Comparison of exact IDA and approximate MPA-based IDA for reinforced concrete frames

H.R. Vejdani-Noghreiyan[1] and A. Shooshtari[2]

[1] *PhD Candidate, Dept. of Civil Engineering, Ferdowsi University of Mashhad, Mashhad. IRAN*
[2] *Assistant Professor, Dept. of Civil Engineering, Ferdowsi University of Mashhad, Mashhad, IRAN*
Email: hrvejdani@gmail.com, ashoosht@ferdowsi.um.ac.ir

ABSTRACT:

Recent decade has witnessed the improvement of performance-based earthquake engineering (PBEE) methods. Therefore, procedures to estimate performance levels of structures have developed in accuracy as well as simplification in practice. Incremental dynamic analysis (IDA) and modal pushover analysis are probably the most important methods in this aspect. IDA was identified as the state-of-the-art method to assess the performance level of structures by FEMA-350 but is a computational demanding technique. On the other hand, modal pushover analysis -despite its inherent approximate nature- is broadly used as the simplified nonlinear static method to evaluate seismic demands of structures. Recently these two methods have combined and constituted a more advanced method called MPA-based IDA which possesses the advantages of the two methods.
In this paper, a comparative study is carried out to evaluate the reliability of MPA-based approximate method for regular and irregular RC plane frames. Results show that MPA-based IDA procedure is satisfactory for structural demands with a huge reduction in computational effort for regular buildings.

KEYWORDS: Incremental dynamic analysis, Modal pushover analysis, Seismic behavior

1. INTRODUCTION

Various types of the analysis of structures for seismic design are linear static, linear dynamic, nonlinear static and finally nonlinear dynamic. The use of linear static analysis for seismic design of structures is often questioned among researchers. Although nonlinear static analysis under monotonically increasing lateral load (pushover analysis) has been gaining momentum of dynamic analysis and also exhibits simplified version of analysis, but it suffers from its approximate nature and cannot yield to an accurate estimation of seismic behavior of structures. A state-of-the-art method to assess the performance level of structures is Incremental dynamic analysis which based on nonlinear time history analysis (Vamvatsikos and Cornell 2002, 2004). This method is an extended procedure of pushover analysis that considers strength and stiffness degradation and also ground motion characteristics. In the other words, IDA is the most accurate procedure to evaluate seismic behavior of structures. The most important drawback of this procedure is its time consuming nature especially with considering full nonlinear analysis (material and geometrical nonlinearity) and strength deterioration and stiffness degradation. In section 3, a brief review of this procedure is given.

As indicated above, Pushover is an alternative method for seismic analysis of structures. In this method, lateral static loads are gradually imposed on the structure. This requires consideration of inelasticity under increasing lateral loading. The pushover procedure has been evaluated in several studies. (Gulkan and Sozen 1974) are probably the first researchers who suggested pushover for representing the response of multi-degree of freedom system by a single degree of freedom equivalent. (Saiidi and Sozen 1981) introduced a simple analytical model to estimate the displacement histories of multi-storey reinforced concrete structures subjected to strong ground motions. In developing this model they made two major simplifications. First, they replaced a multi-degree-of-freedom (MDOF) model of a structure by a single degree-of-freedom (SDOF) oscillator. Secondly they approximated the variation of incremental stiffness properties of the whole structure by a single nonlinear spring. The specifications of SDOF oscillator were determined based on a calculated relationship between base moment and lateral displacement under monotonically increasing load. These researchers compared displacements of eight small-scale reinforced concrete structures which were tested under strong ground motions with those obtained analytically. The results showed that the method produced good correlations in both high and low amplitude ranges. (Moghadam and Tso 1995) conducted nonlinear static pushover analysis of asymmetric buildings. They designed two 7-storey reinforced concrete ductile moment resisting frame buildings, one symmetric and the other one asymmetric. A 3-D analysis was carried out using computer program CANNY-C. They investigated displacements; inter storey drift, ductility and hinging patterns. It was shown that for the same level of lateral load, the exterior frame of the asymmetrical building experienced significantly larger inter-storey drift and larger ductility demands for both columns and beams.

Despite the usefulness of pushover analysis, it suffers from many fundamental deficiencies compared to inelastic time history analysis. Some of them are as follows:
1-Pushover analysis implies a separation between structural capacity and earthquake ground motion.
2-Damage in pushover analysis is just related to the lateral deformation of the structure. Results obtained by nonlinear time history analysis show that, earthquake duration has an effective role in the response of structures. In other words, cumulative damage caused by the reversal loading is one of the most important parameter in the response of structures.
3-Inelastic dynamic analysis shows that height distribution of mass influence the response of structures that cannot take into account in conventional pushover analysis.
4-Pushover analysis cannot consider the changes in dynamic characteristics of structures during analysis.
5-Pushover method is limited to a single-mode response and hence, only buildings with a dominant mode shape may be evaluated reliably.

For the above reasons, possible developments to conventional pushover are suggested by researchers (Antonio 2004a, b). Among the publications in this area, adaptive pushover analysis accounts for the changes in dynamic characteristics of structures during analysis. Another important improvement over conventional pushover procedure is modal pushover analysis (MPA). In this method, the effects of higher modes are considered in the analysis. This method is based on structural dynamics and proposed by (Chopra and Goel 2002). In the following section, a brief review of MPA is introduced.

2. MODAL PUSHOVER ANALYSIS

As indicated earlier, one of the most important drawbacks of incremental dynamic analysis is its time consuming nature. In the MPA-based IDA procedure, the MPA procedure is used to estimate the nonlinear response of the structure due to each ground motion intensity level. Thus, a great amount of time could be saved. In MPA procedure, ground motion is interpreted as effective earthquake forces and can be expanded as follows:

$$\{P_{eff}\} = -[m]\{1\}\ddot{u}_g(t) = -\sum_{n=1}^{N} \Gamma_n [m]\{\phi_n\}\ddot{u}_g(t) \tag{2.1}$$

Where $\{\emptyset_n\}$ is the nth-mode of natural vibration and $\Gamma_n = \frac{\{\phi_n\}^T[m]\{1\}}{\{\phi_n\}^T[m]\{\phi_n\}}$
The peak response of the building to the ground motion record is then calculated by combining the peak response of the building to each modal inertia force by appropriate combination rule (such as SRSS or CQC). The modal inertia force according to the definition is as follows:

$$\{P_n(t)\} = \Gamma_n[m]\{\phi_n\}\ddot{u}_g(t) \tag{2.2}$$

In the MPA procedure, the peak response to $\{P_n(t)\}$ is determined by pushover analysis using the force distribution $\{F_n\} = [m]\{\phi_n\}$

After obtaining the pushover curve for each load pattern, idealization of the curve is carried out and a bi-linear curve is extracted. After that, a nonlinear response history analysis for a SDOF system is carried out and the peak demand parameters are calculated. It should be noted that in practice two or three mode shapes are enough for estimating seismic behavior of the building.

3. INCREMENTAL DYNAMIC ANALYSIS (IDA)

Equilibrium equations governing the response of a planar reinforced concrete structure are:

$$[m]\{\ddot{u}\} + [c]\{\dot{u}\} + \{f_s(t)\} = -[m]\{1\}\ddot{u}_g(t) \tag{3.1}$$

In this equation {u} represents floor displacements relative to the ground, [m], [c] and $\{f_s\}$ denote mass, damping and nonlinear relation between lateral load and displacements respectively. Nonlinear response history analysis involves direct solution of the above coupled equations mainly numerically like newmark or $\theta - wilson$ procedures.

IDA is parametric analysis method to estimate structural performance under seismic loads. It involves subjecting a structural model to an ensemble of ground motions, each scaled to intensity levels from elastic behavior to global dynamic instability. The IDA requires a series of nonlinear RHA for an ensemble of ground motions while each record is scaled to represent several intensity levels for the ground motion. Since IDA requires nonlinear response analysis of the structure, it is certainly computationally demanding for practical structures. Therefore, simplified procedure to decrease computational cost of the analyses was proposed by (Han & Chopra 2006). They used MPA to approximate response of the structure under each ground motion. Thus, each of the nonlinear response history analysis required in IDA is replaced by a MPA.

4. NUMERICAL EXAMPLES

In this section, a comparative study is carried out to compare IDA and MPA-based IDA. Two kinds of plane RC frames (regular and irregular buildings) are investigated. For each kind, two buildings (4 and 8 storey buildings) are considered. Before investigation, these buildings were designed based on ACI 318-99 and then, SeismoStruct -freely downloadable software from www.seismoSoft.com- is used to model the buildings. This software is a finite element program and considers geometric and material nonlinearity simultaneously. Units used in these examples are (kN-m). Material properties are assumed to be 21 MPa for the concrete compressive strength and 240 MPa for the yield strength of both longitudinal and transverse reinforcement. The spectral Pseudo-acceleration corresponding to the first-mode vibration of the elastic structure with 5% damping ratio is selected as the intensity measure of the ground motion. The response of the structure is chosen to be the peak roof drift ratio, defined as the roof displacement divided by building height.

4.1. Four-Storey Regular Frame

4-storey RC building illustrated in Fig. 1 is explored. Sections used in this building are shown in Fig.2. Vertical loads are exerted on the structure by point loads on each node of the structure. These loads are important for considering $P - \Delta$ effects on columns and stability of the whole structure. Roof lateral displacement versus lateral load using adaptive and conventional pushover analyses are compared in Fig. 5. As is observed, adaptive pushover response is between triangular pattern and uniform pattern of conventional pushover analysis.

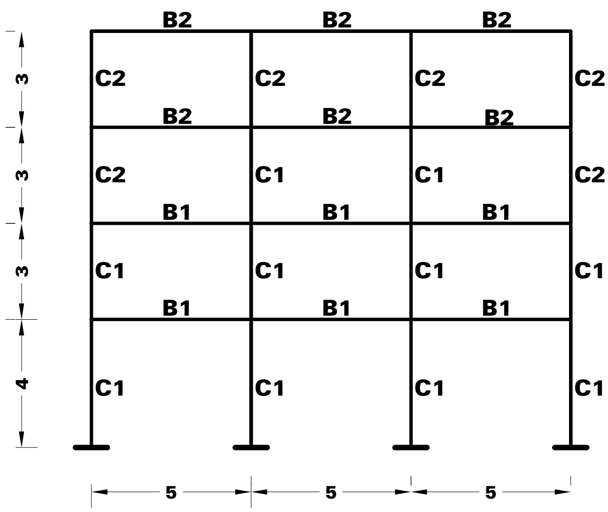

Figure 1 Four-Storey regular building

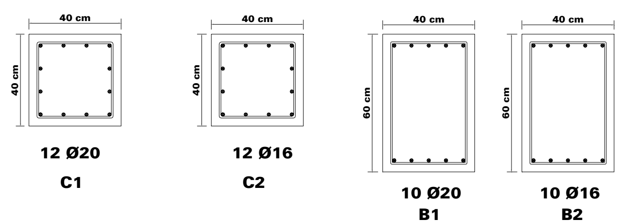

Figure 2 Column and beam sections

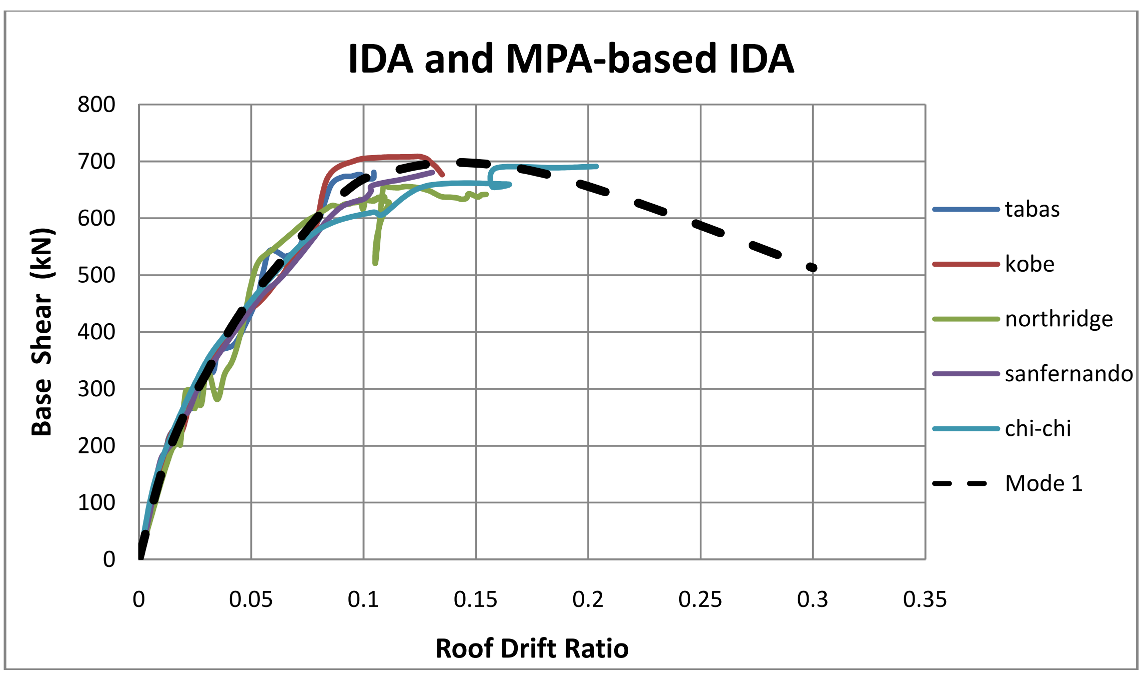

Figure 3 Comparison of IDA and MPA-based IDA

4.2. Eight-Storey Regular Building

Eight-storey regular building is another example that is shown in figure 4. Like 4-storey building, columns and beams of this building were designed and then modeled in SeismoStruct. Exact IDA and MPA-based IDA curves are compatible in a suitable manner. Although pushover with one mode is not appropriate, using three modes yields to a proper response of the structure.

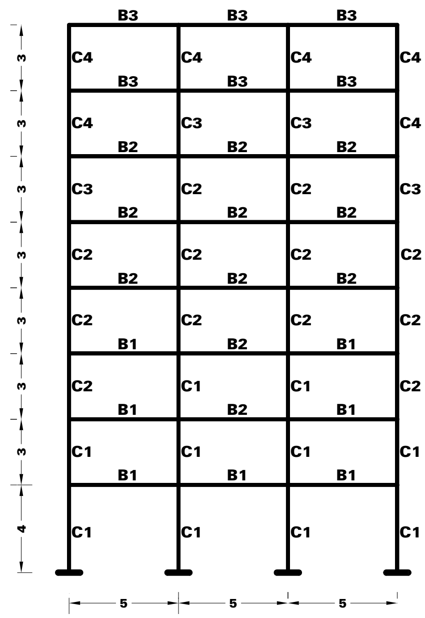

Figure 4 Eight-Storey building

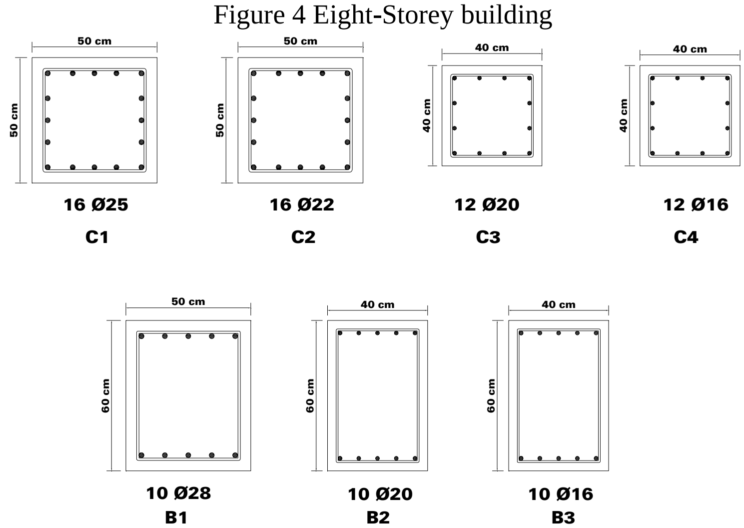

Figure 5 Column sections and beam sections of the 8-storey building

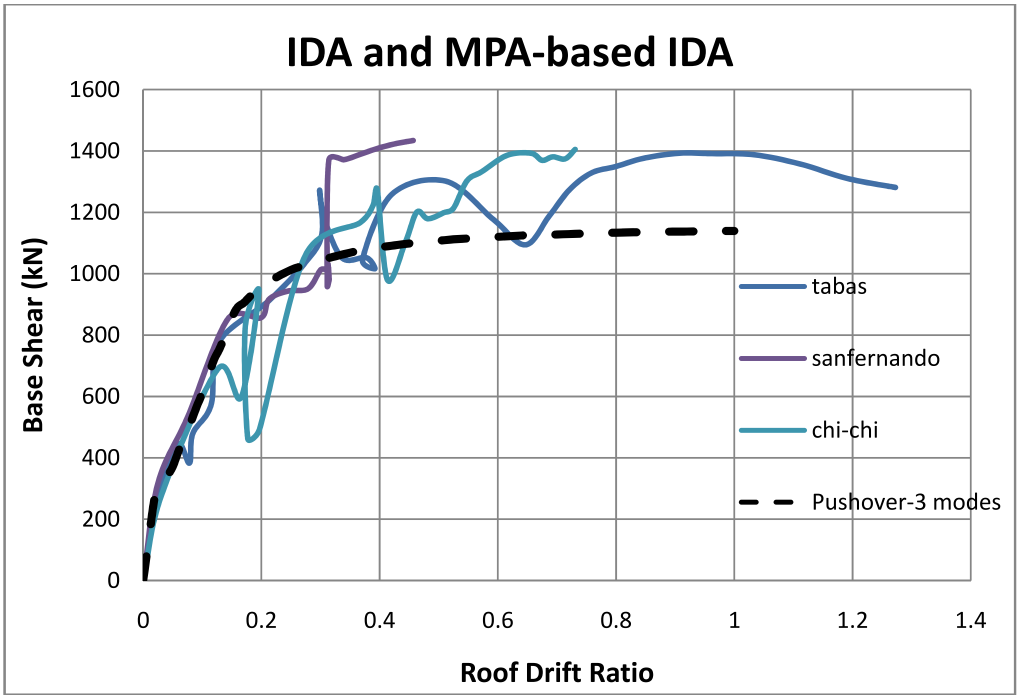

Figure 6 Comparison of IDA and MPA-based IDA

4.3. Four-Storey Irregular Building

Irregular frames are the other sort of buildings that are going to be explored in this study. Four-storey building is the first to be investigated. Figure 7 shows this building. Column and beam sections are the same as shown for regular counterpart. Although IDA curves show dispersion in comparison with regular building, but exact IDA and MPA-based IDA are comparative.

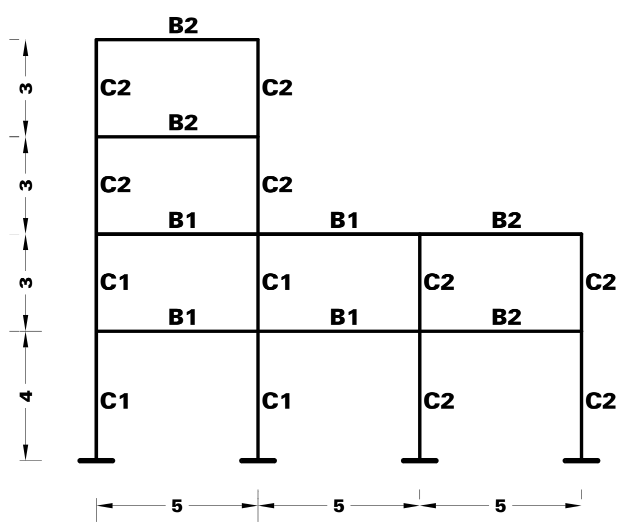

Figure 10 Four-storey irregular building

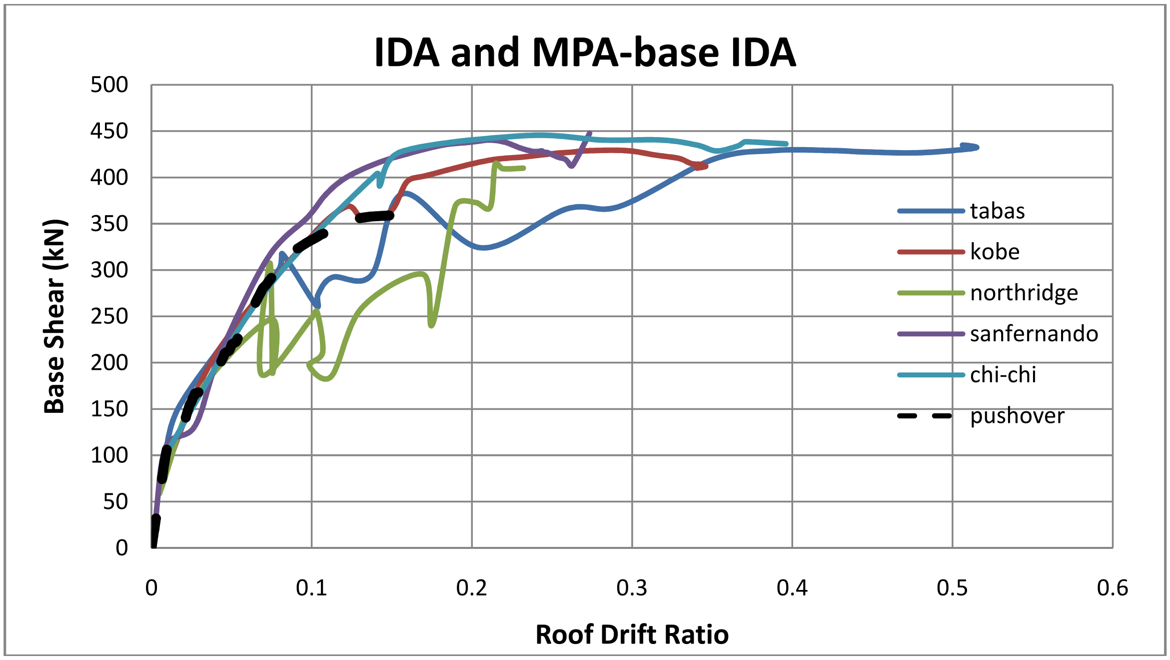

Figure 11 Comparison of IDA and MPA-based IDA

4.4. Eight-Storey Irregular Frame

For the sake of comparison, 8-storey building is also explored. In this building, even using 3 modes are not sufficient for yielding a good accuracy. As shown in figure 13, dispersion of IDA curves is considerable and MPA-based IDA is not a good representative of its behavior.

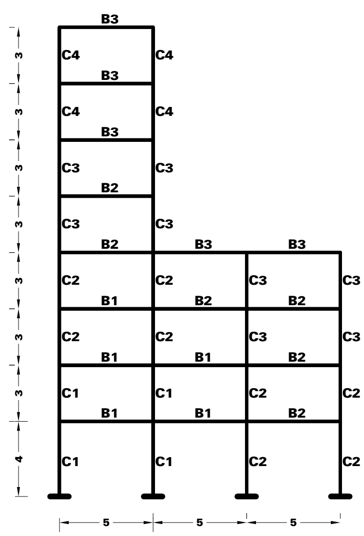

Figure 12 Eight-storey irregular building

5. CONCLUSION

In this paper, a comparative study is carried out to compare exact IDA and MPA-based IDA for regular and irregular 4 and 8 storey buildings. SeismoStruct was used to model and analyze the structures. Results of the analysis show that MPA-based IDA is a good alternative for exact IDA with a great reduction in time required for analysis. For irregular buildings this method is not reliable as indicated in the above examples.

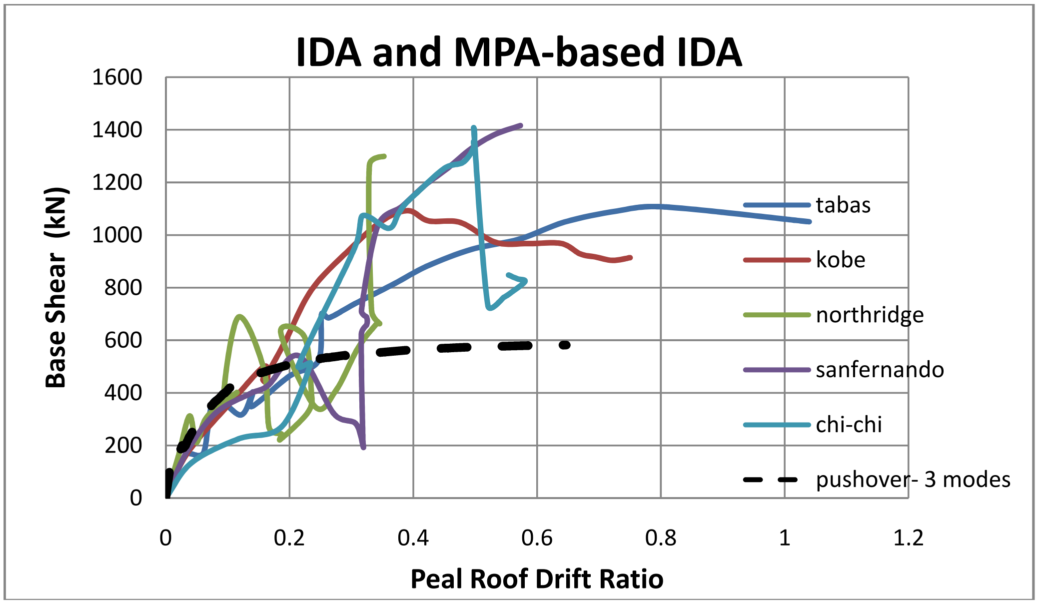

Figure 13 Comparison of IDA and MPA-based IDA for Eight-storey irregular building

REFERENCES

Antonio, S. and Pinho, R., (2004a). Development and verification of a force-based adaptive pushover procedure, Journal of Earthquake Engineering **8:5**, 643-661.

Antonio, S. and Pinho, R., (2004b). Advantages and limitations of adaptive and non-adaptive force-based pushover procedures, Journal of Earthquake Engineering **8:4**, 497-522.

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

Gulkan, P. and Sozen, M. (1974). Inelastic response of reinforced concrete structures to earthquake motions, ACI Journal **71:6**, 604-610.

Han, S.W. and Chopra, A.K. (2006). Approximate incremental dynamic analysis using the modal pushover analysis procedure. Earthquake Engineering and Structural Dynamics **35**, 1853-1873.

Moghadam, A. S. and Tso, W. K. (1995). 3-D pushover analysis for eccentric buildings, Proc. 7th Canadian conference on earthquake engineering, Montreal, 381-388.

Saiidi, M. and Sozen, M. A. (1981). Simple nonlinear seismic analysis of RC structures, Journal of Structural Engineering **107**, 937-952.

Vamvatsikos, D. and Cornell, C.A. (2002). Incremental dynamic analysis. Earthquake Engineering and Structural Dynamics **31: 3**, 491-514.

Vamvatsikos, D. and Cornell, C.A. (2004). Applied incremental dynamic analysis. Earthquake Spectra **20: 2**, 523-553.