Assessment of Improved Modal Pushover Analysis for Eccentrically Braced Frames

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ABSTRACT
This paper concentrates on evaluation of current Pushover Procedures to assess the seismic demands of Eccentrically Braced Frame (EBF). Three 5, 10 and 15 storey EBF frames, designed by Iranian codes, analyzed for five ground motions by MPA, IMPA, and as a proposed method MPA based on Energy-Based capacity curve (briefly E-B.MPA), also story drift of frames were estimated by conventional pushover using two Load distributions of FEMA-356, ELF and uniform patterns. It was considered, the 10 and 15 storey frames have reversal capacity curves, therefore the pushover curve of another story (not roof) was plotted to perform MPA but E-B.MPA was done with no difficulty. Comparing the responses of procedures with the results of Nonlinear Time History Analysis (NTHA) demonstrates that MPA.E-B determines drift demands of models with reversal capacity curves more accurate than other procedures. Moreover there are serious concerns about estimated drift demands of two load patterns.

Keywords: E-B.MPA, EBF, Reversal capacity curve

1. INTRODUCTION

Unpredictable behavior of designed structures based on conventional criteria such as allowable stress method against earthquake loads, convinced the structural and earthquake engineers to study about more efficient ways. Finally the above attempts led to new analysis and design methods like performance-based design. Because of codification of instructions deal with nonlinear static analysis method as a suitable tool for performance-based design and evaluation, use of mentioned methods have been growing. FEMA-356 (ASCE 2000) and ATC-40 (1996) were one of the first references, exploited coefficient displacement and capacity spectrum methods respectively. They estimate the target displacement point based on assumption that the responses are control by unchanged fundamental mode of vibration. Therefore there are two sources of errors here, first of all only one deformation mode is considered in the response of structures and secondly the load distribution is not verified with current stiffness of structures. In many cases the drift demands determined by FEMA-356 and ATC-40 not only differ with each other but they are not enough precise in comparison with NTHA responses (Miranda and Akkar 2002) .In order to resolve such inconsistencies, improvement made to CSM and coefficient method which are reported in FEMA-440 (ATC 2005). Chopra et al. (2002) showed that by combining the first mode responses with higher modes participation, the exactitude of responses can be increased and they called this method Modal Pushover Analysis (MPA). MPA uses invariant load pattern; since invariant load pattern is based on the initial elastic dynamic properties of the structure, as a result MPA cannot ignore the weakness of invariant load distribution to incorporate changes in the modal attributes of the structure during inelastic phase of deformation. Many researchers such as Gupta (2000), Elnashi (2000), Aydinoglu (2003), Antonio et al (2002) and Antonio and Pinho (2004) have suggested considering progressive change in the dynamic attributes of structures, which are generally called adaptive pushover.

Mao jianmeng et al. (2008) presented an improved MPA considering redistribution of load pattern after structure yield point in the first mode load applying. This method has enough simplicity to run contrary to most of adaptive procedures.
On the other hand, though the roof displacement is useful for characterizing the behavior of moment resisting frames, it is not clear that it is the most meaning index for other structures (such as braced frames). In some cases, when nonlinear behavior develops during a pushover analysis especially in higher mode load patterns, the displacements of the floors and roof may increase disproportionately with increasing load. However this "reversal" in higher mode pushover curves was found to be very rare in several investigations that examined behavior of many moment resisting frames. Goel et al. (2005) investigated on the guidelines for implementing the Modal Pushover Analysis for buildings that display "reversal" in a higher-"mode" pushover curve. On the other side to overcome the reversal problem, Hernandez-montes et al. (2004) suggested to compute the energy absorbed by the structure in generating capacity curve of structures when the modal patterns are used. By following the basic idea of ATC-40 and MPA, they estimated the effective peak response from intersection of the E-B capacity curve for each mode and the spectral elastic demands curve, then the ductility of system in the effective point is calculated, and the effective response is converted to the main response by multiplying the effective response and the ductility. Since this is a graphical way there can be a source of error here, so E-B.MPA is recommended to use NTHA procedure to compute the peak response of SDOF system where there is a SDOF relation by E-B formulation.
Although MPA and other similar methods have been evaluated in many articles by now, for instance the recently presented paper of Nguyen et al (2010), but researchers often utilize some limited structural systems for assessment of procedures, so there is not an obvious aspect about the accuracy of nonlinear static procedures for other structural systems. As a result, this paper aims to evaluate MPA guideline to solve the problem of reversal in higher mode pushover analysis, IMPA, E-B.MPA and pushover analysis by ELF and uniform load patterns in seismic analysis of EBF frames.

2. BRIEF DESCRIPTION OF PROCEDURES

2.1. MPA Procedure

This method was presented by Chopra et al. (2002), to consider the contribution of higher modes of vibration.
The difficulties associated with implementation of MPA procedure in conjunction with reversal in higher modes when the structure deforms beyond the elastic limit can be solved by the suggestions of Goel et al (2005). In this condition any reversal of traditional pushover curve may be eliminated by plotting new capacity curve for a different floor above the yielding stories. The resulted pushover curve is usable in the MPA procedure. In addition to this solution they issued to perform MMPA method by Chopra et al. (2004) what considers the participation of higher modes by assuming elastic behavior of structure.

2.2. Improved MPA

An improvement for MPA was provided by Mao jianmeng et al. (2008) which can be explained in two phases, in the first phase MPA is performed using first some elastic natural mode shapes of structure to achieve the adequate precious, in the second phase MPA is repeated only for the first mode but the load distribution is updated in the first mode yield point. Therefore the new capacity curve is generated by new load distribution and MPA is run again. The higher mode demands resulted from first phase and demands from first mode got in the second phase are combined by SRSS to gain multi-mode responses.

2.3. MPA procedure by using E-B capacity curve (E-B.MPA)

In some frame systems, there are reverse condition for the higher mode capacity curves due to formation of yielding mechanisms in some stories of frames. Generating the E-B capacity curve in place of the conventional curve modifies the mentioned problem.

When there are some floors that their displacements are not proportional to the elastic mode shape (generally in higher modes), E-B.MPA procedure uses the E-B capacity curve to compute the peak displacement of the multi degree of freedom (MDOF) system due to the responses of a SDOF from NTHA or a design spectrum. In order to identify the roof displacement corresponding to the peak response of SDOF system, the absorbed energy should be determined from the E-B capacity curve and the load step associated with this to know the relevant roof displacement. Obviously for the displacements proportional to the elastic mode shape (first mode load pattern) conventional relations between the peak displacement of the equivalent SDOF and the MDOF system can be used.

2.3.1. Generating the E-B capacity curve

Enrique Hernandez-montes presented a formulation to this purpose, based on the dynamic equilibrium of structures expressed in term of energy concept, which was described by Uang and Bertero (1988):

$$\frac{1}{2}\dot{U}_t^T.m.\dot{U}_t + \int \dot{U}^T.Cdu + \int f_s^T du = \int (\sum_{j=1}^{N} m_j \ddot{U}_{tj})du_g \tag{2.1}$$

m_j, $\ddot{U}_{tj}$ are the mass and acceleration of jth story, C is the classic damping and U_g and f_s^T are equal with ground displacement and restoring force.

The corresponding base shear associated with the nth mode pushover in terms of its modal components and the absorbed energy, E_n, or work done by lateral load distribution f_n can be computed respectively by Eqn. 2.2, 3:

$$V_{bn} = f_n^T * l = \omega_n^2 \Gamma_n \phi_n^T ml D_n(t) = \omega_n^2 \Gamma_n^2 m_n D_n(t) \tag{2.2}$$

$$E_n = \int f_n^T du_n = \int \omega_n^2 \phi_n^T m \phi_n \Gamma_n^2 dD_n^2(t) = \int \omega_n^2 \Gamma_n^2 m_n dD_n^2(t) \tag{2.3}$$

While Γ_n , ϕ_n , ω_n and D_n are modal participation factor, mode shape, natural frequency and displacement of a SDOF system in nth mode, respectively.

The work done by V_{bn} in a differential displacement dD is dE:

$$dE_n = V_{bn}.dD_n \tag{2.4}$$

By an incremental formulation during pushover analysis for instance in a "r" storey frame, the spectral displacement $S_{d,n}$ is calculated by summation of $\triangle D_n$ up to step i:

$$S_{d,n} = \sum \Delta D_n^{(i)} = \sum \frac{\Delta E_n}{V_{bn}} = \sum\{(\sum_{j=1,r} (F^{(i)}{}_{n,j} \Delta d_{n,j}) /(\sum_{j-1,r} (F^{(i)}{}_{n,j})\} \tag{2.5}$$

The ordinate of E-B capacity curve $S_{a,n}$, may be obtained by the conventional conversion of base shear $V_{b,n}$, to acceleration response spectrum format:

$$S_{a,n} = \frac{V_{bn}}{W\Gamma_n \phi_n^T ml} = \frac{V_{bn}}{W\alpha_n} \tag{2.6}$$

W is total weight of frame and α_n is called modal mass coefficient expressing as Eqn. 2.7:

$$\alpha_n = (\phi_n' ml)^2 /[(\phi_n' m\phi) / \sum_n m_n] \tag{2.7}$$

3. STRUCTURAL SYSTEMS AND ANALYTICAL MODELS

Three 5, 10, 15 storey dual frames, EBF and MRF structural systems (see Fig. 3.1), which are named f5, f10, f15 respectively, with rigid connections (except the connections of braces) designed based on allowable stress criterion by the code from Iranian steel design. For seismic loading, the Iranian code of practice for seismic resistant design (Standard 2800) was used. In order to establish shear yielding mechanism in the link beams, because of lateral deformation of frames, Length of link beam as a fixed parameter is e=0.6 *meter* for three models. Story height and bay length are 5 and 3 *meters* in each frame.

3.1. Nonlinear analyses

For performing nonlinear static procedures (NSP) including MPA, IMPA and E-B.MPA and conventional pushover analysis by ELF and Uniform load patterns and NTHA procedure, nonlinear modeling by assigning Plastic hinges for the members of each model (Table 3.1) was done. For design of models, running pushover procedures and NTHA, SAP 2000, Ver. 12 was used. For generating E-B capacity curve, a program which has been named ENERGY was written by author in Macro, Excel (by Visual Basic compiler) in accordance with mentioned formulation. Energy either can compute E-B capacity curve of MRF or CBF systems, for further researches.

Table 3.1. Plastic hinges properties and location

Frame system	Member of Frame	Hinge Location along member	Mechanism of control	Hinge Type
EBF	Link beam	Start & End	Deformation	M3
		Middle	Deformation	
	Brace	Middle	Force	V2
	Beam out of link	Start & End	Force	P
	Column	Start & End	Force	PM3
MRF	Column	Start & End	Deformation	PM3
	Beam	Start & End	Deformation	PM3

(a) 15 Storey (b) 10 Storey (c) 5 Storey

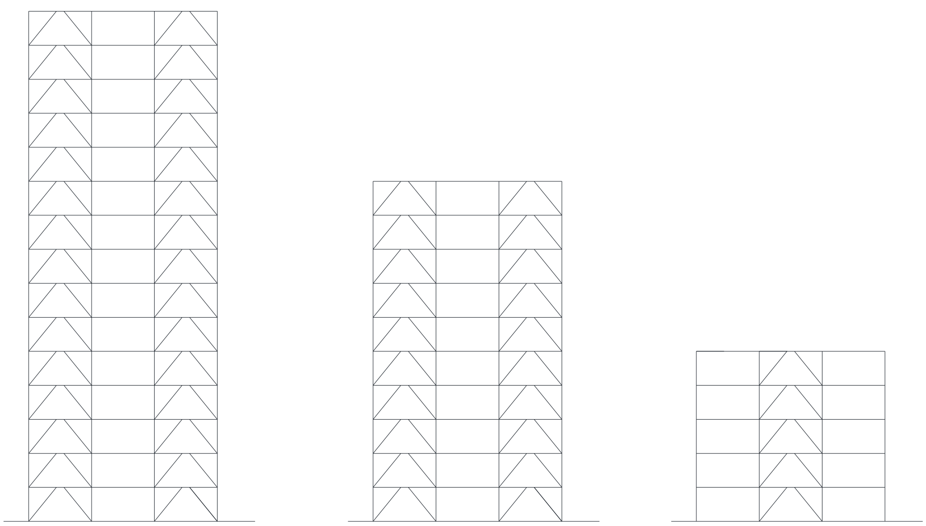


Figure 3.1. Frame evaluation of (a) f15, (b) f10 and (c) f5

4. GROUND MOTIONS

In order to develop a set of benchmark responses against which to compare the mentioned nonlinear static procedures, five pair of ground records having far-fault characteristics were compiled. These records were selected with the objectives of almost same properties such as soil type (NEHRP classification) and closest distance to rupture, between popular strong ground motions.

According to the direction of Standard 2800, each pair of records were processed to compute relevant scale factors to amplify the records to induce each model to respond sufficiently beyond the elastic limit. The resultant scale factors for models f5, f10, and f15 are respectively 0.49g, 0.57g, and 0.62g. The ground motions used for evaluation study are summarized in Table 4.1.

The responses of each building to each ground motions were determined by NTHA as the accurate responses and NSPs e.g. MPA, IMPA and E-B. Synthetic response spectrums of ground motions for each record are illustrated in Fig. 4.1.

Table 4.1. Ground motion ensemble

Earthquake	Year	Station	Component	Magnitude (M)	Distance (km)	Site class	PGA (g)	PGV (cm/s)
Coyote lake	1979	57191 Halls Valley	HVR-240	5.7	31.2	D	0.05	4.8
			HVR-150				0.039	2.2
Imperial Valley	1979	6621 Chihuahua	H-CHI-012	6.5	28.7	D	0.27	24.9
			H-CHI-282				0.254	30.1
Loma Pieta	1989	57191 Halls Valley	HVR-000	6.9	31.6	D	0.134	15.4
			HVR-090				0.103	13.5
North Ridge	1994	Hollywood stor ff	HOL-090	6.3	25.5	D	0.231	18.3
			HOL-360				0.358	27.5
Victoria (Mexico)	1980	6621 Chihuahua	CHI-192	5.5	36.6	D	0.092	15.6
			CHI-102				0.15	24.8

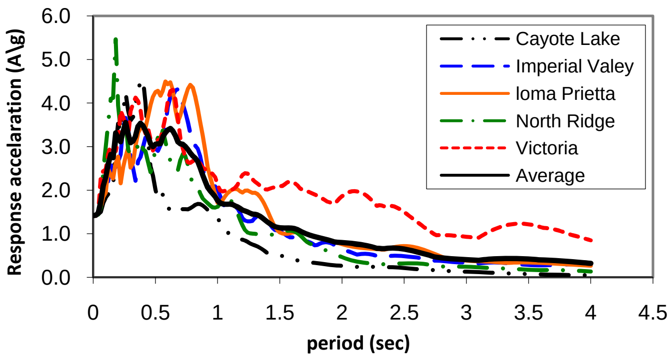


Figure 4.1. Synthetic response spectrums of ground motions

5. EVALUATION OF NONLINEAR STATIC PROCEDURES

Since the responses of frames to inspiration of ground motions are directly related to the SDOF (spectral) capacity curve, so the first three spectral capacity curves resulted from pushing model frame are presented. Furthermore, the accuracy of MPA, IMPA, and E-B.MPA and pushover procedure using ELF and uniform (only for drift) for seismic analysis of frame models are evaluated by comparing the peak floor displacements and story drifts in comparison with the more precise results from NTHA.

5.1. Capacity curves

Spectral pushover curves which are needed to get SDOF relation for model F10 due to the first three modes load patterns used in MPA as the conventional spectral capacity curves and the new spectral capacity curve generated by E-B formulation are illustrated in Fig.5.1. Because of reversal in second and third mode conventional capacity curves of models f10 and f15, MPA was performed in accordance with the instruction of Goel et.al. (section.2.1), by plotting a capacity curve for seventh and eleventh story of model f10 and f15, respectively. Nevertheless the capacity curve of third mode is reverse but since in this mode the response of f10 was located in elastic domain, only it is necessary to have elastic stiffness.

As it is clear the reversal apparent of capacity curves in higher modes are neglected by using E-B capacity curve. Alternatively capacity curve of seventh story of model f10 was normal, in this condition all of quantities what are necessary to reach the responses in MPA should be based on the attributes of this story.

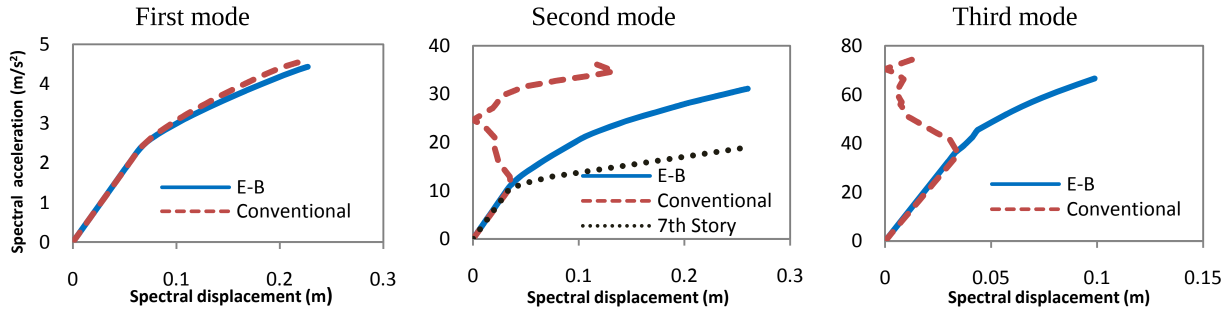


Figure. 5.1. Conventional and E-B spectral capacity curves of first three modes of frame f10

5.2. Peak floor displacements

The error of median peak floor displacements of the frames due to the set of ground motion was determined by MPA, IMPA, and MPA.E-B and also by conventional pushover is presented in Fig. 5.2. Frames were pushed to the median roof displacements estimated from NTHA. For each frame the contribution of first three modes were considered. The trend of displacement for f5 by MPA and MPA.E-B are similar, IMPA for this frame and upper stories of f10, f15 could determine the displacements more precise. The displacements estimated by MPA.E-B for f10, f15 in lower stories are more accurate. Overall the error of estimated demands is in an acceptable range nevertheless floor displacement is not an effective parameter in damage assessment having been imposed by an earthquake to structures.

5.3. Story drift demands

Fig. 5.3 demonstrates median drift demands and the related error for each frame estimated by MPA, IMPA and MPA.E-B procedures in comparison with NTHA responses. As it was expected, because the conventional capacity curves of f5 in first three modes were normal, drift demands estimated by IMPA and MPA.E-B are nearly similar. To sum up, drift demands of f 10, f15 by MPA.E-B are better estimated than other procedures, it means that for reverse position E-B.MPA estimates more realistic answers compared to MPA. Although during performing IMPA the applied load was updated in yielding point of frames but it led to an inconsistency for estimating drifts. On the other hand error of drift demands from ELF and uniform distribution shows the great limitation of them to compute the answers; especially uniform pattern underestimates drift demands in lower stories and vice versa in upper stories.

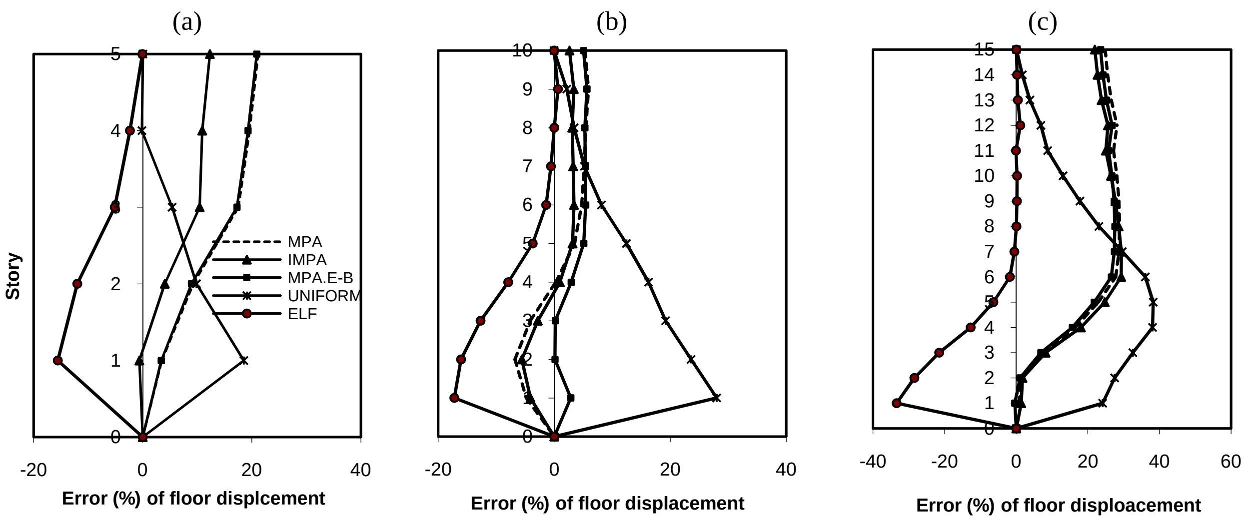
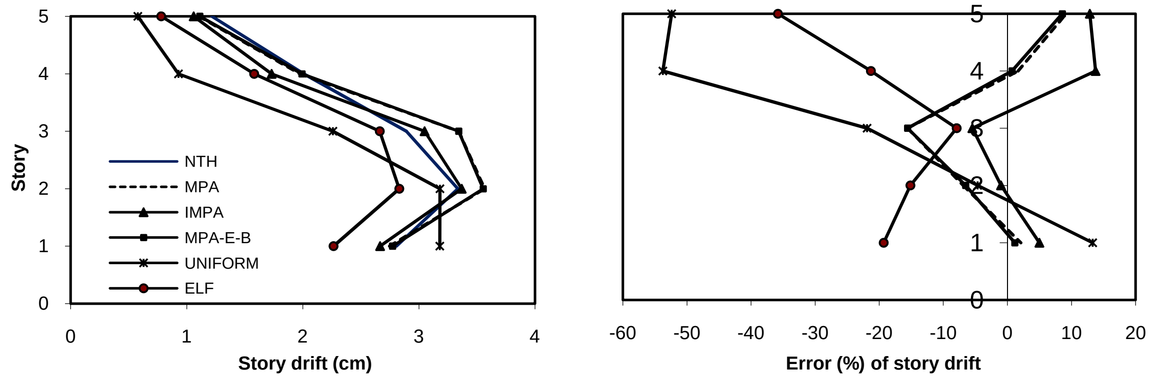
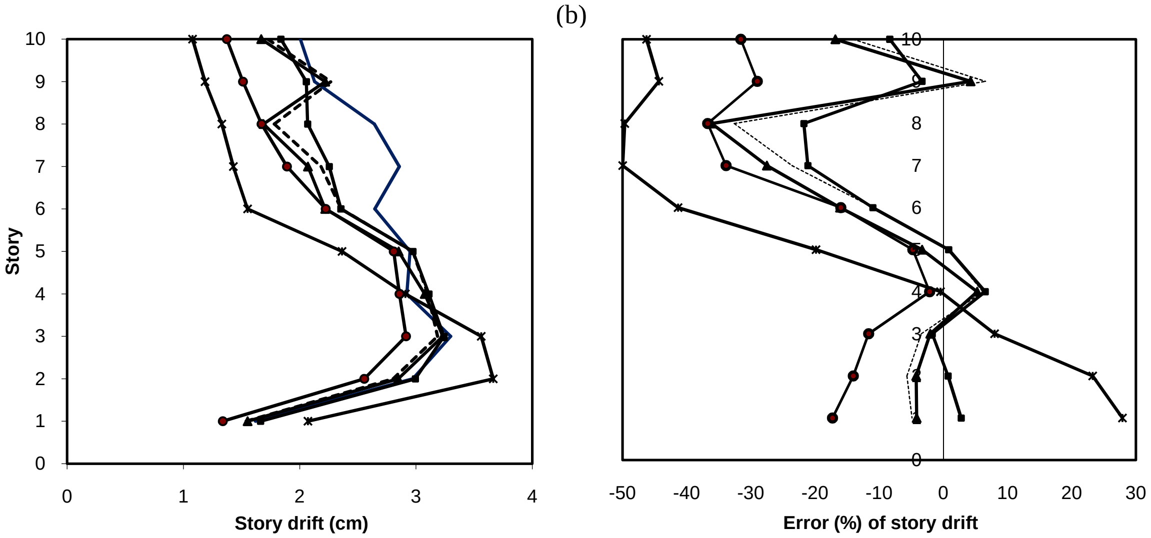


Fig 5.2. Percentile error of median floor displacements of (a) f5, (b) f10 and (c)f15 frames

(a)



(b)



(c)

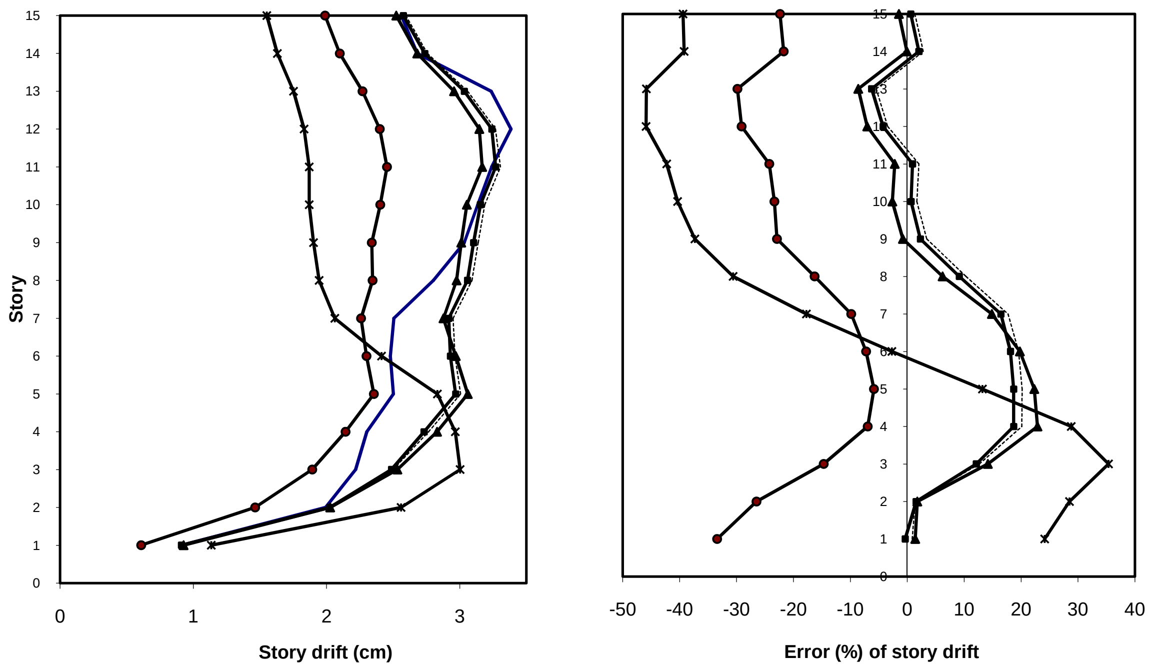


Fig 5.3. Median story drift and related percentile error of (a) f5, (b) f10 and (c)f15 frames

6. CONCLUSION

1. Generally, the displacement demands are estimated by all of procedures properly.
2. For building frames with reversal in higher modes capacity curve, the proposed method MPA.E-B determines drift demands comparatively better than MPA and IMPA. It seems that if the contribution of higher modes surges, the difference of responses between MPA and E-B.MPA would grow up.
3. There are huge amounts of error for drifts estimated by conventional pushover analysis using ELF and Uniform load patterns. So there are serious concerns about seismic assessment by this method.

It may be a good idea to perform an adaptive MPA and evaluation for a broad range of structural systems and noticing to reversal capacity curves and using E-B capacity curve.

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