Using energy -based pushover methods in Seismic Evaluation of Steel Bracing Structures

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Abstract:

Nonlinear static analysis is a simple and practical method to evaluate seismic demands in structures that has been considered in most of seismic instructions in recent years. Since the concept of energy is more theoretic than other similar methods, the present article evaluated the models of lateral loads discussed in the concept of energy. This approach can be updated in the steps of nonlinear static analysis or remains constant in all steps of the analysis. One of updated pushover models called “story shear-based pushover" has used the concept of energy to estimate the target displacement; so that instead of control point displacement, all stories displacement has been used. Multiple mode load model (MPA) has used energy method to adjust single freedom degree curve and eliminate the problems of rood point displacement reverse in loading models. In the present research, different bracing structures have been subject to lateral loading to evaluate energy-based methods, and the results were compared and assessed by dynamic analytical results. The results of Steel Bracing structural analysis show that energy-based methods have been successful to estimate the storey shear values as the most important parameter in the design of structures.

Keywords: Lateral load pattern, energy, non-linear analysis time history; pushover

١- Introduction

It seems that nonlinear static analysis methods are one of the most popular analysis methods due to the ease of use, and also present an effective graphical display of general response of structure directly to the pushover curve. This curve is directly related to the system capacity, usually defined by base shear with an important structural node (controller node) response. This kind of overall response allows a direct idealization of structure as a single degree of freedom (SDOF) system that simplifies design or evaluation. Essential steps to perform a nonlinear static analysis method would be as follows:

Conducting a static pushover analysis.

Defining an equivalent SDOFS, based on pushover curve, obtained from a static pushover analysis.

Estimating maximum total displacement demand, based on a selected design response spectrum.

Equivalent and Actual SDOFS response of structure are related by a shape factor, usually determined in the first mode participation factor.

Finally, the response parameters, in-floor drift and forces on each structural member can be evaluated through pushover curve (or capacity curve) by knowing the overall demand of the system. All non-linear static methods have been proposed are different, especially in defining the overall displacement demand (step ٣) and they can vary in two main groups: equivalent linearization and coefficient classification methods. Among the equivalent linearization methods, Rosenblueth and Herrera, Gülkan and Sozen, Iwan, Priestley and Kowalsky, Freeman CSM, and adjusted CSM (Chopra and Goel) can be pointed out. Methods of Newmark and Hall, Miranda, Federal Emergency Management Agency (FEMA) ٣٥٦, and N٢ method of Fajfar can be implied for coefficient methods. Some researchers such as Hernàndez-Montes and Shakeri have used the energy concept to define structural capacity curve with single degree of freedom for equivalent linearization and obtained better results with stronger theories. In this research, these methods have been evaluated.

٢- Literature Review

As it was described by Kunnath, the term "pushover analysis" makes a new change in classic collapse analysis, thereby a repetitive-incremental solution of static equilibrium equations will be done to obtain the response of a structure under bilateral incremental lateral load pattern. The structural strength is evaluated and stiffness matrix is updated at each step of the loading function. The solution will continue until (1) a predetermined level of performance is reached, (2) collapse of structure is formed or (3) the program fails to converge. In this manner, each point of the basic shear capacity curve shows a state of effective and equivalent stress against displacement, in other words, indicates a state of the deforming directly corresponded to the vector of applied external load.

Even by the simplified analytical tool against nonlinear dynamic analyses, important information for structural response, such as the followings may be provided:

Recognizing the progress of overall capacity curve of the structure.

Recognizing the critical areas, where large inelastic deformations may occur.

Recognizing resistance irregularities in plan and height which could cause significant changes in the inelastic dynamic response characteristics (for example, Krawinkler and Seneviratna, 1998).

Energy demand estimation in the potential fragile elements.

Predicting sequence submission or failure in structural members.

Modal pushover analysis (MPA) has been proposed by Chopra and Goel. In this method, Pushover analyses in each mode have been performed independently, using lateral load profiles showing the expected response in any of the modes. Pushover curve related to each modal pushover analysis is idealized as a bilinear SDOF system. And the responses were combined with each other using SRSS or CQC to define overall answer of the system.

One of the main deficiencies of MPA, as shown in Figure 1, is reversible capacity curve for the higher modes. Since the roof displacement changes in higher modes is not appropriate with the changes of other modes, the roof displacement in the higher modes of some structures are reduced by the increase of base shear after the establishment of structure and formation of plastic hinges, then the pushover curve is moved reversibly that make it difficult to use this method and its application in engineering offices as an alternative approach to the regulations methods.

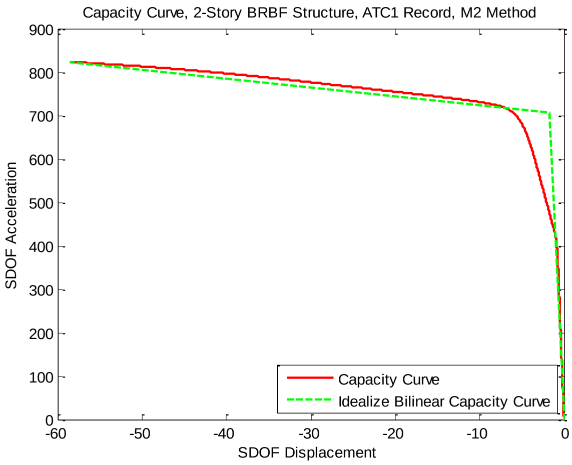

Figure 1: The pushover curve of a two story building, buckling bracing for the second mode

Hernàndez-Montes in 2004 solve this problem focusing on the concept of energy. So in order to determine displacement characteristic in the capacity spectrum of single degree of freedom system, the displacement of all stories is used. The increase of displacement characteristic in capacity spectrum curve in each stage is obtained by dividing the work done in all stories due to the increased load on the base shear at the same story.

In recent years, FIMA 440 (ATC, 2005) has compared this approach with another pushover model. The results show that, although this method has been advanced to the most of simple load mode vectors, the estimations of in-story drift on the total height of structure might be unreliable. It seems that the main limitations of MPA is in connection with the precision of engineering parameters such as forces and rotation of plastic hinges, structural characteristics, and specific details of the method.

A new pushover method called SSAP has been proposed by Shakeri and Shayanfar, in which the energy concept is used to obtain the target displacement of the structure. Such new pushover procedures have the following features:

- Are based on the energy method and solve the problems associated with displacement of roof control.
- Calculate the effects of higher modes by combining multiple response modes.
- Have very simple concepts that applicable in seismic codes and simple programming.
- Apply progressive degeneration and loss of stiffness and strength directly to the load pattern.

٣- complete description of the research methodology

The accuracy of SSAP, FAP, DAP, ELF, EMPA, the distribution of the first mode, the inverted triangular distribution, regulative distribution, and uniform distribution based on mass by using dynamic time history as the most accurate method were compared and evaluated in this research. Except traditional pushover methods, first three modes have been used for the rest of nonlinear static methods to include the effects of higher modes. The target displacement is obtained by maximum inelastic deformation resulted from nonlinear dynamic analysis of a single degree of freedom system.

A nonlinear dynamic analysis has been used to analyze this system, and then the submission and failure of the member is considered. Thus, system capacity is not based on initial submission or even the failure of single member, and it is defined when the rate of lateral displacement increase of the system is exceeded. Therefore the predicted seismic capacity of this method is different for each earthquake.

The parameters selected for assessing the accuracy of different methods include drift ratios of the stories, the displacement of stories and storey shear. The drift ratios within the storey indicate the maximum values of in-storey drift between two adjacent balances, which are calculated for each storey over time and are normalized to the height of associated storey. The results of the mean and standard deviation are shown based on the maximum values obtained in the building height for each earthquake record. To estimate the maximum peak of in-storey drifts created in each of these structures for the earthquake records, nonlinear dynamic analyses have been used. In this study, the normal in-storey drift (normalized to the height of each floor) is used as a parameter to describe the damage to the overall structure. It is expected that, in-storey drift is related to the maximum plastic deformations in the structural elements, the degree of damage to sensitive- to-displacement non-structural elements, and inclination of the structure to create general instability due to P-Δ effects. In this study, in order to detect damage imposed to the building in a certain earthquake, the maximum in-storey drift of each floor is used. Considering a set of earthquakes and assuming a normal probability distribution, the mean and standard deviation for the maximum in-storey drift were calculated and also were used as an index to express the dispersion of answers.

Also storey shears were compared as one of the most important engineering parameters.

The error criterion used to evaluate the accuracy of estimation obtained by different pushover methods is the index proposed by Lopez and Mengivar that is presented as formula (1). It should be noted that this criterion is applicable only to describe the difference between methods and do not represent the absolute error.

$$\text{Error}_{\Delta}\ (\%) = 100 \times \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(\frac{\Delta_{i-NSP} - \Delta_{i-NTHA}}{\Delta_{i-NTHA}}\right)^2} \quad (1)$$

In this equation, n represents the number of floors, Δ_{i-NTHA} the mean of maximum response obtained by dynamic time history analysis, and Δ_{i-NSP} the mean of response obtained from nonlinear static analysis.

٤- structural models

Index model for BRBF system has been designed in accordance with the requirements of AISC 341-05 design, Seismic Provisions for Structural Steel Buildings, ASCE / SEI 7-05 regulations, Minimum Design Loads for Buildings and other structures. The beams, columns, and bracing components are designed such that excessive strength doesn't create in the structure. These samples have adapted from the reference [21] and have been analyzed and evaluated in the software OpenSEES.

In this research, two 6-storey and 12-storey braced samples were used as the representatives of average and high structures; the gap between columns is 30 feet as type and the height is 15 feet. Buckling braces are arranged as two story- X. Additional information on these models are available in [21].

Ground motions used to evaluate the performance of different pushover methods in converging braced steel frames in this study have been prepared by FEMA P-695 which are the representative of far-fault ground motions scaled for soil type SD and risks corresponding to a probability of 10% at 50 years in downtown Los Angeles. These earthquakes include 7 ground's motions, these movements are scaled such that their average response spectrum is consistent with the spectrum of ASCE / SEI

7-05 [20] of the same risk level and soil. The technical specifications of these records are presented in Table 1.

Table (1):

EQ label	PEER-NGA Rec. Num.	Description	Earthquake Magnitude	Campbell Distance (km)	Joyner-Boore Distance (km)	Number of Points	Time Step (sec)	PGA (g)
GM۱	۹۵۳	۱۹۹۴, Northridge, Beverly Hills - Mulhol	۶,۷	۱۷,۲	۹,۴	۲۹۹۸	۰,۰۱	۰,۵۲
GM۲	۹۶۰	۱۹۹۴, Northridge, Canyon Country-WLC	۶,۷	۱۲,۴	۱۱,۴	۱۹۹۸	۰,۰۱	۰,۴۸
GM۳	۱۷۸۷	۱۹۹۹, Hector Mine, Hector	۷,۱	۱۲	۱۰,۴	۴۵۲۹	۰,۰۱	۰,۳۴
GM۴	۱۶۹	۱۹۷۹, Imperial Valley, Delta	۶,۵	۲۲,۵	۲۲	۹۹۹۰	۰,۰۱	۰,۳۵
GM۵	۱۱۱۱	۱۹۹۵, Kobe, Japan, Nishi-Akashi	۶,۹	۲۵,۲	۷,۱	۴۰۹۵	۰,۰۱	۰,۵۱
GM۶	۱۱۵۸	۱۹۹۹, Kocaeli, Turkey, Duzce	۷,۵	۱۵,۴	۱۳,۶	۵۴۳۶	۰,۰۰۵	۰,۳۶
GM۷	۱۱۴۸	۱۹۹۹, Kocaeli, Turkey, Arcelik	۷,۵	۱۳,۵	۱۰,۶	۵۹۹۹	۰,۰۰۵	۰,۲۲

۵- Results and interpretation

Following figures show the results of the seismic response of structures under dynamic time history analysis and different nonlinear static analyses.

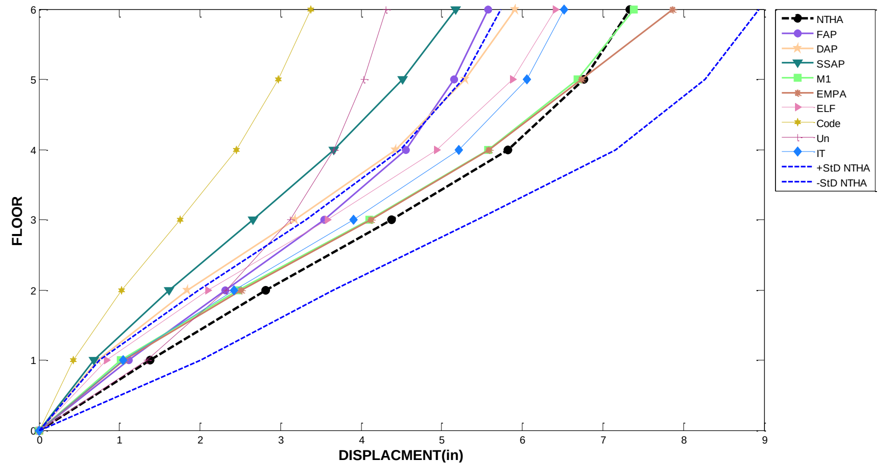

Figure 2: Mean of maximum displacement obtained from all selected records in the height

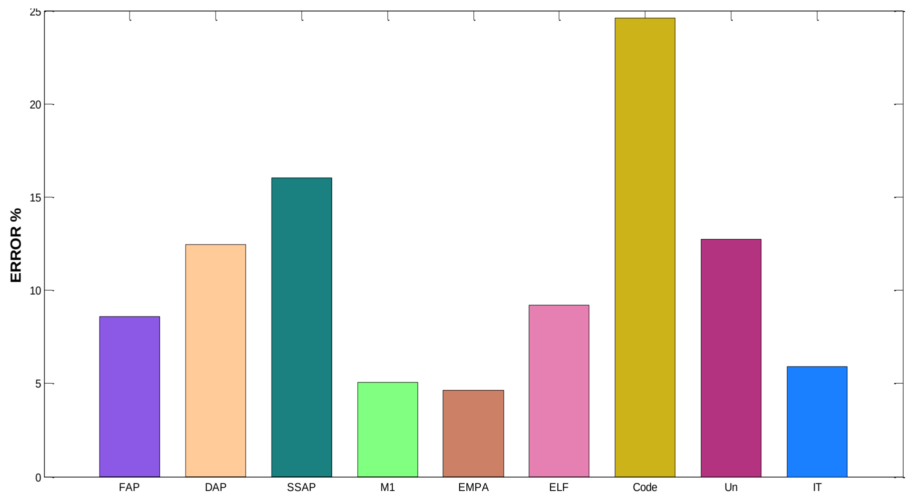

Figure 3: The displacement error obtained by different methods towards time history analysis for all selected records

Figure 2 shows the mean of maximum displacement of the 6-storey building in the height for the average of all selected records with the standard deviation values. Figure 3 shows the error rates of different methods toward non-linear time history analysis.

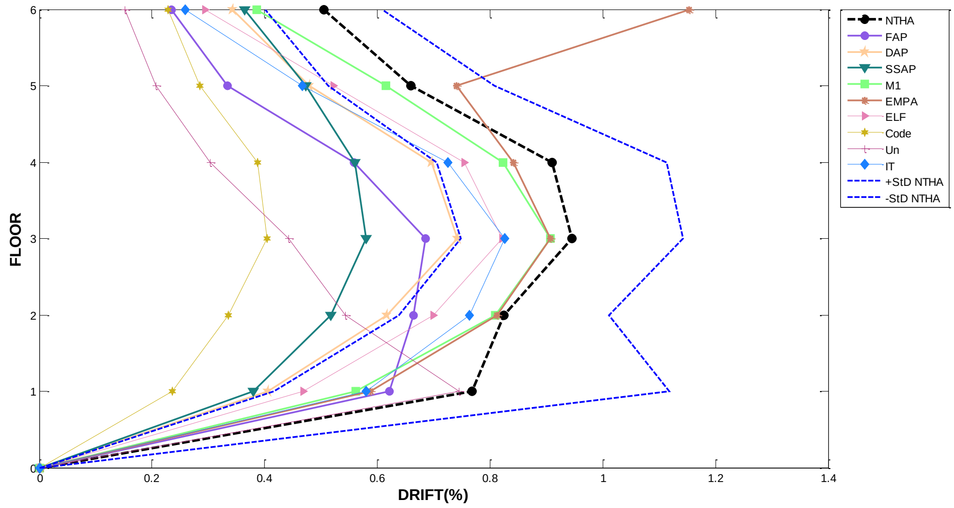

Figure 4: Mean of maximum in-story drift obtained from all selected records, in the height

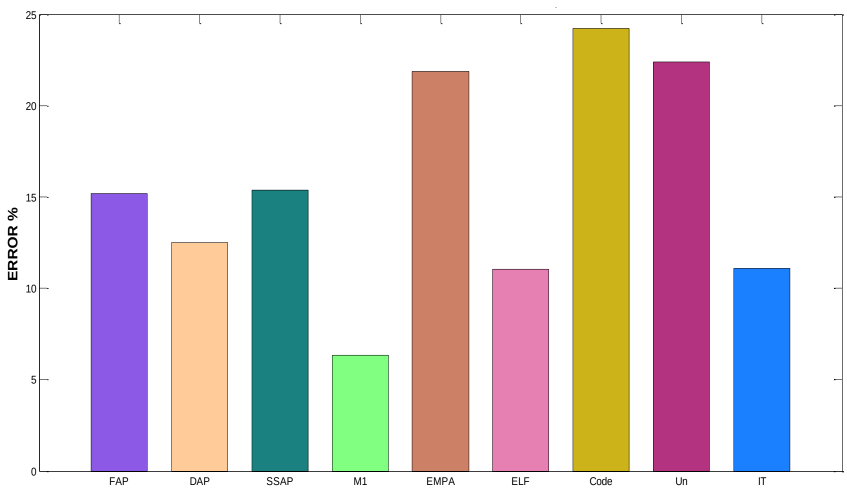

Figure 5: Error of in-story drift obtained from different methods toward time history analysis for all selected records

Figure 4 shows the mean of maximum in-story drift of ٦-storey structure for all selected records with the standard deviation values. Figure ٥ shows the error rates of different methods toward non-linear time history analysis.

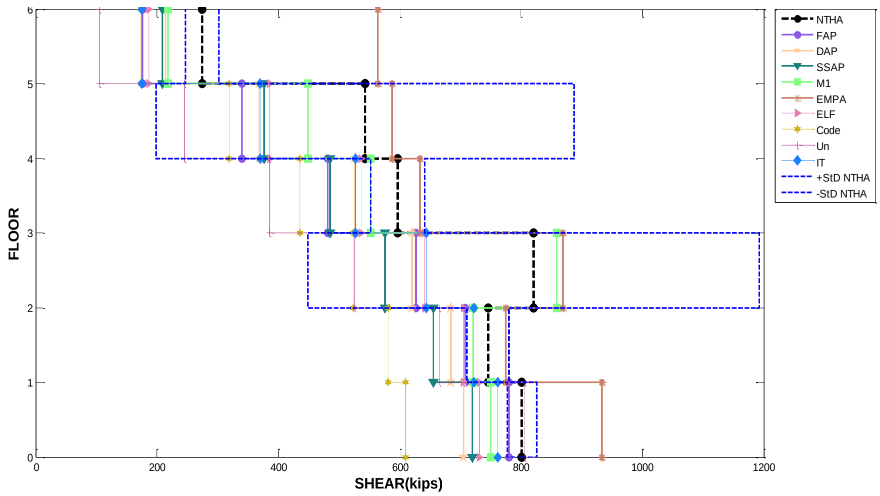

Figure 6: Mean of maximum story shear obtained from all selected records, in the height

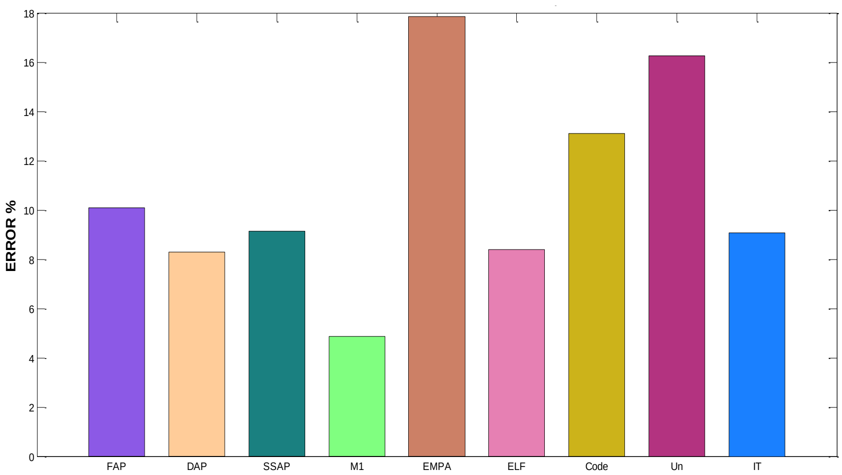

Figure 7: Error of in-story shear obtained from different methods toward time history analysis for all selected records

Figure 6 shows the mean of maximum in-story shear of 6-storey structure for all selected records with the standard deviation values. Figure 7 shows the error rates of different methods toward non-linear time history analysis.

As it can be seen in above figures, SSAP method still presents reliable estimations of maximum structural response. Another point can be observed in these figures is that, unlike most of engineers who estimate stroey shear forces by the distribution recommended in regulations, it seems that inverted triangular simple method is considerably better than the state where whip force is applied in roof balance. It should be noted that the results are calculated for converging braced structures with buckling bracings and necessitate the evaluation of other structures to present definite results.

As it is evident in above figures, M١ method in shorter structures presents better performance of displacement and drift, as one of the most important parameters of damage control. Regulative methods as well as other advanced updated methods did not achieve such accuracy. It can be due to the lateral behavior of bending bracing structures and overall deformation of the structure appropriate for the first mode of vibration. It can be also observed that EMPA method has a weak performance to estimate the storey shear that can be due to the selected combination law and requires further expertise revisions.

Although regulative methods couldn't cover the results of time history analysis with acceptable accuracy, the results show that conservative estimations are presented which can reduce the concerns about sufficient strengths.

As it can be inferred from above figures, SSAP method among updated methods showed a good estimation of displacement and drift and also had the least standard deviation. It also provide better performance in storey shear estimation by increasing the height.

As above, Figures ٨, ١٠, ١٢ show the mean of maximum displacement, in-storey drift and shear of a ١٢-storey structure for all selected records with the standard deviation values. Figures ٩, ١١, ١٣ show the error rates of different methods toward non-linear time history analysis.

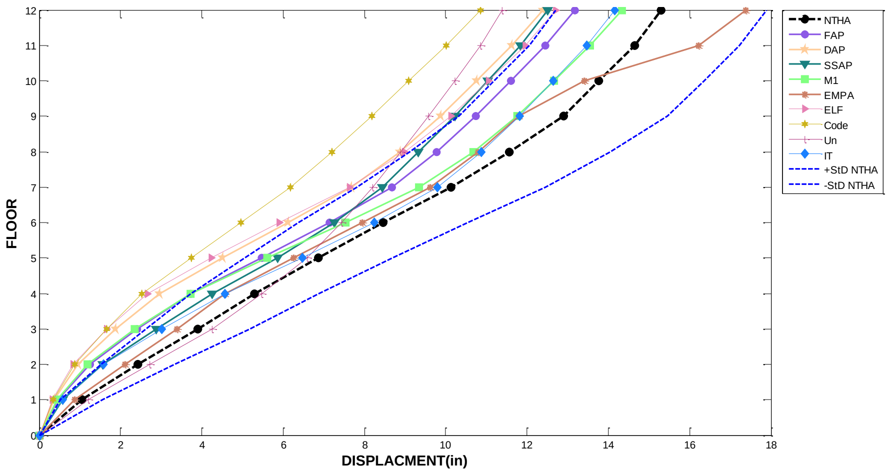

Figure ٨: Mean of maximum displacement obtained from all selected records, in the height

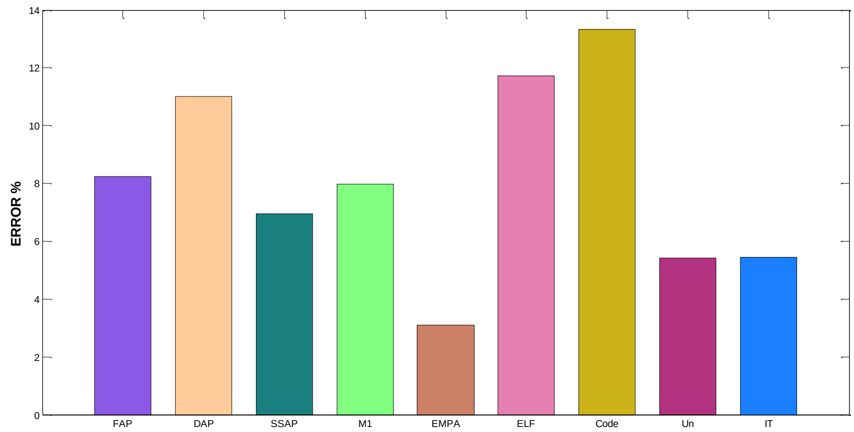

Figure ٩: The displacement error obtained from different methods toward time history analysis for all selected records

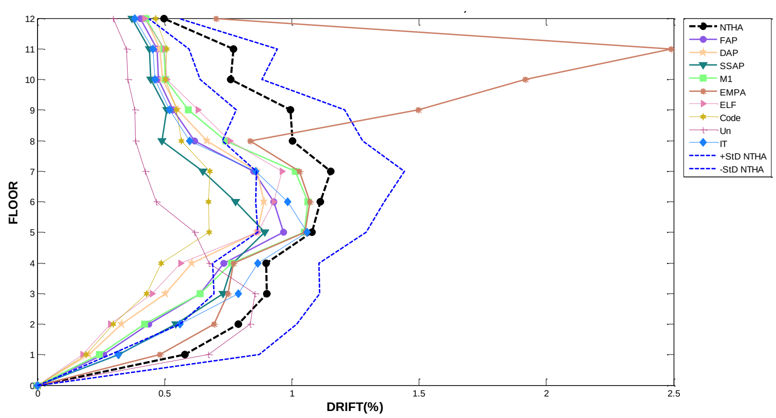

Figure ١٠: Mean of maximum in-storey drift obtained from all selected records, in the height

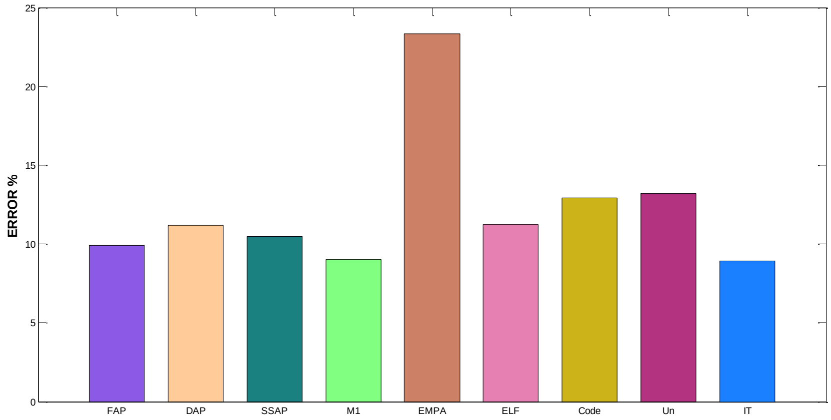

Figure ١١: Error of in-storey drift obtained from different methods toward time history analysis for all selected records

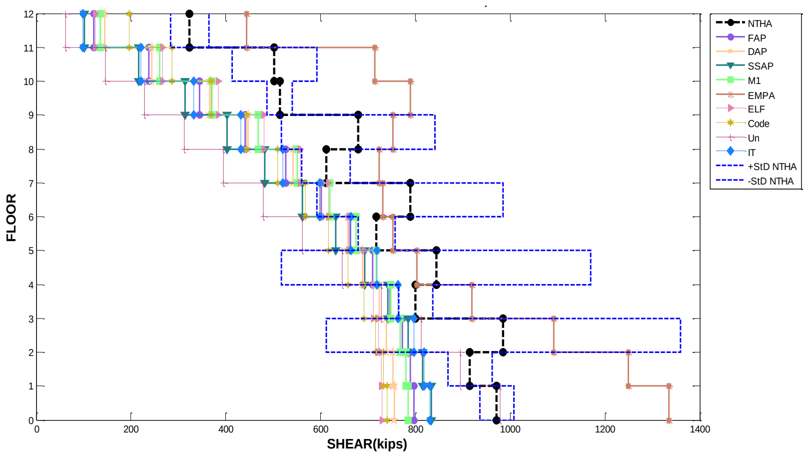

Figure ١٢: Mean of maximum in-storey shear obtained from all selected records, in the height

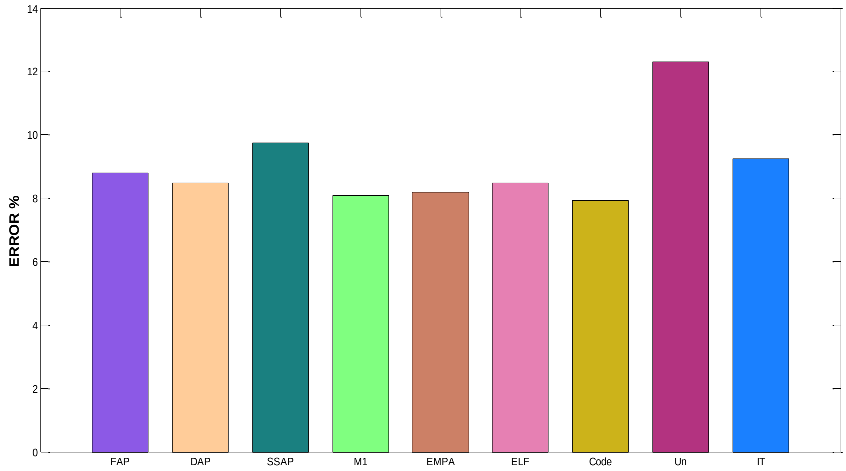

Figure ١٣: Error of in-storey shear obtained from different methods toward time history analysis for all selected records

The above figures show that the performance of storey shear-based methods such as SSAP is increased by increasing the height and inclination to shear behaviors; and the performance of methods such as DAP will be decreased.

The above figures for ١٢-storey model show that EMPA, unlike the poor performance in short structures, has shown better results in the high structures. It shows that SRSS combination principle has greater error within elastic responses rather than resilient responses. However, achieving better results in storey shear requires further researches that seems to be related to the higher modes' response (as three modes used in this study).

٦- Conclusion

As evident, SSAP method has the lowest standard deviation among the existing methods and thus increase the reliability of the results. By increasing the height, the precision of SSAP method for the estimation of response is increased and present better results of response values, especially for storey shear. Another point is that, the difference between seismic provisions for load distribution estimations toward time history method requires a revision in these methods.

Although regulative methods couldn’t cover the results of time history analysis with acceptable accuracy, the results show that conservative estimations are presented which can reduce the concerns about sufficient strengths. It is interesting that inverted triangular simple method is considerably better than the state where whip force is applied in roof balance.

Despite the poor performance of EMPA method in short structures, has shown better results in the high structures. It shows that SRSS combination principle has greater error within elastic responses rather than resilient responses.

The results show that in low to average structures, M١ method gives better and acceptable results, and it is better to use updated methods for higher structures. SSAP method gives good results in the high structures. Among non-updated methods, M١ in the short and medium height structures and EMPA method for high structures are recommended.

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