, as well as from SM and RSA procedures for 10-15 and 20-30 storey frame.As shown in plastic hinge rotation figures, MLP control the plastic hinge rotations especially at the mid and upper floors. At some lower floor levels, the MLP procedure tends to slightly overestimate the plastic rotation of the hinges compared to other procedures.At some lower floor levels, the MLP procedure occasionally provides better estimates of plastic hinge rotations than the other procedure, and vice versa. Also, the MLP procedure tends to slightly overestimate the plastic rotation of the hinges at some lower floor levels.

The consecutive implementation of modal pushover analysis means that rotations of the plastic hinges are continuously accumulated at mid and upper floor level during the modes of interest in MLP analysis, while other method procedure attempts to estimate the total response quantities by combining the individual peak responses obtained separately from each mode.

1.3 Capacity Curve

In pushover analysis simulation all structures were being push until displacement on the roof was equal as 0.04 of the total building height or until first critical plastic hinge rotation was formed in the structure.The curves in **Figure 7** and **Figure 8** depicted in the figures defined as relationships between the lateral load-carrying capacity (or base shear) and the roof displacement of the building for 10-15 and 20-30 storey.



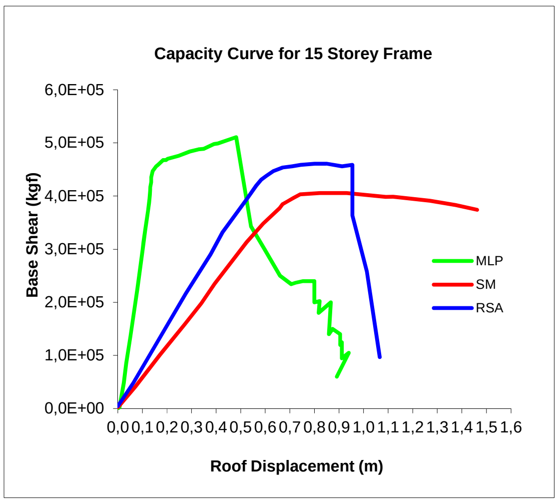
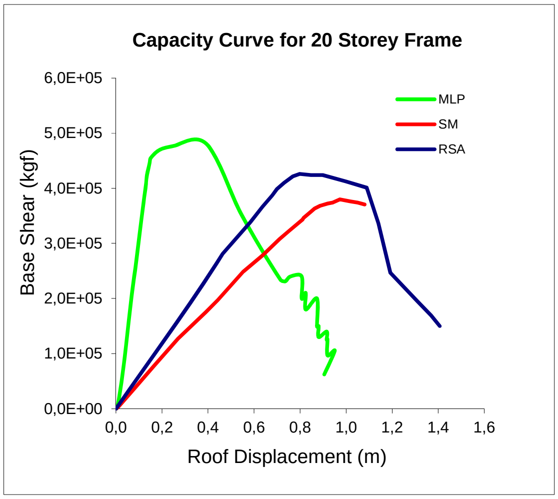


Figure 7. Capacity curve for for 10 and 15 storey frame



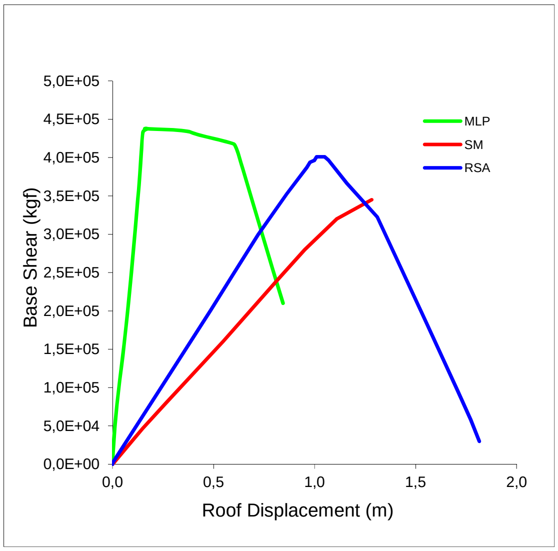


Figure 8. Capacity curve for for 20 and 30 storey frame

Capacity curve resulted from MLP procedure [see in **Figure 7** and **Figure 8**] shows ductile behavior where there is an elastic range followed by a plastic range with non-negligible residual strength and ability to support gravity loads. The plastic range includes a strain hardening or softening range and a strength-degraded range. Different for 30 storey analysis, capacity curve shows that the structure experiencing ductile behavior where there is an elastic range and a plastic range followed by loss of strength and loss of ability to support gravity loads.

The MLP distribution generally leads to pushover curve with higher elastic stiffness, higher yield strength, lower yield displacement, and more rapid decay in post-yield lateral capacity compared to other distributions.

The RSA distribution, on the other hand, leads to pushover curve with lower elastic stiffness, lower yield strength, higher yield displacement, and a more gradual decay in post-yield lateral capacity.

2.CONCLUDING REMARKS

The implication of using multimode with consecutive manner in multimode load pattern analysis, Its show that the higher modes in the MLP analysis strongly affect the responses at the mid and upper storey of tall buildings, contrary to the lower storey. From the comparison to each capacity curves in term of analysis procedure performance, MLP also can describe structure performance in handling earthquake force.

As the preliminary study, It is demonstrated that the MLP procedure is able to predict the structure respond to the earthquake excitation for mid and upper storey.

In order to confirm the conclusion above with greater certainty, the MLP procedure should be verified for different lateral force-resisting system, reinforced concrete buildings, and variety of ground motion sets.

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