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# PERFORMANCE EVALUATION OF VERTICALLY IRREGULAR RC FRAMES USING NONLINEAR STATIC PROCEDURES

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## Abstract

A new shear distribution pattern for the pushover analysis of Reinforced Concrete (RC) frames with vertical geometric irregularity (asymmetric setbacks) is proposed in this paper. Evaluation of vertically irregular frames using the existing methods like the Modal Pushover Analysis, Extended N2 method etc. are known to have certain drawbacks due to the elastic higher modes they consider. The method proposed here is based on the inelastic drift patterns of irregular frames. It is developed from the shear distribution model proposed by Chao et al (2007) for eccentrically braced steel frames. It eliminates the computational complexity involved in the adaptive load pattern procedures which are considered suitable for irregular frames. Comparison of the proposed procedure with the extended N2 method is done on three dimensional 10 storey RC frame with vertical geometric irregularity. Results show that better predictions of structure stiffness and inter-storey drift demands are obtained by the proposed method.

*Keywords: Nonlinear static procedures, Vertical geometric irregularity, Incremental dynamic analysis, Inter storey drift.*

## 1. Introduction

Nonlinear Static Procedures (NSPs) or pushover analysis methods [1-5] are considered to be the efficient alternatives for costly dynamic analyses. To account for the higher mode and torsional effects, advanced pushover techniques like Modal Pushover analysis [6, 7], Adaptive Pushover Analysis [8, 9], Extended N2 method [10] etc. are developed by different researchers. Such methods are more suitable than conventional pushover procedures for the structures with geometric irregularity like setbacks. But the unavailability of proper guidelines for such procedures in the International standards or lack of their direct application in the commercial software packages puts limit on their use in the industry. Hence a load pattern which can be used with the conventional pushover procedures will be helpful for analysing the irregular structures.

The shear distribution pattern (load pattern) used for the pushover analysis plays an important role in the accuracy of analysis results. Moghadam and Tso [11, 12] analysed different asymmetric structures using a response spectrum based POA method. The authors found that the load distribution in setback structures at the inelastic range may differ substantially from the elastic load distribution, as their stiffness and strength distributions are not uniform. Incremental dynamic analyses (IDA) of multi-storey regular frames by Mwafy and Elnashai [13] also shows the limited capability of the fixed load distribution and multimodal analyses to predict higher mode effects in the post-elastic domain. It can be understood from the study of Chintanapakdee and Chopra [14] that the difference in response of frames with vertical geometric irregularity from that of regular frames will mainly occur at the upper storeys. They also find that the MPA procedure is less suitable for frames with stiffer/ stronger lower half. Athanassiadou [15] states that the pushover analyses using elastic multi-modal load distribution underestimate the response quantities at the upper floors of such structures.

It can be understood from literature that the behaviour of setback structures differs considerably from that of regular structures. As the mass and stiffness of vertically irregular (setback) frames are varied along their height, their responses during strong ground shaking include considerable higher mode contribution. The modifications to the basic NSPs to make them suitable for setback structures may be based on the response quantities like top displacement, inter-storey drift ratio and base shear, as most of the existing studies [13-16] suggest the importance of these quantities in the setback structures. It can also be concluded from such studies that the modified NSPs based on the elastic higher modes [6, 10] are not much effective in predicting the inelastic behaviour of structures with asymmetric setbacks. Hence, certain modification to the existing basic NSPs, to make them suitable for the setback structures, is of vital importance.

The design load pattern for irregular steel frames by Chao et al. [17] can be used with certain modifications for the displacement and drift predictions of vertically irregular RC frames using NSPs, as known from the previous studies [18]. Displacement and drift demand predictions from nonlinear dynamic analyses were used as the benchmarks for the studies mentioned above [18]. The present work tries to analyse the global strength and stiffness predictions by the NSPs using different shear distribution (load) patterns. Incremental dynamic analysis (IDA) curves in the present study shows that further improvement to the modified Chao load pattern [18] can be achieved by better stiffness predictions of asymmetrically setback frames. Hence, an improvement over the existing method for the displacement predictions of vertically irregular RC frames, incorporating better correlations in strength and stiffness demands, is proposed in this paper. Capacity curves developed from IDA methods are employed as benchmark curves for the assessment of NSP capacity curves. The proposed method is found to give better results for frames with vertically asymmetric setbacks, when compared with the extended N2 method [10], one of the popular elastic- multimodal NSPs which is considered suitable for the demand predictions of irregular frames.

## 2. Analysis models and methods

To have an understanding of the behaviour of setback frames compared to that of regular frames, the setback and regular RC frames are designed under the same load conditions. These two dimensional 10 storeyed frames (Fig.

1) are designed as special moment resisting frames as per IS 1893: 2002 for seismic zone V (pga 0. 36g) and importance factor 1.5, using response spectrum analyses.

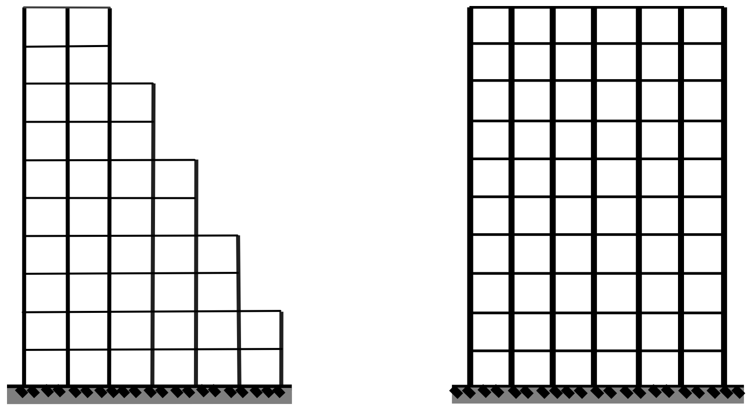

Fig. 1 – Two dimensional Models

Lumped plasticity is assumed for all members to reduce the computational efforts, retaining the accuracy of global level responses [19, 20]. All the modelling and analyses are done using SAP 2000 [21]. Beams and columns are modelled as plane frame elements and End length offsets are provided at beam and column ends to ensure joint rigidity. i.e., the beam–column joints are modelled as rigid joints using the end offset property assignment in SAP [20, 21]. Nonlinear modelling of the frames includes the moment hinges in beam ends and axial- moment interaction hinges in column ends [19, 20]. The rotation parameters of the hinges are taken from tables of FEMA 356:2000 [3]. Shear hinges are not provided [19, 22], as lateral ties (confinement) of columns are given as per latest ductile detailing provisions in IS 13920:1993 [23]. Default hinges from SAP 2000 are chosen for all frame members owing to the large time required for the analyses. As the main aim of the study is to identify the methods for predicting global/storey responses such as drift and base force demands, for the design and evaluation of asymmetric frames, this modelling approach can be justified. Cyclic response of concrete is defined by tri-linear Takeda hysteresis model defined in SAP 2000.

Table 1 – Ground motion records used for the study

| **Earthquake event** | **year** | **Station** | **Magnitude** | **Vs 30 (m/s)** | **PGA (g)** |
|---|---|---|---|---|---|
| Northridge-01 | 1994 | Northridge - 17645 Saticoy Station | 6. 69 | 280. 9 | 0. 582 |
| Northridge-01 | 1994 | Rinaldi Receiving Station | 6. 69 | 282. 2 | 0. 400 |
| Northridge-01 | 1994 | Arleta - Nordhoff Fire Station | 6. 69 | 297. 7 | 0. 524 |
| Northridge-01 | 1994 | Canoga Park - Topanga Can | 6. 69 | 267. 5 | 0. 561 |
| Imperial Valley-06 | 1979 | El Centro Differential Array | 6. 53 | 202. 3 | 0. 585 |
| Imperial Valley-06 | 1979 | El Centro Differential Array | 6. 53 | 202. 3 | 0. 623 |
| Imperial Valley-06 | 1979 | El Centro Array #4 | 6. 53 | 208. 9 | 0. 795 |
| Imperial Valley-06 | 1979 | El Centro Array #8 | 6. 53 | 206. 1 | 0. 748 |

Note: Vs 30 is the time-averaged shear-wave velocity of the ground motion to a depth of 30 m.

These frames are then subjected to incremental nonlinear time history analyses, such that, the scale factor of accelerograms started from the intensity corresponding to their design earthquake. The ground motion records used are shown in Table 1. Scale factors to the records are increased in successive iterations of the analyses, until collapse of the structure is reported from three or more ground motions. IDA curves of the frames are shown in Fig.2. The regression coefficient R and the equations of the IDA curves are also shown in Fig. 2. The IDA curves are drawn as polynomial curves representing the dispersion of maximum roof displacement – base shear pairs from different seismic intensities. The polynomial is chosen such that the regression coefficient R is approximately 0.95. It can be understood from the IDA curves (Fig. 2) that the strength capacity of irregular frame is lower than that of the regular frame.

Studies by the authors [18] has shown that the load pattern for the design of steel frames by Chao et al [17] can be modified suitably for predicting the inelastic drift and displacement demands of vertically irregular RC frames, using the basic NSPs. The present study analyses the strength and stiffness predictions of such frames by different load patterns. Different load patterns used for the study are shown in Fig. 3.

The following load distribution patterns are used for the analyses:

a. The pattern proposed by Chao et al [17] for eccentrically braced steel frames regular in elevation, using inelastic drift ratios, which is later modified by Manjula et al [18], for displacement predictions of vertically irregular RC frames.
b. Mass proportional uniform load pattern (MPU), which is applied as the load proportional to the mass at each floor, hence obtaining same load for similar floor masses.
c. Mass proportional triangular load pattern (MPT), which is a load varying in triangular pattern for the floors with same masses
d. Uniform loading irrespective of mass or height (Uniform), applied as the same load for all the floors
e. The elastic analysis lateral force distribution for design in the Eurocode (EC 8) [5].
f. The modified Chao load pattern, in which the bottom one third of the frame is loaded with the uniform load pattern (Chao-U).

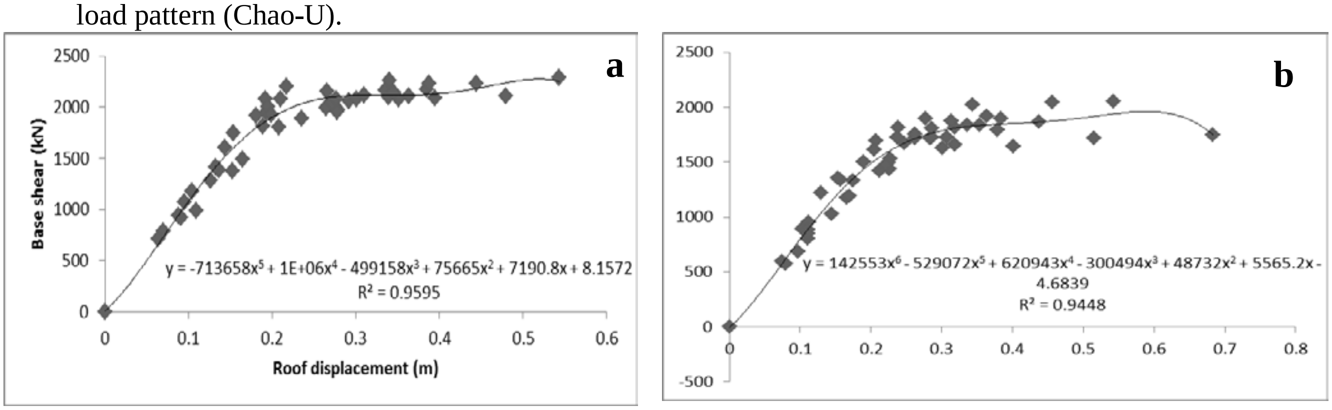


Fig. 2 – IDA curves  a) Regular frame  b) Frame with asymmetric setback

The pattern proposed by Chao et al. [17], which was tested for many regular steel frames, can be written as,

$$F_j = S'_{vj} V \quad (1)$$

where,

$$S'_{vj} = (\beta_j - \beta_{j+1}) \left( \frac{w_n h_n}{\sum_{i=1}^{n} w_i h_i} \right)^{\alpha T^{-0.2}} \quad \text{when } j = n,\ \beta_{j+1} = 0 \quad (2)$$

$$\beta_j = \frac{V_j}{V_n} = \left( \frac{\sum_{i=j}^{n} w_i h_i}{w_n h_n} \right)^{\alpha T^{-0.2}} \quad (3)$$

where $\beta_j$ is the shear distribution factor at level $j$; $V_j$ and $V_n$ respectively are the storey shear forces at level $j$ and at the roof ($n$th) level; $w_i$ is the seismic weight at level $i$; $h_i$ is the height of level $i$ from the base; $w_n$ is the weight at the roof level; $h_n$ is the height of roof level from the base; $T$ is the fundamental period; $F_j$ is the lateral force at level $j$; and $V$ is the total design base shear. $\alpha$ was taken as 0.75 for eccentrically braced steel frames[17].

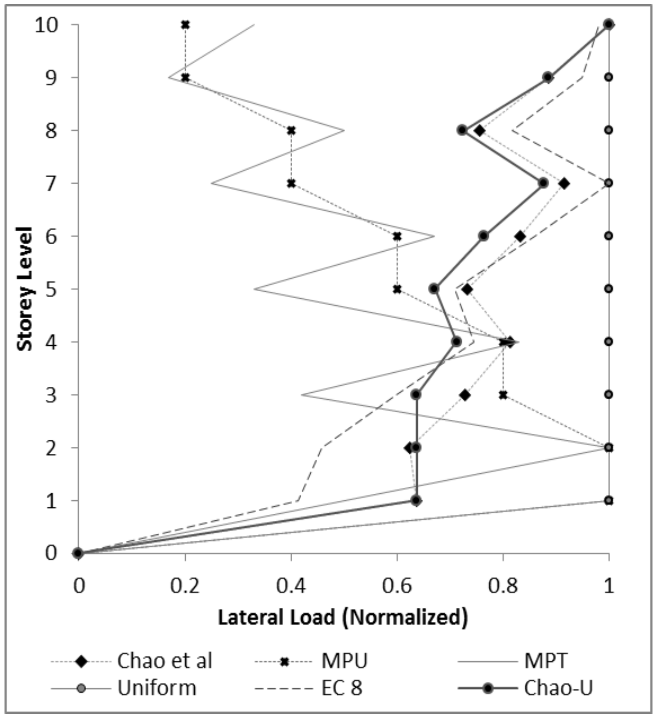


Fig. 3 – Pushover Load Patterns for Asymmetric frame

The factor $\alpha$ for RC frames with asymmetric setbacks was found to be 0.95, from previous studies [18] based on the inter-storey drift patterns of different asymmetric RC frames from extensive dynamic analyses. The increase in the value of $\alpha$ from 0.75 to 0.95 indicates a decrease in the loading at the top most floor. This can be understood from the fact that concrete structures generally have lesser ductility and deformation capacity than steel structures. Also, the vertically asymmetric RC frames considered in the study have less number of bays towards the top of the structure, giving rise to a reduction in shear force at the upper floors. However, these structures will deform more towards the upper floors compared to that of the regular structures, because of the reduction in their effective stiffness due to reduction in number of bays. Hence, the shear distribution pattern for NSPs could be found out such that the drift pattern from NSP is most similar to the dynamic drift pattern. This load pattern was indicated as 'Chao et al' [18] as the only difference was in the value of $\alpha$. This method was found to give satisfactory results for the displacement predictions of vertically asymmetric RC frames [18].

However, a consideration to the dynamic capacity curves may lead to more reliable results regarding the strength and stiffness capacity of the structure. For a successful prediction of building responses from the NSPs, the following factors may be considered important.

i. A good correlation of the inter storey drift values from the NSPs and the dynamic analyses, representing better displacement predictions.
ii. A considerable match between the pushover capacity curve and the IDA curve, representing better strength and stiffness predictions.

Two common analysis methods used in the NSPs include the secant stiffness based procedures and the initial stiffness based procedures [24], as described in Fig. 4. The major difference between the linear and nonlinear responses under earthquake arises from the system ductility ($\mu$) and hysteretic damping ($\zeta$). The hysteretic damping term in a nonlinear dynamic system under earthquake, is an inseparable function of both displacement and velocity, which is represented by the term $f(x, \dot{x})$ in Eq. 4. The secant stiffness based approaches make the equation of nonlinear parameters (Eq. 4) to the one containing corresponding linear parameters, by suitably approximating the effective values of damping and stiffness terms ($C_{eff}$ and $K_{eff}$) as their secant values ($C_{sec}$ and $K_{sec}$ respectively), as shown in Eq. 5. In the NSPs which use the initial stiffness based procedures, the initial effective stiffness ($K_e$) will be used in eqn. 5. R-μ-T relations* are then applied to this

*$R$-$\mu$-$T$ *relations* are the relations between the structure's fundamental time period $T$, ductility $\mu$ and the strength ratio $R$. The strength ratio $R$ is the ratio between the elastic strength demand and the yield strength (calculated from the NSPs) of the structure. The $R$-$\mu$-$T$ *relations* can be defined for different SDF systems based on parametric studies. When the MDF systems are converted to SDF counterparts, the nonlinear response of such SDF systems can be approximated using the $R$-$\mu$-$T$ *relations*.

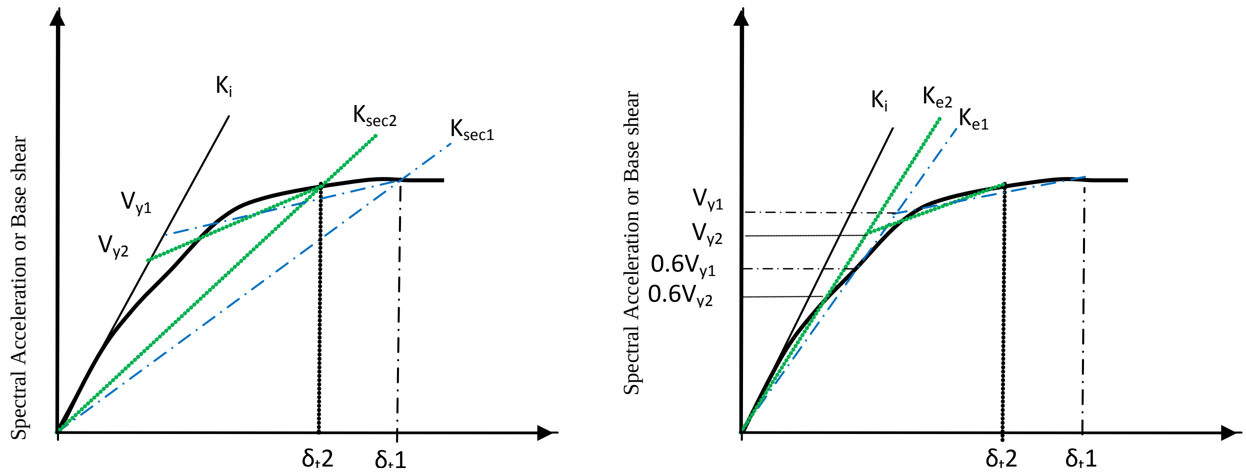


Fig.4 (a) Secant stiffness based procedure (b) Initial stiffness based procedure

system, to obtain the inelastic responses, i.e., instead of using a direct secant stiffness based approximation, Eq. 5 is first formed using the initial effective stiffness coefficients, and later, the results (displacements) based on this formulation are modified to the ones corresponding to that of nonlinear systems, using the R-μ-T relations.

$$M\,\ddot{x}_{nonlin} + C\,\dot{x}_{nonlin} + K\,x_{nonlin} + f(x, \dot{x}) = -M\,\ddot{u}(t) \qquad (4)$$

$$M\,\ddot{x}_{lin} + C_{eff}\,\dot{x}_{lin} + K_{eff}\,x_{lin} = -M\,\ddot{u}(t) \qquad (5)$$

Hence, for both the initial and secant stiffness based pushover analysis methods, the stiffness of the pushover curve plays an important role in the accuracy of results. The load pattern which predicts the structure stiffness within permissible variations from the dynamic results can be identified by a comparison of the pushover curves with the IDA curves. The load pattern which could lead to drifts and displacements within permissible deviations from those of dynamic analyses and stiffness values within permissible deviations from those of IDA curves, may considered to be suitable for the evaluation of asymmetric frames.

Hence, different improvements are tried for the modified Chao load pattern [18]. It is identified that a combination of this load pattern with the Uniform load pattern can give better estimates of stiffness and drift. Further studies including the IDA curves has shown that the factor α= 0.85 is more suited for asymmetric RC frames. In this new pattern, the bottom one third of the frame is loaded with the Uniform load pattern, such that the value of the uniform load is equal to the load in the previous floor. This pattern is referred as 'Chao-U' in this paper. As this load pattern can be used with the existing basic NSPs like the ATC [2] and FEMA [3, 4] procedures, it leads to a simplified seismic evaluation of RC frames with vertical geometric irregularity.

## 3. Results and Discussion

Pushover curves of the frames in Fig. 2 using the selected load patterns are plotted together with their IDA curves in Fig. 5. It can be understood from Fig. 5 that the capacity of Regular frame using the Uniform load pattern is larger than its IDA capacity curve. The other two load patterns viz. Eurocode 8 (EC 8) and Triangular (TRINGL) patterns gives conservative results for the regular frame. The shear distribution pattern in Eurocode 8 is better correlating with the IDA curve in predicting the stiffness capacity of irregular frame, as observed from Fig.5. But the drift predictions by this pattern are not much comparable with dynamic analyses results for irregular frames as known earlier [18]. It is known that the inelastic drift predictions of asymmetric frames from load patterns based on elastic force distributions will not be much satisfactory [11-15].

Fig. 5(b) shows that the Chao- U pattern (α = 0.85 and Uniform loading in bottom one-third height) predicts the structure stiffness better than the modified Chao (α = 0.95) pattern. It should be mentioned here that the modified Chao pattern with α = 0.95 is sufficient for the predictions of drift and displacement demands, as observed from previous studies [18]. However, better stiffness predictions can lead to better design (force) demand estimations at different storey levels. Further studies in this regard considering buildings with different heights and more detailed nonlinear modelling is required to have better formulations for the seismic evaluation of RC frames with asymmetric setbacks using NSPs.

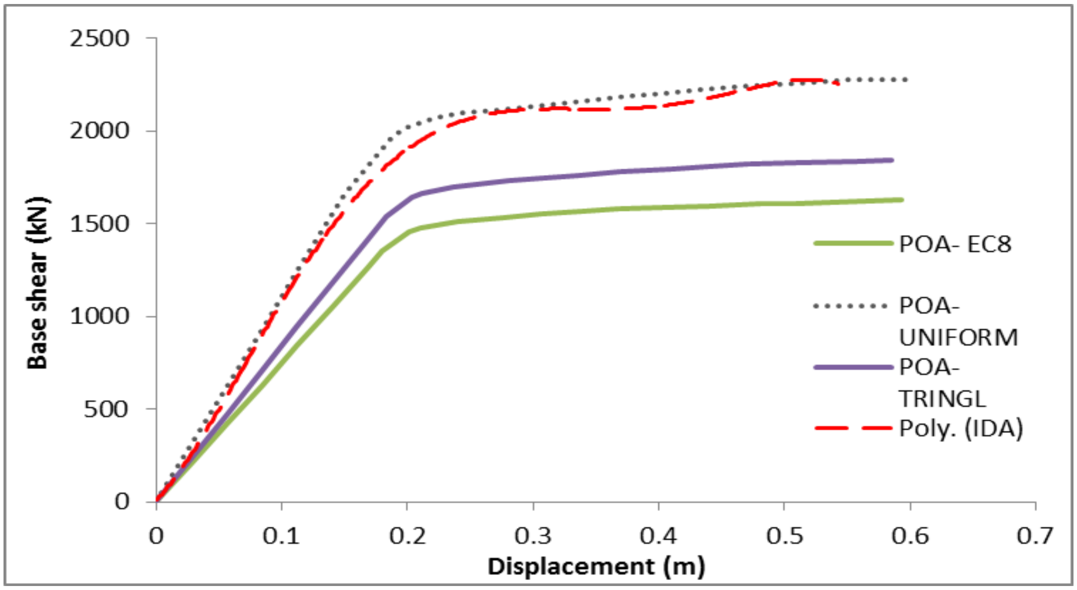


Fig. 5 a) – Pushover and IDA curves- Regular frame

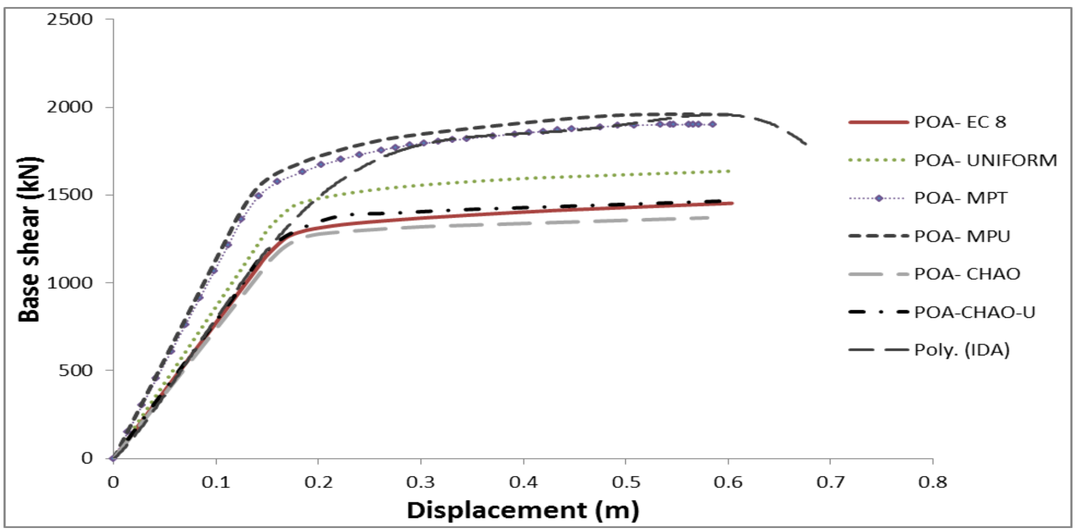


Fig. 5 b) – Pushover and IDA curves- Asymmetric frame

A comparison of the proposed pushover analysis method including the 'Chao-U' load pattern with the Extended N2 method [10] of pushover analysis is done for three dimensional RC setback frame shown in Fig. 6. The extended N2 method is chosen for comparison as it is an easy and convenient method widely used for the seismic evaluation of frames with considerable higher modes [10], whose basic principle (the N2 method) is described in a national building code [5]. Three dimensional frames are used for the comparison analysis, to account for the higher mode effects considered in the extended N2 method. It should also be mentioned here that the coupled deformations in an asymmetric structure could only be represented by a three dimensional analyses, even though two dimensional analyses are permitted for structures with setbacks only on one side [5], and hence followed in this paper.

The frame has setbacks in the X- direction. Time history analyses for this frame are done using the ground motion records in Table 1. Geometric means of the results (represented as 'TH- Geomean' in the graphs) are used for the analyses. Comparison of the drift patterns from extended N2 method, time history analysis and the method proposed in this paper are given in Fig. 7. Results of the N2 method [25] are modified suitably to get the results of the Extended N2 method. Correction factors [10] obtained using elastic modal analyses are used for this purpose. As the frames are symmetric in the Y- direction, special shear distribution patterns are not required in that direction. As well established load patterns are available for the drift and displacement estimations of symmetric frames, evaluation of the proposed Chao- U pattern against such frames are not performed here, in view of the main aim of the paper.

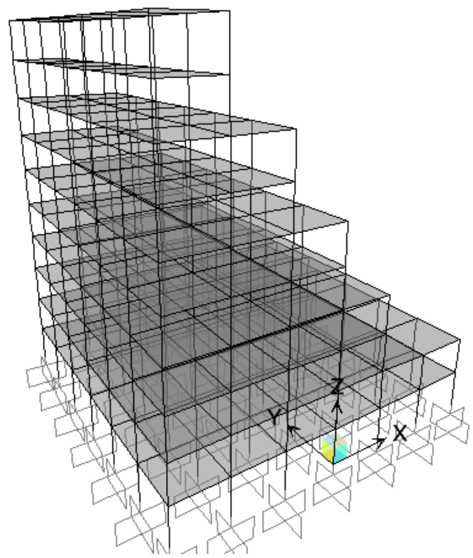


Fig. 6 – 10 storey RC setback frame model for Extended N2 analysis

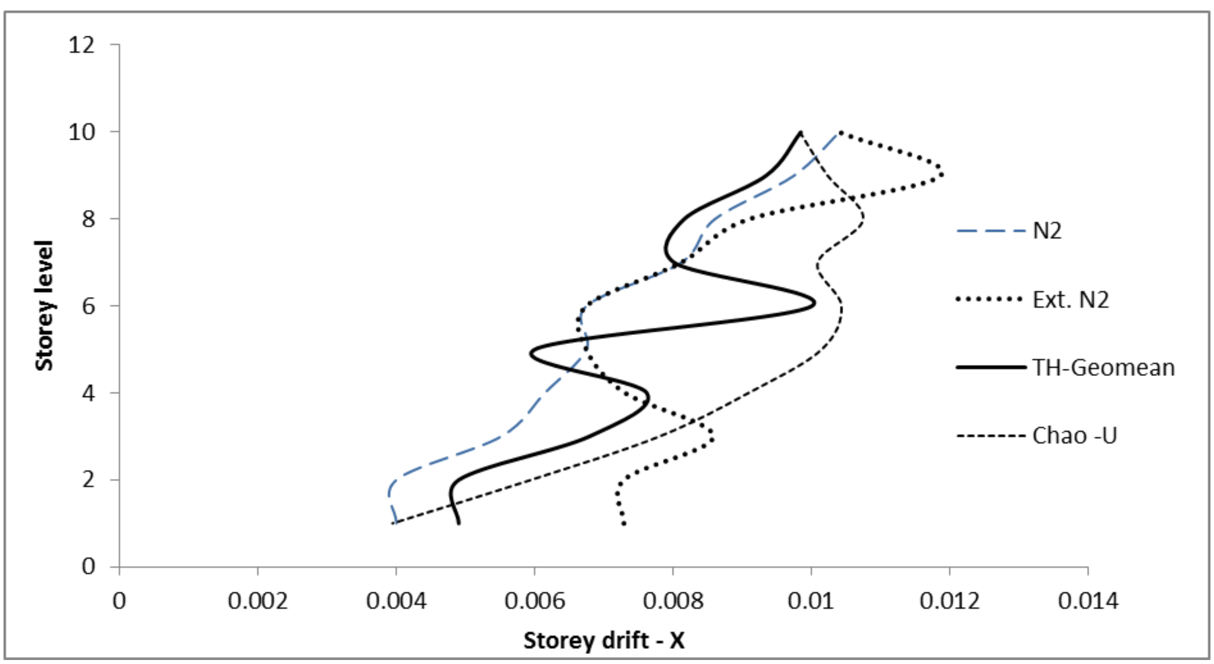


Fig. 7 a) – Inter-storey drift values for 10 storey RC setback frame model for different analyses- X direction

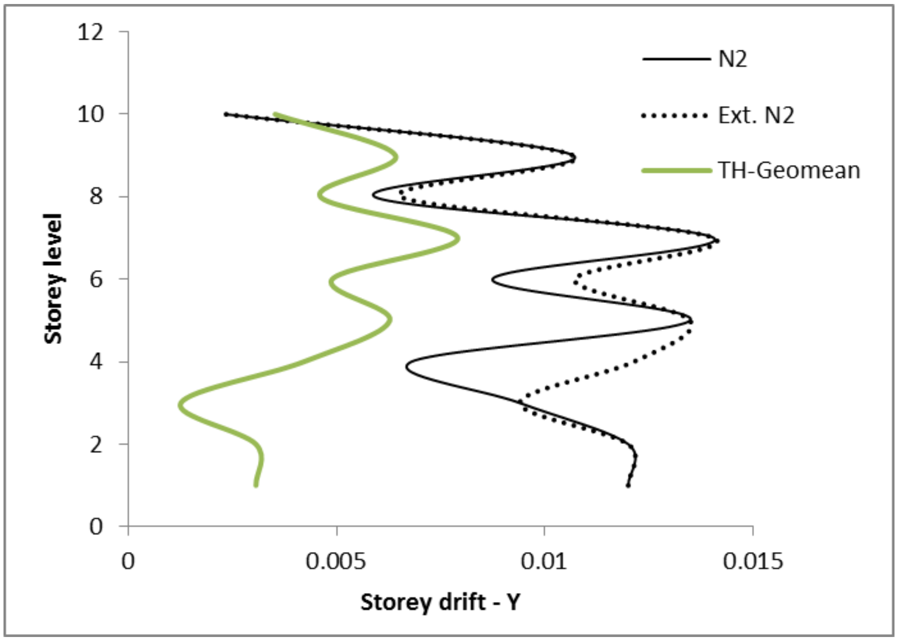


Fig. 7 b) – Inter-storey drift values for 10 storey RC setback frame model for different analyses- Y direction

Fig. 7 (a) shows that the storey drifts in the direction of setbacks are better predicted by the Chao- U load pattern. Many previous studies [26, 27] has shown that the storey drifts at the mid-height of irregular frames are much larger compared to their regular counter parts. These increased drift values play an important role in the increased moment demands of such frames. Hence it is important not to underestimate the mid-height drifts of setback frames. It is seen from Fig. 7(b) that in the regular frames orthogonal to setback frames, the drift values obtained by the basic NSPs (e. g., N2 method using regular design load patterns) are sufficient.

## 4. Summary and Conclusion

Evaluation of vertically irregular frames using the existing methods like the Modal Pushover Analysis, Extended N2 method etc. are known to have certain drawbacks due to the elastic higher modes they consider. It can be identified from the previous studies that the inter storey drifts in the inelastic responses play an important role in the seismic behaviour of such frames. Design load patterns for steel frames based on the inelastic drifts were proposed by Chao et al. [17]. Certain modifications to this load pattern were found suitable for the drift and displacement predictions of asymmetric RC frames using NSPs [18]. Further improvements to the above load pattern regarding the stiffness capacity of the structure is proposed in the present study. It is identified that the proposed pattern (Chao- U) predicts the strength and stiffness capacity and inelastic drift demands better than the existing patterns. It is also identified that the frames orthogonal to setback frames can be analysed with the existing basic NSPs.

## 5. Acknowledgements

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## 5. References

[1] *ASCE*/SEI *41*-06 (2007): Seismic Rehabilitation of Existing Buildings, *American Society of Civil Engineers*, USA.

[2] ATC 40 (1996): Seismic Evaluation and Retrofit of Concrete Buildings, *Applied Technology Council*, USA.

[3] FEMA 356 (2000): Prestandard and Commentary for the Seismic Rehabilitation of Buildings, *American Society of Civil Engineers*, USA.

[4] FEMA 440 (2005): Improvement of nonlinear static seismic analysis procedures, *Applied Technology Council*, Washington, D. C., USA.

[5] Eurocode 8 (2004): *BS EN 1998-1*, Design of Structures for Earthquake Resistance, Part-1: General Rules, Seismic Actions and Rules for Buildings, European Committee for Standardization (CEN), Brussels, Belgium.

[6] Chopra, A. K. and Goel, R. K. (2001): A modal pushover analysis procedure to estimate seismic demands for buildings: Theory and preliminary evaluation, PEER *Report 2001/03*, Pacific Earthquake Engineering Research Centre, College of Engineering, University of California, Berkeley.

[7] Chopra, A. K. and Goel, R. K. (2002): A modal pushover analysis procedure for estimating seismic demands for buildings, *Earthquake Engineering and Structural Dynamics*, Vol. 31, pp. 561-582.

[8] Gupta, B., and Kunnath, S. K. (2000): Adaptive spectra-based pushover procedure for seismic evaluation of structures, *Earthquake Spectra*, 16(2), 367–391.

*[9]* Antonio, S., and Pinho, R. (2004): Development and verification of a displacement-based adaptive pushover procedure, *J. Earthquake Eng.*, 8(5), 643–661.

[10] Kreslin, M. and Fajfar, P. (2012): The Extended N2 method considering higher mode effects in both plan and elevation, *Bulletin of Earthquake Engineering*, Vol. 10, No.2, pp. 695 - 715.

[11] Moghadam, A. S. and Tso, W. K. (2000): Pushover analysis for asymmetric and set-back multi-story buildings, *Proceedings of the 12th World Conference on Earthquake Engineering*, Auckland, New Zealand January, paper 1093.

[12] Moghadam, A. S. and Tso, W. K. (2002): A pushover procedure for tall buildings, *Proceedings of the 12th European Conference on Earthquake Engineering*, *Barbican Centre*, London, UK, September, Paper 395.

[13] Mwafy, A. M. and Elnashai, A. S. (2001): Static pushover versus dynamic collapse analysis of RC buildings, *Engineering Structures*, Vol. 23, No.5, pp. 407 -424.

[14] Chintanapakdee, C. and Chopra, A. K. (2004): Seismic response of vertically irregular frames: Response history and modal pushover analyses, *ASCE Journal of Structural Engineering*, Vol. 130, No. 8, pp. 1177-1185

[15] Athanassiadou, C. J. (2008): Seismic performance of R/C plane frames irregular in elevation, *Engineering structures*, Vol. 30, pp. 1250-1261.

[16] Kalkan, E. and Kunnath, S. (2006): Assessment of current nonlinear static procedures for seismic evaluation of buildings, *Engineering Structures*, Vol. 29, 2007, pp 305–316.

[17] Chao, S. H., Goel, S. C. and Lee, S. S. (2007): A Seismic design lateral force distribution based on inelastic state of structures, *Earthquake Spectra*, Vol. 23, No. 3, pp. 547-569.

[18] Manjula N. K., Nagarajan, P., Pillai, T. M. M and Karthiga, S.(2016): On the relevance of Nonlinear Static Procedures for buildings with Vertically Asymmetric Setbacks, *Advances in Structural Engineering*, DOI: 10.1177/1369433216630826

[19] Inel, M. and Ozmen, H. B. (2006): Effects of plastic hinge properties in nonlinear analysis of reinforced concrete buildings, *Engineering Structures* Vol. 28, No. 11, pp. 1494-1502.

[20] Powell, G. H. (2006): A State of the Art Educational Event: Performance Based Design using Nonlinear Analysis- *seminar notes* - Computers and Structures, Inc, Berkeley, California.

[21] SAP 2000 NL (2008), V 14.0, **Computers and Structures, Inc.** Berkeley, California.

[22] Pampanin S, Magenes G. and Carr A. (2003): Modelling of shear hinge mechanism in poorly detailed RC beam-column joints, *Proceedings of the fib 2003 Symposium: Concrete Structures in Seismic Regions*, Athens, Greece, May, Paper no. 171.

[23] IS 13920: 1993 (Reaffirmed 2008): Ductile detailing of reinforced concrete structures subjected to seismic forces- Code of practice, *Bureau of Indian Standards*, New Delhi, India.

[24] Sullivan, T. J., Calvi, G. M. and Priestley, M. J. N. (2004): Initial stiffness versus secant stiffness in displacement based design, *Proceedings of the 13th WCEE*, Vancouver, B. C., Canada, August.

[25] Fajfar, P. (2000): A nonlinear analysis method for performance-based seismic design, *Earthquake Spectra*, Vol. 16, No. 3, pp. 573–592.

[26] Salawdeh, S. (2009): Displacement based design of vertically irregular frame wall structures, *Dissertation for Master degree in earthquake engineering*, ROSE school, London.

[27] Karavasilis, T. L., Bazeos, N. and Beskos, D. E. (2008): Seismic response of plane steel MRF with setbacks: Estimation of inelastic deformation demands, *Journal of Constructional Steel Research*, Vol. 64, No.6, pp. 644-654.