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Performance Based Seismic Design of High-rise Setback Structures

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Abstract—*In this twenty first century the globe of infrastructural development moving towards the architectural demands, this leads to irregularities in high-rise building. The most common type of vertical irregularities called as setback buildings. The setback buildings causes sudden jump in earthquake. Vertical irregularity arises in the building due to the significant changes in stiffness and strength. Setback is an example of an extreme case of vertical irregularities. Setback buildings with geometric irregularities (both plan and elevation) are now increasingly encountered in modern urban construction. In past major earthquakes it is noticed that the seismic risk in urban areas is increasing and the infrastructure potential is far from socio-economical tolerable levels. A performance based seismic design technique is a promising way used for various purposes such as seismic evaluation of large structures, design verification of new constructions, evaluation of an existing structures to identify damage states for various amplitudes of ground motions. The performance of such buildings under seismic excitations can be improved by providing lateral load resisting systems. In this paper seismic performance of high-rise setback buildings are evaluated. Performance and hinge formation pattern of high-rise setback buildings are studied. Pushover analysis is the important tool used in performance based seismic deign. To quantify the performance of structure different parameters have been used such as pushover points, performance points, base shears, roof displacements, storey drifts, number of hinges formed. The performance of building is assessed as per procedure prescribed in ATC-40 and FEMA-356. Present study aims towards nonlinear static pushover analysis and nonlinear time history analysis of (G+19) storied R.C.C. frame buildings subjected to earthquake. The objective of this paper is to evaluate the nonlinear behaviour of the high-rise building having setbacks by nonlinear static pushover analysis and time-history analysis and to evaluate the accuracy and effectiveness of these methods.*

Keywords*: Base shears, Nonlinear Time-History analysis, Pushover analysis, Performance point, Plastic hinges.*

1. INTRODUCTION

The newly designed concept performance based seismic Design is the future direction to the seismic design code. Performance based seismic design predicts how building will perform in the given earthquake. Pushover analysis is the tool used in performance based seismic design to assess the seismic demand of building.

In 2006, FEMA published FEMA 445, next generation Performance-Based Seismic Design Guidelines. The performance-based design process explicitly evaluates how building systems are likely to perform under a variety of conditions associated with potential hazard events. The process takes into consideration the uncertainties inherent in quantifying the frequency and magnitude of potential events and assessing the actual responses of building systems and the potential effects of the performance of these systems on the functionality of buildings. Identifying the performance capability of a facility is an integral part of the design process and guides the many design decisions that must be made. Performance-based design starts with selecting design criteria articulated through one or more performance objectives. Each performance objective is a statement of the acceptable risk of incurring different levels of damage and the consequential losses that occur as a result of this damage.

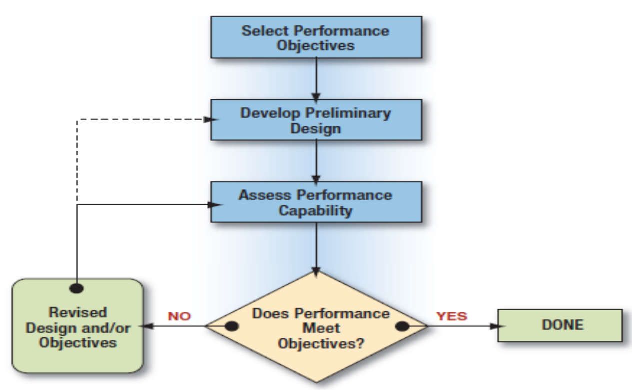

Fig. 1: Performance-based design flow diagram

These performance levels are summarized in a matrix (Table No-1) and allow specification of an overall performance level by combining the desired structural performance with a desired nonstructural performance. "Mild" is similar to Operational (1-A); "Moderate" Is similar to Intermediate Occupancy (1-B); "High Impact" is similar to Life Safety (3-C); and "Severe" is similar to Collapse Prevention (5-C).

Table 1: Combinations of structural and nonstructural seismic performance

Nonstructural Performance Levels	Structural Performance Levels and Ranges					
	S-1 Immediate Occupancy	S-2 Damage Control Range	S-3 Life Safety	S-4 Limited Safety Range	S-5 Collapse Prevention	S-6 Not Considered
N-A Operational	Operational 1-A	2-A	Not Recommended	Not Recommended	Not Recommended	Not Recommended
N-B Immediate Occupancy	Immediate Occupancy 1-B	2-B	3-B	Not Recommended	Not Recommended	Not Recommended
N-C Life Safety	1-C	2-C	Life Safety 3-C	4-C	5-C	6-C
N-D Hazards Reduced	Not Recommended	2-D	3-D	4-D	5-D	6-D
N-E Not Considered	Not Recommended	Not Recommended	Not Recommended	4-E	Collapse Prevention 5-E	No Rehabilitation

Goel and Chopra [1] evaluated the MPA procedures for code designed buildings to estimate the seismic demand of structures, the conclusion derived from the study is MPA is the improved procedure of analysis. For elastic range, MPA has been proven consistent with Response History Analysis. Chopra and Chintanapakdee [2] evaluated that FEMA invariant load distributions are systematically based in predicting storey drift when compared to accurate NTH analyses results, this paper observed the accuracy of recent Adaptive Modal Combinations procedures to estimate demand parameters in setback structures. Devesh Soni and Misty [3] focused on the seismic behavior of vertically irregular structures with their limitations given in building code. They showed that the increase in drift demand in the tower portion of setback structures with increase in seismic demand for irregular distribution of mass, stiffness and strength. Kappos [4] investigated a new inelastic response history analysis for RC irregular building with setbacks and their performance for different levels of earthquakes. A.R.Akhare and S.S.Bhende [5] studied the seismic performance of setback structures by pushover analysis and concluded that, due to higher modes effects setback buildings needs advanced non linear static pushover analysis i.e. modal pushover analysis. This is because, if number of storey increases, the higher mode effects will become important part in analysis.

2. PERFORMANCE ANALYSIS PROCEDURES

2.1 Modal Pushover Analysis

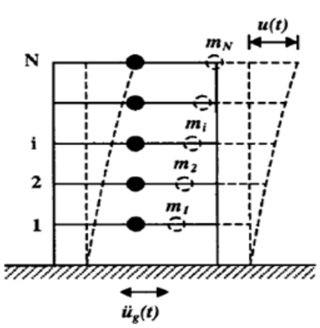

Fig. **2: N-DOF system under ground motion**

Modal Pushover Analysis (MPA), developed by chopra and Goel (2002), is an improved procedure to calculate target displacement. This procedure is developed based on the differential equations governing the response of a multi-storey building subjected to an earthquake ground motion with acceleration, $\ddot{u}_g(t)$:

$$[m]\{\ddot{u}\} + [c]\{\dot{u}\} + [k]\{u\} = -[m]\{1\}\ddot{u}_g(t) \quad [1]$$

Where, $\{u\}$ is the floor displacement relative to the ground, [m], [c], and [k] are the mass classical damping and lateral stiffness matrices of the system. The right side of above equation (Eq. 1) can be interpreted as the effective earthquake force vector:

$$\{p_{eff}(t)\} = -[m]\{1\}\ddot{u}_g(t) \quad [2]$$

Thus, the height wise distribution of these forces can be defined by $\{s\} = [m]\{1\}$And their time variation by $\ddot{u}_g(t)$.This force distribution can be expanded as a combination of modal contributions$\{s_n\}$:

$$\{s\} = \sum_{n=1}^{N}\{s_n\} = \sum_{n=1}^{N}\Gamma_n\,[m]\{\emptyset_n\} \quad [3]$$

Where, $\{\emptyset_n\}$ is the n^{th} mode of structure an N is the number of modes to be considered. The modal pushover analysis method recommends to carryout pushover analysis separately for first few modes satisfying response spectrum using load pattern as given in above equation (Eq. 3).

By utilizing the orthogonality property and decoupling of modes the solution of the differential equation (Eq. 1) can be written as:

$$\{u_n(t)\} = \{\emptyset_n\}q_n(t) = \Gamma_n\{\emptyset_n\}D_n(t) \quad [4]$$

Where, $q_n(t)$ is the modal coordinate,Γ_n is modal participation factor of the nth mode and $D_n(t)$ is governed by the equation of motion for a SDOF system, with nth mode natural frequency ω_n and damping ratio

ξ_n subjected to $\ddot{u}_g(t)$:

$$\ddot{D}_n + 2\xi\omega_n\dot{D}_n + \omega^2{}_n D_n = -\ddot{u}_g(t) \quad [5]$$

Now, the displacement at the roof due to n^{th} mode can be experessed as:

$$u_{n,roof}(t) = \Gamma_n\emptyset_{n,roof}\,D_n(t) \quad [6]$$

Where, $\emptyset_{n,roof}$ is the value of the nth mode shape at the roof level.

The peak value of the roof displacement due to nth mode can be expressed as:

$$u_{n,roof} = \Gamma_n\emptyset_{n,roof}\,D_N \quad [7]$$

Where, D_n, the peak value of $D_n(t)$ can be determined by solving equation (Eq.5) or from the inelastic response spectrum. $u_{n,roof}$ is the target displacement of the building at the roof due to nth mode. The peak modal responses from all the modes considered are combined to appropriate modal combination rule such as SRSS, CQC, etc. However, it seems reasonable because it provides results for elastic buildings that are identical to the well known RSA procedure. The lateral force distribution (Eq. 3) and target displacement (Eq. 7) suggested for modal pushover analysis possesses two properties: (a) it keeps the invariant distribution of forces and (b) it provides the exact modal response for elastic systems. The steps in MPA procedure to estimate target displacement of a multi-storeyed building are summarized as below:

i. Compute the natural frequencies$\{\omega_n\}$ and modes shapes $\{\emptyset_n\}$ for linear elastic vibration of the building.

ii. For the nth mode, develop the base shear versus roof displacement curve i.e. pushover curve for force distribution, $\Gamma_n[m]\{\emptyset_n\}$or $[m]\{\emptyset_n\}$.

iii. Idealise the pushover curve as a bilinear curve. Convert the idealized base shear versus roof displacement curve for the multi storeyed building to force displacement relation for nth mode inelastic SDOF system using the following relations:

$$D_n = \frac{u_{n,roof}}{\Gamma_n \emptyset_{n,roof}} \quad [8]$$

$$\frac{F_{sn}}{L_n} = \frac{V_{Bn}}{M_n} \quad [9]$$

Where, $F_{sn}F_{sn}$ and D_n are the force and displacement for equivalent SDOF system corresponding on the mode. V_{Bn} and $u_{n,roof}$ are base shear and roof displacement obtained from pushover analysis with nth mode shape as lateral load pattern. The purpose of this step is to obtain the properties of nth mode equivalent inelastic SDOF system.

i. Compute the peak deformation (D_n) of nth mode inelastic equivalent SDOF system defined in the previous step, either design spectrum or from the empirical equations.

ii. Calculate the peak roof displacement associated with nth mode using the relation

$$u_{n,roof}\,(t) = \Gamma_n \emptyset_{n,roof}\, D_n(t) \quad [10]$$

iii. Repeat the process for as many modes required for sufficient accuracy.

iv. Determine the total response by combining the peak modal responses using SRSS combinations rule.

Recent research shows that this procedure is capable of analyzing buildings with plan asymmetry (chopra and Goel, 2002) and some forms of vertical irregularity (Chintanapakdee and Chopra, 2004).

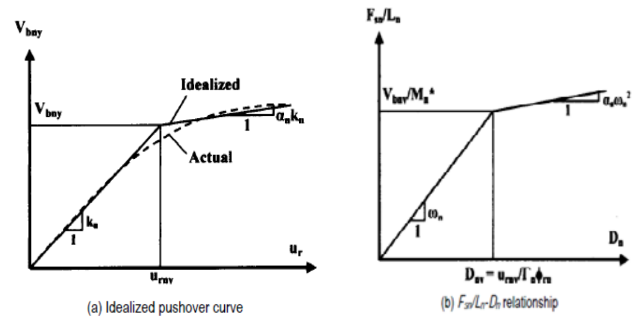

Fig. 3: Idealized Pushover Curve of the n^{th} Mode of the MDOF System, and Corresponding Capacity Curve for the *n*th Mode of the Equivalent Inelastic SDOF System.

2.2 Time History Analysis

In order to examine the exact nonlinear behavior of structures, nonlinear time history analysis has to be carried out. In this method, the structure is subjected to real ground motion records. This makes this analysis method quite different from all of the other approximate analysis methods as the inertial forces are directly determined from these ground motions and the responses of the building either in deformations or in forces are calculated as a function of time, considering the dynamic properties of the structure.

3. BUILDING SELECTION AND MODELING

At present work regular and five irregular (G+19) high-rise with various setbacks buildings are modeled using ETABS (version 9.7.4), having six bays in both direction and the storey's on the ground story having 4m bay width and the storey height 4m, M-25 grade of concrete and Fe-415 grade of reinforcing steel are used for all members of buildings. Building is located in seismic zone V, zone factor 0.36, response spectra as per IS 1893:2002 (part 1) 5% damping. Size of all columns for regular building 0.75mx0.75m and beams are 0.23mx0.23m and for all setback buildings size of all columns 0.9mx0.9m and size of beams are 0.23mx0.5m. Imposed load 3kN/m^2. Regular building and building having setbacks to identify the effect of mass irregularity on the shape of building geometry changed by reducing the no of bays in x-direction vertically downward, as per specifications in IS 1893:2002(part 1) the structural data is same for all frames. A three dimensional model of each structure has been created to carry out the nonlinear analysis. ETABS provides default hinge properties and recommends P-M-M hinges (i.e. Axial Forced and Biaxial Moment Hinge) for columns and M3 (i.e. Bending Moment Hinges) and V2 hinges for beams as described in FEMA 356. From structural analysis program, ETABs (Version 9.7) 3D Computer models of regular building and irregular building is as below:

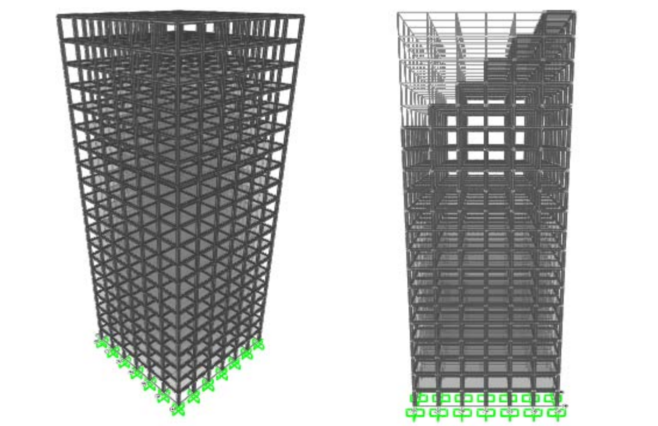

Fig. 4: 3D View of Modeling in ETABs of Frame Model (M-01) and (M-02)

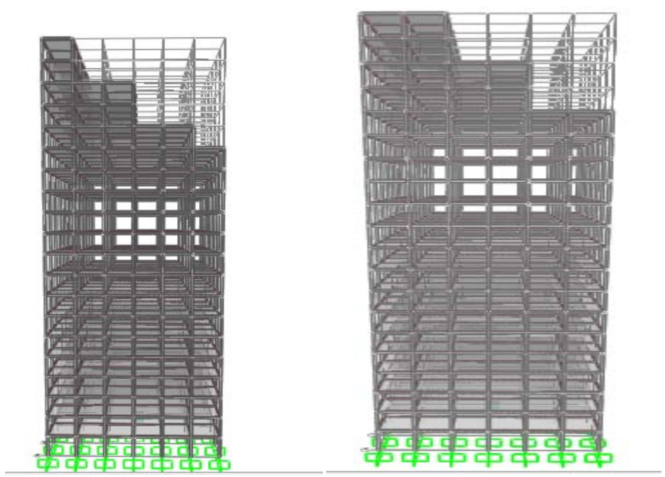

Fig. 5: 3D View of Modeling in ETABs of Frame Model (M-03) and (M-04)

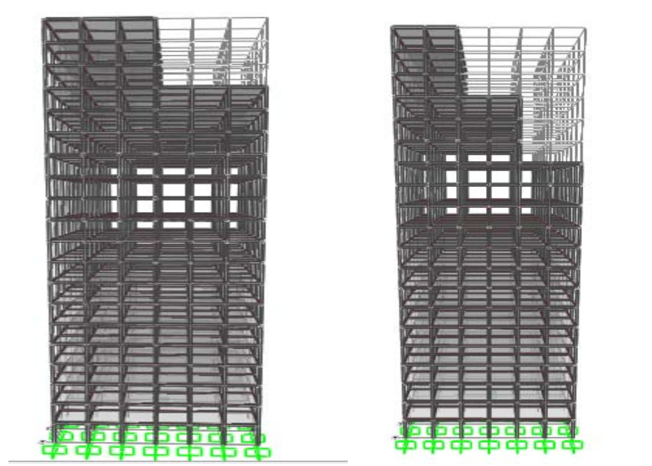

Fig. 6: 3D View of Modeling in ETABs of Frame Model (M-05) and (M-06)

4. PERFORMANCE ANALYSIS

4.1 Pushover Curves

Results of the modal pushover approaches were evaluated by comparing them with those from the NL-THA. To this effect, a time acceleration records compatible with the design spectrum was used in the NL-THA analyses. MPA procedure which accounts for three transverse modes predicts well the roof displacements of the building. On the other hand, the MPA procedure is much closer to NL-THA and gave better prediction of the building. As the level of excitation increases and higher mode contributions become more significant.

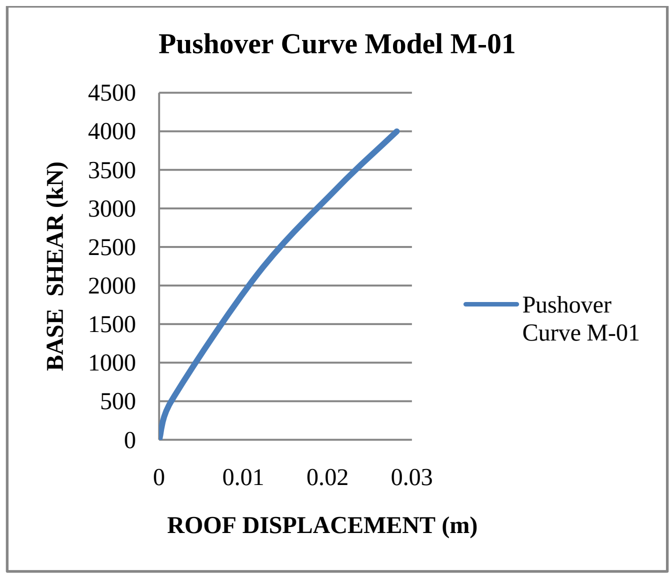

Fig. 7: Standard Pushover Curve For Highrise Regular Building M-01

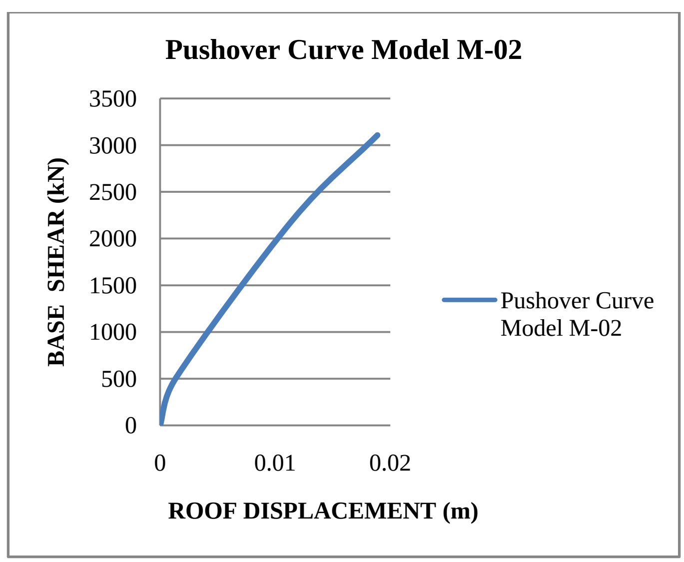

Fig. 8: Standard Pushover Curve For Highrise Setback Building M-02

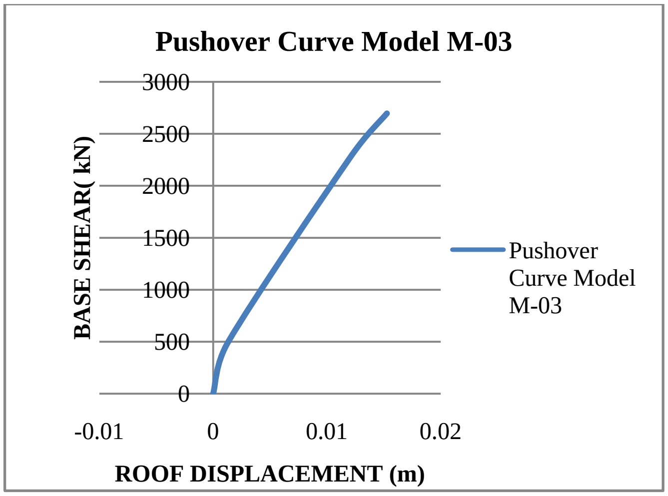

Fig. 9: Standard Pushover Curve For Highrise Setback Building M-03

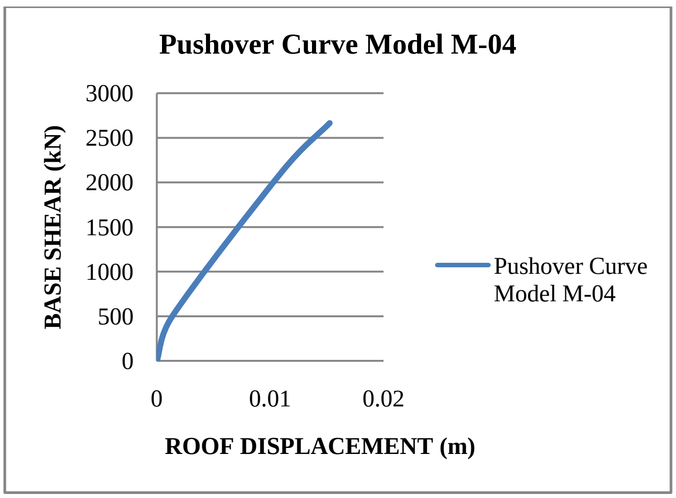

Fig. 10: Standard Pushover Curve For Highrise Setback Building M-04

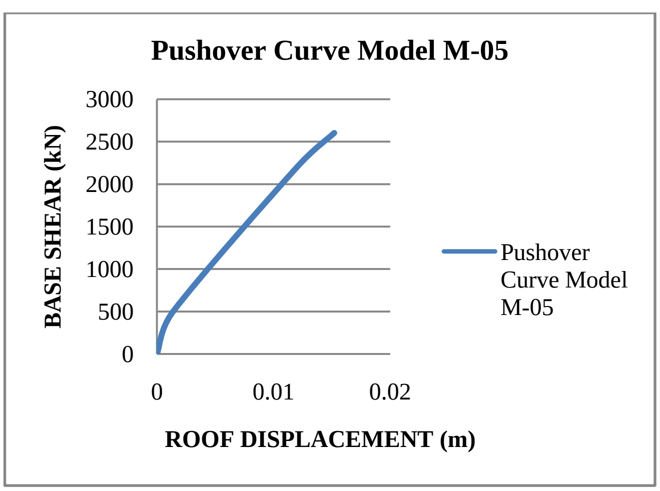

Fig. 11: Standard Pushover Curve For Highrise Setback Building M-05

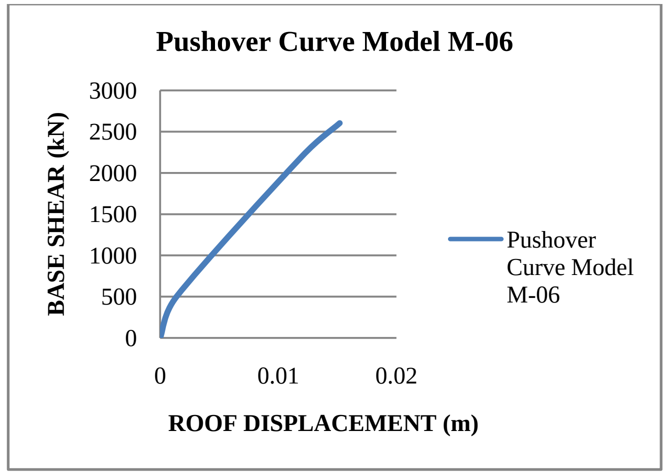

Fig. 12: Standard Pushover Curve For Highrise Setback Building M-06

4.2 Plastic Hinge Mechanism

It has been observed that, on subsequent push to building, hinges started forming in beams first. Initially hinges were in B-IO stage and subsequently proceeding to IO-LS and LS-CP stage.

4.3 Results of Modal Pushover analysis Method

The procedure was applied on high-rise reinforced concrete regular and setback buildings by considering the contribution of third mode of vibration to the total response and a comparative evaluation of MPA and standard pushover analysis with invariant lateral load patterns in predicting the seismic demands was conducted. The 'modal' capacity curves for case study frames considering the first three modes of vibration are presented in Fig. s below:

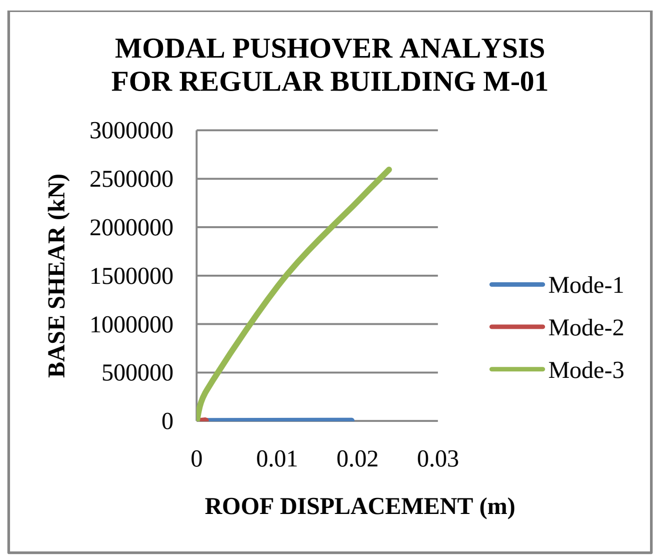

Fig. 13: Modal Pushover Curve For Highrise Regular Building

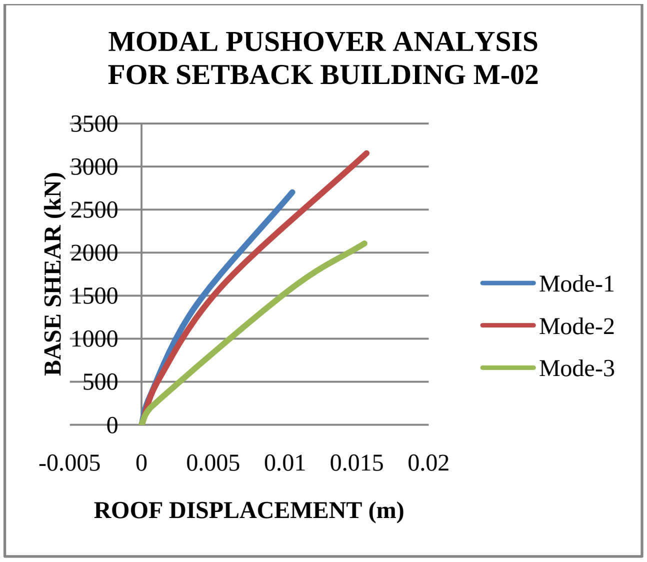

Fig. 14: Modal Pushover Curve For Highrise Setback Building

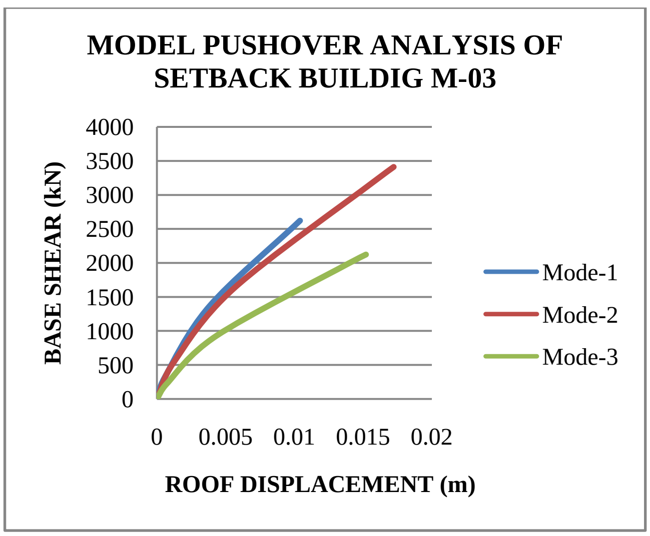

Fig. 15: Modal Pushover Curve For Highrise Setback Building

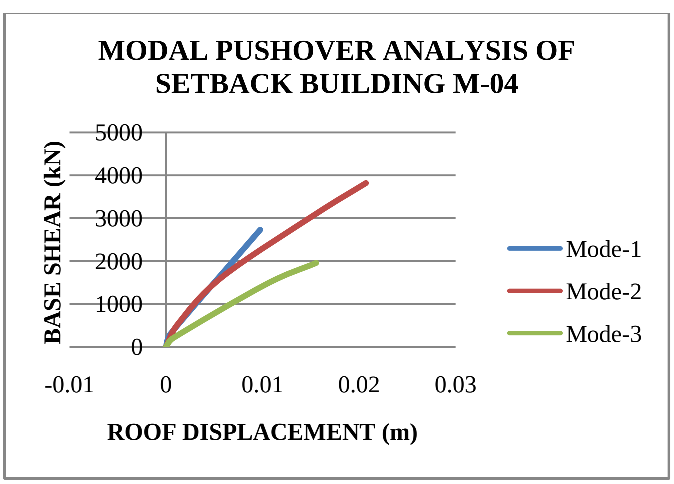

Fig. 16: Modal Pushover Curve For Highrise Setback Building

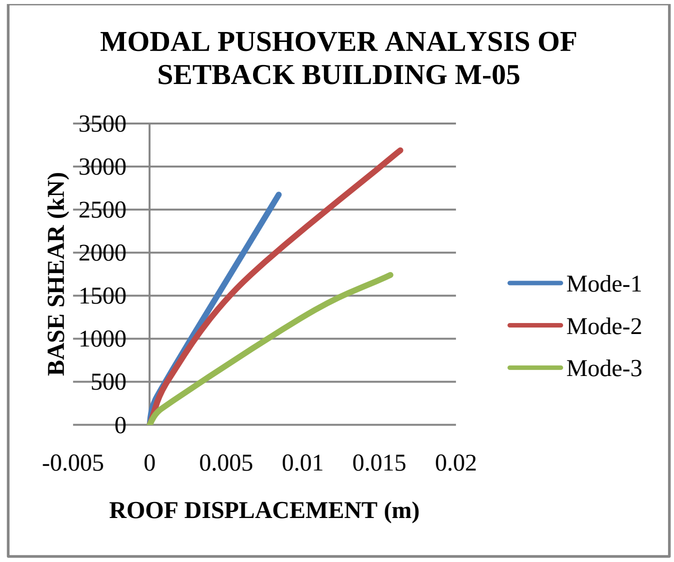

Fig. 17: Modal Pushover Curve For Highrise Setback Building

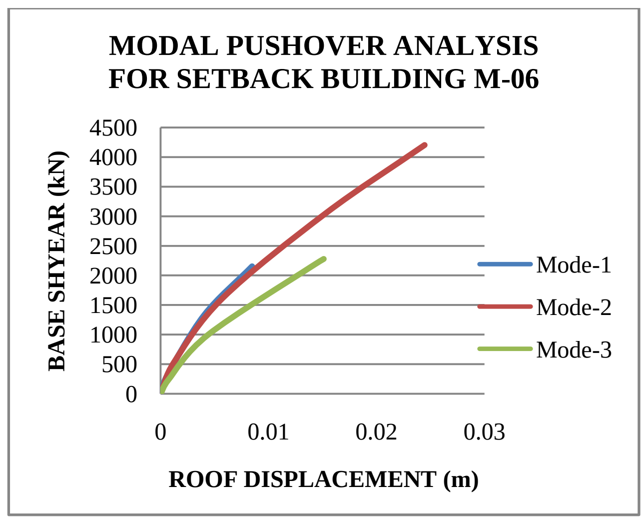

Fig. 18: Modal Pushover Curve For Highrise Setback Building

4.4 Performance Point by Capacity Spectrum Method

Performance point is the point of interseection of capacity curve and demand cureve.Performance point obtained by capacity spectrum method for all selected building models are shown in Fig. below. In Fig. green curve shows capacity curve and yellow curve shows demand curve.

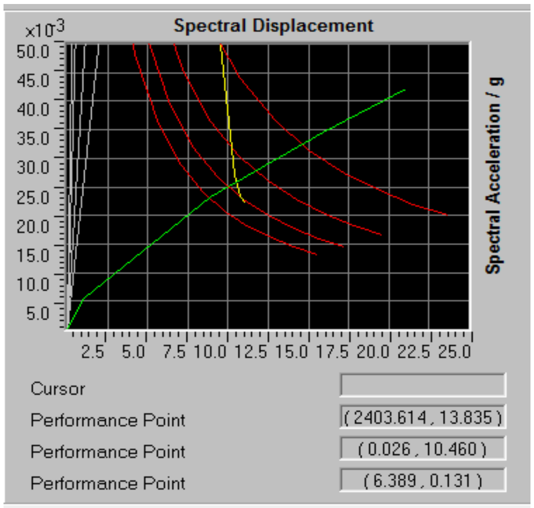

Fig. 19: Performance Point For Frame Model (M-01)

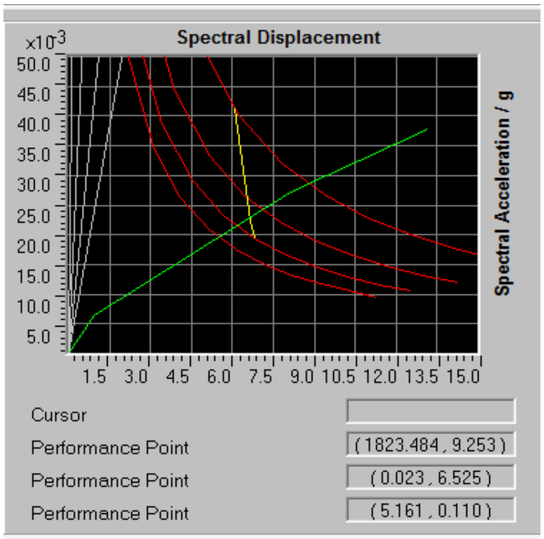

Fig. 20: Performance Point For Frame Model (M-02)

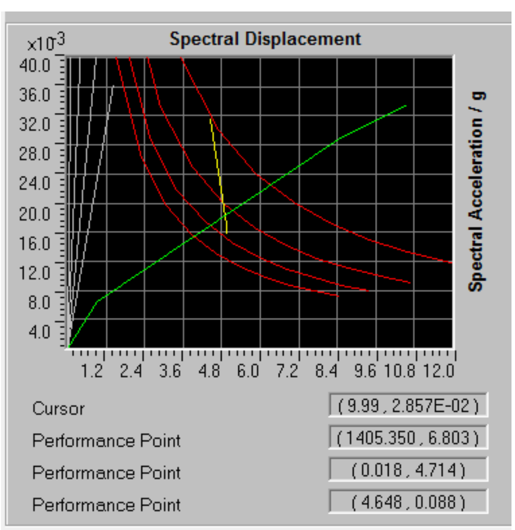

Fig. 21: Performance Point For Frame Model (M-03)

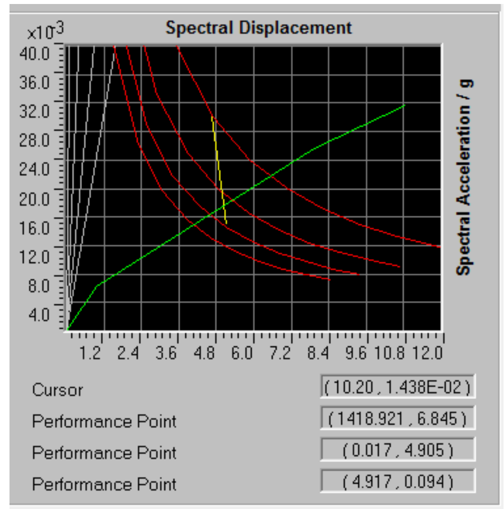

Fig. 22: Performance Point For Frame Model (M-04)

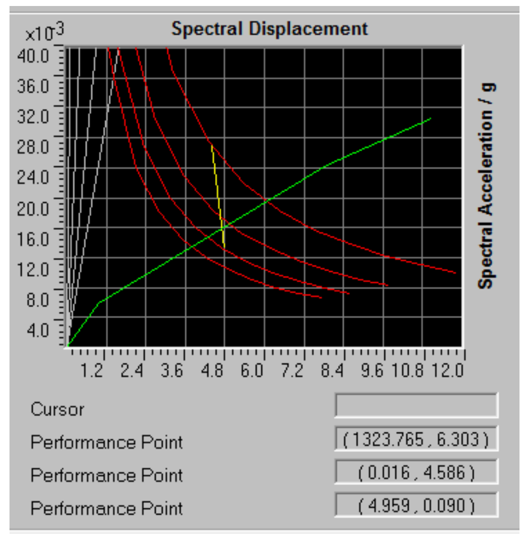

Fig. 23: Performance Point For Frame Model (M-05)

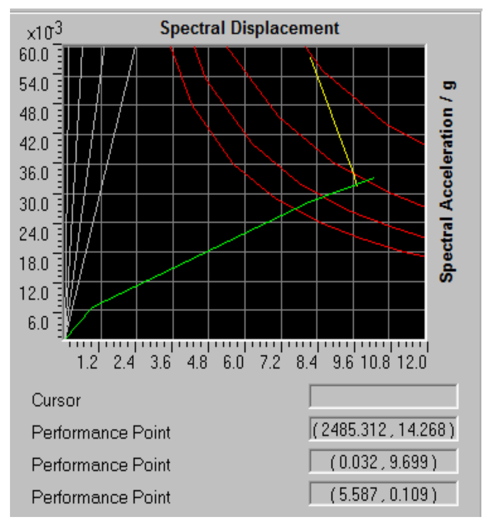

Fig. 24: Performance Point For Frame Model (M-06)

4.5 Storey drifts

After comparing pushover curves from both pushover analysis and time history analysis, storey drifts are also compared as an evaluation parameter. Fig. 25, Fig. 26, Fig. 27, Fig. 28, Fig. 29 and Fig. 30 shows the storey drifts for regular and setback high-rise buildings respectively.

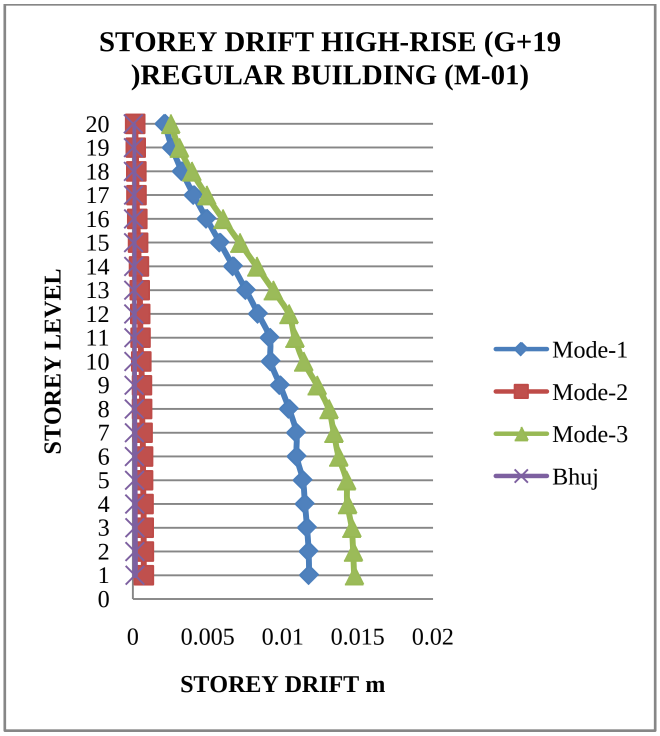

Fig. 25: Storey Drift For Regular Building (M-01)

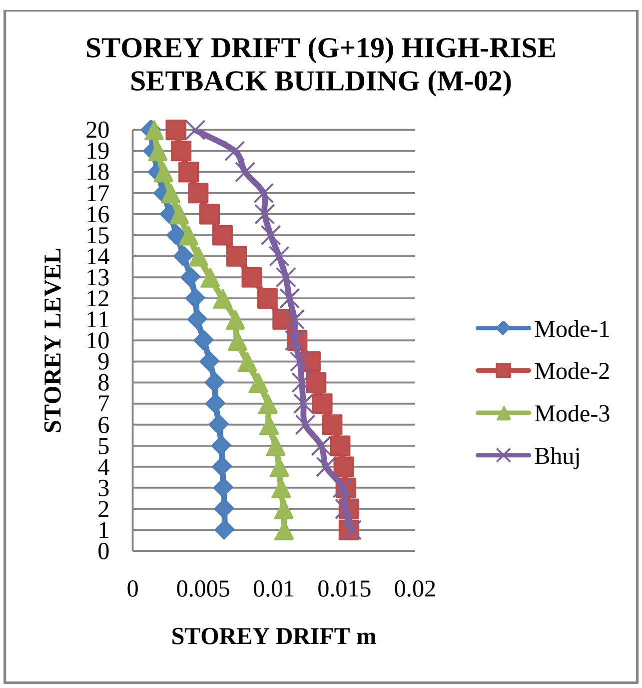

Fig. 26: Storey Drift For Setback Building (M-02)

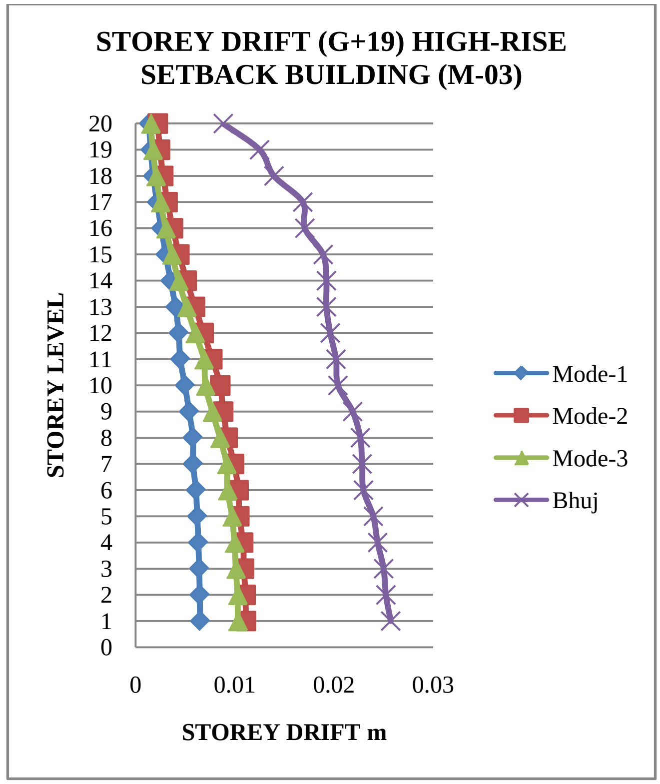

Fig. 27: Storey Drift For Setback Building (M-03)

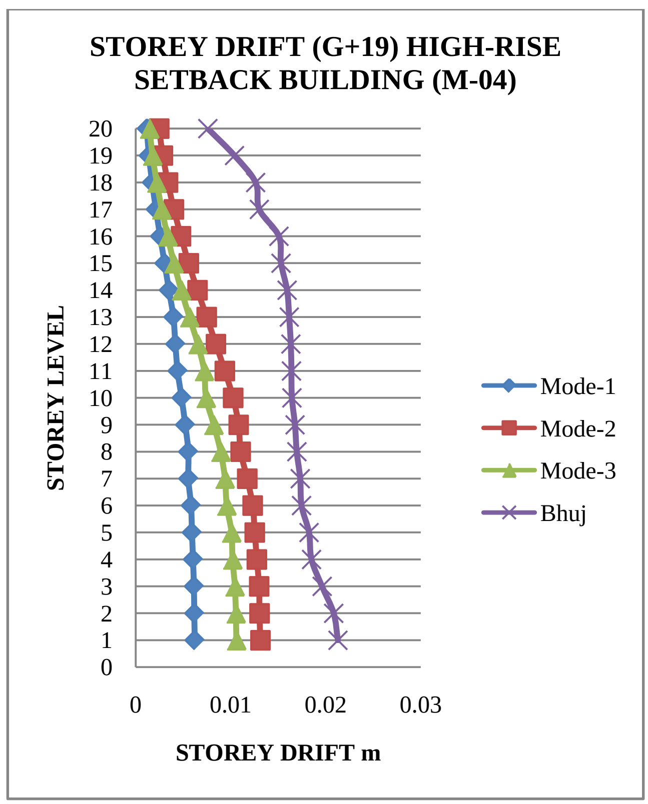

Fig. 28: Storey Drift For Setback Building (M-04)

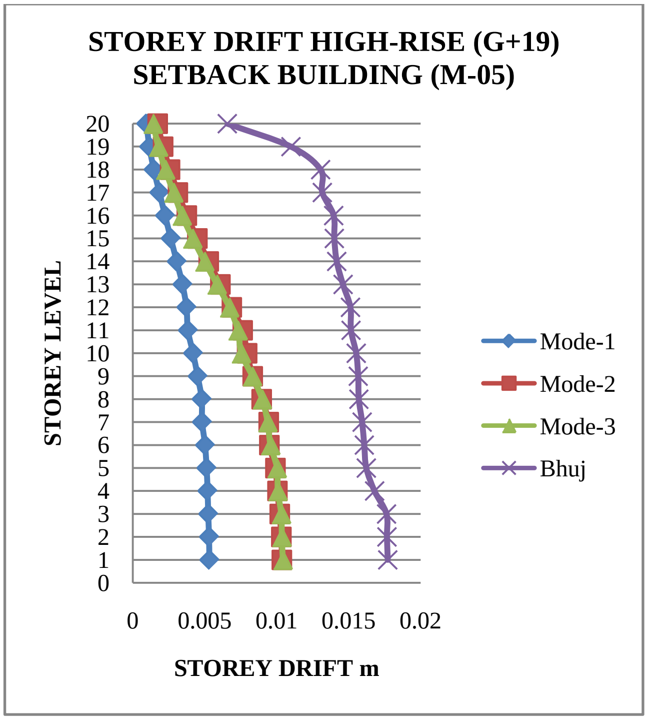

Fig. 29: Storey Drift For Setback Building (M-05)

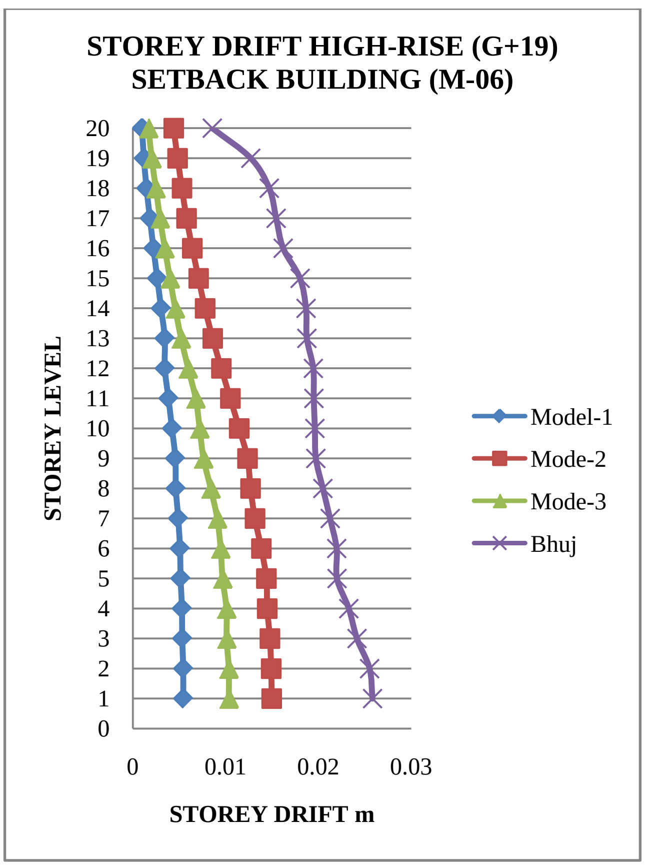

Fig. 30: Storey Drift For Setback Building (M-06)

5. CONCLUSION

By analyzing the structure using Modal Pushover Analysis (MPA) and Non Linear Time History Analysis (NL-THA) method, it is concluded that:

1) MPA seems to be a promising approach that yields more accurate results compared to the standard pushover, without requiring the higher modeling efforts and computational cost, as well as the other complications involved in NL-THA.
2) Base shear by SPA, it is observed that base shear for regular building is 3476.816kN which reduces to 2701.86kN for setback (M-02) model.
3) MPA provided a significantly improved estimate with respect to maximum displacement pattern reasonably matching the more refined NL-THA method, even for increasing level of earthquake loading that triggers increased contribution of higher modes.
4) SPA underestimates the base shear by about 27% while MPA gives better results and underestimates the base shear by only 21%.
5) By NL-THA inter story drift observed to be increasing than modal pushover analysis for all irregular building while it reduces for regular building.

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