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Estimating seismic demand parameters using the endurance time method

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Abstract: The endurance time (ET) method is a time history based dynamic analysis in which structures are subjected to gradually intensifying excitations and their performances are judged based on their responses at various excitation levels. Using this method, the computational effort required for estimating probable seismic demand parameters can be reduced by an order of magnitude. Calculation of the maximum displacement or target displacement is a basic requirement for estimating performance based on structural design. The purpose of this paper is to compare the results of the nonlinear ET method with the nonlinear static pushover (NSP) method of FEMA 356 by evaluating performances and target displacements of steel frames. This study will lead to a deeper insight into the capabilities and limitations of the ET method. The results are further compared with those of the standard nonlinear response history analysis. We conclude that results from the ET analysis are in proper agreement with those from standard procedures.

Key words: Endurance time (ET) method, Nonlinear static pushover (NSP), Nonlinear dynamic analysis (NDA), Target displacement

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1 Introduction

Recent advances in computer hardware and software have provided a suitable environment for implementing new methods for the analysis and design of structures. Major recent seismic events in Northridge, California (1994), Kobe, Japan (1995), Central-Western India (2001), and Bam, Iran (2003) have continued to reflect the power of earthquakes. The destruction by earthquakes of engineering based buildings, bridges, and industrial facilities is associated with great economic losses. Thus, the need to improve the safety and the reliability of the built environment through the development of performance oriented procedures has been repeatedly highlighted (Chandler and Lam, 2001).

Such methods should be capable of minimizing structural damage and saving lives. These needs have been the impetus for many scientists to focus on performance-based design approaches and particularly nonlinear approaches. As a result, various new nonlinear static and dynamic analysis procedures have been developed.

The endurance time (ET) method is an innovative time history based procedure for the seismic analysis of structures (Estekanchi *et al.*, 2004). An intensifying acceleration is imposed to the structure whose performance is to be assessed. The goal is to measure the maximum time during which it can meet the specified performance objectives (Estekanchi *et al.*, 2006; Riahi *et al.*, 2009b). The ET method can be considered as an alternative to the equivalent static method and response spectrum procedures (Estekanchi *et al.*, 2007; Valamanesh and Estekanchi, 2010). Estekanchi *et al.* (2008) used the ET method as a device to estimate structural damage and other damage indexes. The application of the ET method was extended to nonlinear seismic analysis (Madarshahian and Estekanchi, 2007; Estekanchi *et al.*, 2009; Riahi *et al.*, 2009a; Riahi and Estekanchi, 2010). In this research, the ET method was applied to estimate structural displacement. To show the ET method's application in assessing the nonlinear demands of structures, its performance was compared with nonlinear static pushover (NSP) which is a common-place method. NSP has a longer history than ET, although it is still new in recent codes. Freeman *et al.* (1975) developed a rapid assessment method which could be considered as the forerunner of the capacity spectrum method. Saiidi and Sozen (1981) presented a simple procedure for the nonlinear seismic analysis of reinforced concrete structures. In view of the inherent simplicity and accuracy of these methods, some seismic codes have begun to include them as effective techniques for the performance assessment of structural systems (e.g., ATC-40, 1996; FEMA 273, 1997; FEMA 356, 2000; Eurocode 8, 2001). These procedures are based on some predefined monotonically increasing load patterns including the incremental nonlinear analysis of structures until some target demands are achieved.

In many of these methods, the capacity of a structure is compared with an earthquake's demand (Fajfar, 2000; Kalkan and Kunnath, 2007). In pushover analysis, the target displacement for the multi degree of freedom (MDOF) structure can be estimated as the displacement demand for the corresponding single degree of freedom (SDOF) system. This approach imposes some limitations, including the assumption that the target displacement is obtained based on a single shape vector without considering higher mode effects (Krawinkler and Seneviratna, 1998; Chopra *et al.*, 2004). Much research has been conducted for assessing static procedures. In most cases, evaluation of the pushover procedure was performed using the ground motion records of buildings (Goel and Chopra, 2004; Kunnath and Kalkan, 2004; Akkar and Metin, 2007; Shattarat *et al.*, 2008). In this research, NSP and nonlinear dynamic analysis (NDA) were applied for the evaluation of the ET method. More than 30 frames were studied and about 500 analyses, including ET, NDA, and NSP analyses, were performed.

The goal of this paper was to evaluate the performance of the ET method compared with the NSP and the NDA methods. We also described how the target displacements were extracted in this method, and compared the statistical results extracted from the analysis of different models.

2 Concept of the ET method

The ET method is a dynamic analysis procedure in which a structure is subjected to a predesigned intensifying excitation and its response to various seismic intensity levels is estimated in a single response history analysis (Estekanchi *et al.*, 2004). The characteristic of the intensifying record is of particular importance and has a direct effect on the usability of analysis results. The early generated ET accelerograms were mostly white noises that were modified by frequency filters, while more advanced accelerograms were later developed that incorporate the characteristics of design level earthquakes (Valamanesh *et al.*, 2010). To reach this goal, the concept of response spectrum was directly employed in generating accelerograms. The new ET records can produce target design response spectrum at a particular time, which is linearly proportional to the target design spectrum at any other time. This makes it possible to compare performance of different structures with different dynamic properties using a single ET record (Estekanchi *et al.*, 2007).

A suitable target time, i.e., the time where the intensity of dynamic excitation matches the average of design level ground motions, has a very substantial role in a successful analysis. A very short target time does not impose enough nonlinear cycles; on the other hand a very long one creates unreasonably high number of nonlinear cycles. This can affect the consistency of the results in models with cyclic degradation that are sensitive to effective duration of ground motions. In this study a target time value of 10 s was chosen based on engineering judgment and some preliminary studies in this regard (Estekanchi *et al.*, 2007). Also the target acceleration response is varied linearly with time, which means the responses at times $t_{\mathrm{Target}}/2$ and $t=2t_{\mathrm{Target}}$, where t_{Target} is the target time, are half and twice of the code value, respectively. The target acceleration response of the ET accelerogram is defined as

$$S_{\mathrm{aT}}(T,t)=\frac{t}{t_{\mathrm{Target}}}S_{\mathrm{aC}}(T), \tag{1}$$

where $S_{\mathrm{aT}}(T, t)$ is the target acceleration response at time t, T is the period of free vibration, and $S_{\mathrm{aC}}(T)$ is the codified design acceleration spectrum. From this function, the target displacement response at time t can be found, which is of particular importance:

$$S_{\mathrm{uT}}(T,t)=\frac{t}{t_{\mathrm{Target}}}S_{\mathrm{aC}}(T)\times\frac{T^2}{4\pi^2}. \tag{2}$$

The problem of finding an excitation function with above mentioned characteristics (Eqs. (1) and (2)) is formidably complicated from an analytical viewpoint. However, this problem can be formulated as an unconstrained optimization problem and tackled through numerical optimization techniques (Estekanchi *et al.*, 2007):

$$\text{Minimize } F(a_g)=\int_0^{T_{\max}}\int_0^{t_{\max}}\left\{\left[S_{\mathrm{a}}(T,t)-S_{\mathrm{aT}}(T,t)\right]^2+\alpha\left[S_{\mathrm{u}}(T,t)-S_{\mathrm{uT}}(T,t)\right]^2\right\}\mathrm{d}t\mathrm{d}T, \tag{3}$$

where $F(a_g)$ is the optimization target function, a_g is the ET accelerogram being sought, $S_{\mathrm{a}}(T, t)$ and $S_{\mathrm{u}}(T, t)$ are the actual acceleration and displacement response values for period T at time t, and α is a relative weight parameter between displacement and acceleration derivations. An α value of 1 balances penalties on both response parameters. A typical code compliant accelerogram that corresponds to BHRC 2800-05 (2005) was used to define the target response as follows:

$$\begin{cases} B=1+1.5\left(\dfrac{T}{0.1}\right), & T<0.1\ \mathrm{s}, \\ B=2.5, & 0.1\ \mathrm{s}\le T<0.5\ \mathrm{s}, \\ B=2.5\left(\dfrac{0.5}{T}\right)^{\frac{2}{3}}, & 0.5\ \mathrm{s}\le T, \end{cases} \tag{4}$$

$$S_{\mathrm{aC}}=\frac{0.35BI}{R}, \tag{5}$$

where B is the building response factor. I is the importance factor, R is the force reduction factor, and both are assumed to be equal to 1.0. Unconstrained nonlinear numerical optimization using custom developed code and FORTRAN language libraries was employed to solve the problem considering the 2048 (2^{11}) accelerogram data points as optimization variables. A typical accelerogram produced by this procedure is depicted in Fig. 1.

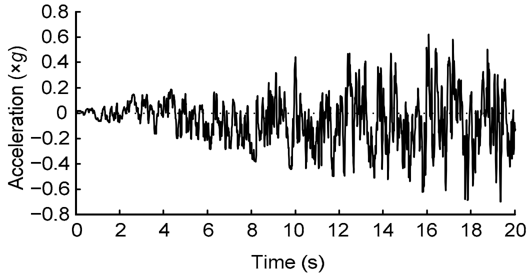

Fig. 1 A typical ET accelerogram

Fig. 2 shows the acceleration response spectra at t=5, 10, and 20 s for the first set of three ET records. The target time in current study is 10 s. The optimization process has been successful in converging to target values within reasonable accuracy (Fig. 2). The chosen target function has led to almost the same conformity level in the whole time range. Using the average result of about three accelerograms can reduce random derivations from the target response due to inherent randomness of input excitations. While a good level of convergence can be achieved by using three ET analyses, in this study, the average of 10 ET

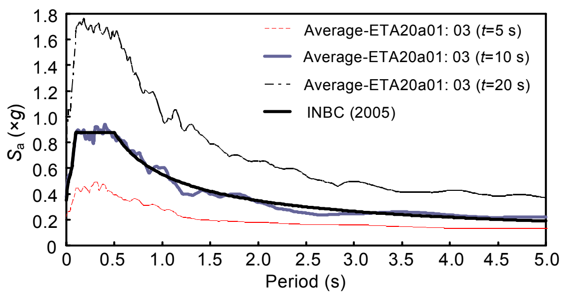

Fig. 2 Pseudo-acceleration response spectra S_{a} of ETA20a series accelerograms for damping ratio ε=5% at different times

accelerograms from the series of ETA20a, where ETA20a denote ‘a’ generation of ET acceleration records with the duration of 20 s, was applied to obtain the maximum level of convergence.

The greatest demand experienced up to the target time can be considered as an estimate of the probable demand of the structure subjected to earthquakes matching the template spectrum during the effective periods with a scale of one. If the desired demand is the displacement of the last floor, the maximum displacement until the target time is the target displacement.

NSP analysis methods are widely used by engineers because of their simple procedures, low financial and time costs, and good estimations. In these methods, lateral loads are imposed on structures by considering a suitable load pattern. Gradually increasing loads accompanied by a step-by-step nonlinear analysis will result in pushover graphs. These graphs usually depict the variation of the base shear vs. roof displacement values. Subsequently, by using the design spectrum, the displacement of the roof can be extracted for the design earthquake. The main differences between these methods stem from the different patterns of applying lateral loads and the different methods which estimate the roof displacement by the design spectrum.

3 Dynamic pushover analysis by the ET method

Fig. 3 shows the roof displacement of a model and its absolute value (Abs(ET)). Fig. 4 shows the maximum of absolute values as a function of time for base shear, after applying the identical procedure.

By plotting the maximum value of the absolute base shear vs. the maximum value of the absolute roof displacement, a graph is obtained which shows the

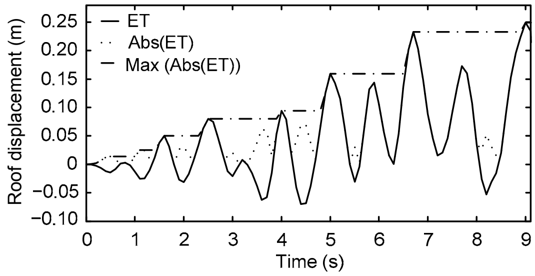

Fig. 3 Maximum of absolute demand of roof displacement

relation between the base shear and the roof displacement (Fig. 5). This graph is called the dynamic pushover diagram in this paper because of its dynamic identity and its similarity to the pushover diagram.

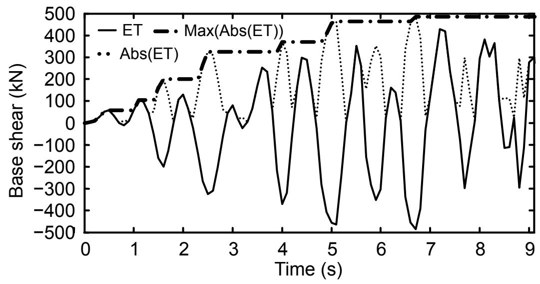

Fig. 4 Maximum of absolute demand of base shear

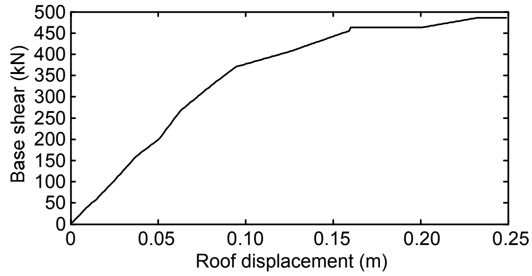

Fig. 5 Dynamic pushover diagram derived from ET base shear and roof displacements

The dynamic pushover diagrams are extracted by averaging the results of 10 acceleration records and are sketched next to the pushover dynamic diagram. Fig. 6 shows the dynamic pushover diagram for a three-story, one-span frame. In all of more than 40 models, there was an acceptable agreement between the dynamic pushover diagram of the ET method and its corresponding nonlinear static pushover. This shows that the ET method can provide satisfactory estimations of the capacity of structures.

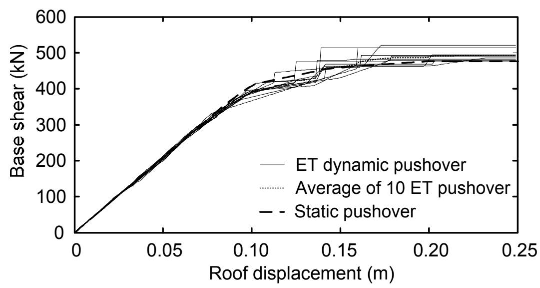

Fig. 6 Average of endurance time pushover diagrams vs. nonlinear static pushover of a particular frame

4 Extracting the results from the ET analysis

The response of the displacement demand of the roof for the nonlinear ET, like the ET acceleration records, follows an increasing trend. To evaluate the displacement of the target time, it is necessary to develop the absolute maximum response demand of displacements with time (Fig. 3).

To attain the best response, it is a good idea to use more than one acceleration record. In this study, as a research project, 10 ET acceleration records were applied. However, it seems that three acceleration records produce an acceptable accuracy for practical applications. In fact, the so called ET diagram is the average of the absolute maximum roof displacements of the ET acceleration records. It is possible to develop a variety of similar diagrams for other demands, such as the drift of floors or the internal forces. Fig. 7 shows an example of the trend for extracting the nonlinear ET diagrams.

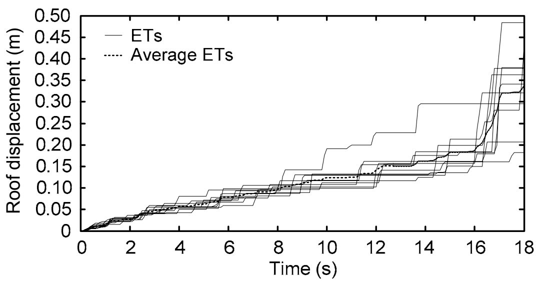

Fig. 7 Nonlinear ET of roof displacement extracted from individual ET diagrams

The target time in this example has been set to 10 s, and as a result, if there were responses after 10 s, then the results converge till the 10th second and the average value related to the 10th second is the target displacement. In cases in which the results do not converge by the 10th second, the reason should be determined. Generally, in the final stages of an analysis, there is a possibility of formation of unstable mechanisms or instabilities. This means that the performance of a structure, a few seconds before the target time, is weak and unsatisfactory. In addition, by following the responses of the ET acceleration records, the damage trends of structures through the passage of time can be understood. This provides a versatile tool for comparing the performance of two different structures.

5 Extracting results in static pushover

The procedure outlined in FEMA 356 (2000) is also called the coefficient method because the structure of the formula applied to specify the target displacement contains several coefficients, which are determined with respect to the properties of structures (Fig. 8):

$$\delta_{\mathrm{t}} = C_0 C_1 C_2 C_3 S_{\mathrm{a}} \frac{T_{\mathrm{e}}^2}{4\pi^2} g, \tag{6}$$

$$T_{\mathrm{e}} = \sqrt{\frac{K_{\mathrm{i}}}{K_{\mathrm{e}}}}, \tag{7}$$

where δ_{t} is the target displacement, S_{a} is the acceleration response spectrum at an effective period, and T_{e} is the effective period. C_0 is the coefficient of shape factor, C_1 is the coefficient of ratio between inelastic and elastic displacements, and C_2 and C_3 are the coefficients for considering the effects of pinching and geometric nonlinearity P−Δ, where P−Δ refers to magnification of lateral displacements (Δ) resulting from second order effects of axial loads (P). K_{i} and K_{e} are the initial and effective stiffnesses, respectively.

In this paper, the shear distribution pattern resulting from the spectral analysis is used as the lateral loading pattern. This method leads to more reasonable results because it is derived from the properties of the structure itself.

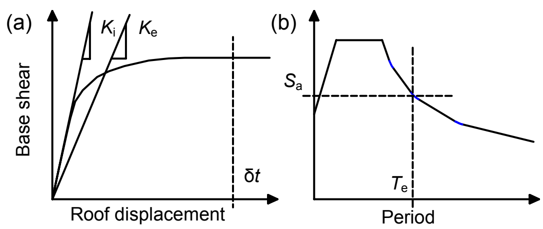

Fig. 8 Components in the coefficient method of displacement modification (FEMA 356, 2000) for estimating the target displacement for a given response spectrum and an effective period

(a) Idealized force-displacement curve; (b) General horizontal acceleration response spectrum

6 Frame models

Frames with one, three, seven, and twelve stories were considered in this study. These frames were divided into 10 categories. They were designed according to the Iranian National Building Code (INBC) Section 10 (INBC, 2005) which is similar to the American Institute of Steel Construction (AISC) allowable stress design (ASD) recommendations (AISC, 1989). Some variations were applied to the design of each frame, i.e., each frame was designed in three intensity levels of design lateral loads to study the applicability of the ET analysis procedure in differentiating the performance implications of adopting different design alternatives. The standard frames were designed using the base shear according to the recommendations of the Iranian Code for a high seismicity area (BHRC 2008-05, 2005). The weak frames were designed based on one-half of the codified base shear and the strong frames were designed for twice the codified base shear. These frames are designated as ordinary (i.e., standard code design), weak, and strong frames by the letters O, W, and S, respectively. Frame loadings were assumed to be the same for these three kinds of frames for ease of comparison. The goal of forming these categories was to investigate the performance of the ET method and compare it to other methods in differentiating these frames and estimating their target displacements. Six of the 10 categories consisted of frames with three alternative designs (O, W, and S frames). These included frames with one story and one span, three stories and one span, three stories and three spans, seven stories and one span, seven stories and three spans, and twelve stories and three spans. Another set of frames consisting of two categories were considered to investigate the effects of damping. These categories included frames with 1%, 2%, 5%, 10%, 30%, and 50% damping ratios with one and three stories. Furthermore, two other categories were defined to investigate the effects of irregularity of mass which consisted of two three-story frames with fixed and pinned connections to the foundation. Frames which were irregular in mass had the same base shears but different mass distributions. All the stories were 3.2 m high and all the spans were 6 m long. HEA profiles were used as beams and HEB profiles as columns. An example of the investigated frames, designed with variable lateral loadings, is depicted in Fig. 9. Table 1 shows some of the properties of these frames. Note that most of the structures were first-mode dominated systems because we did not want to

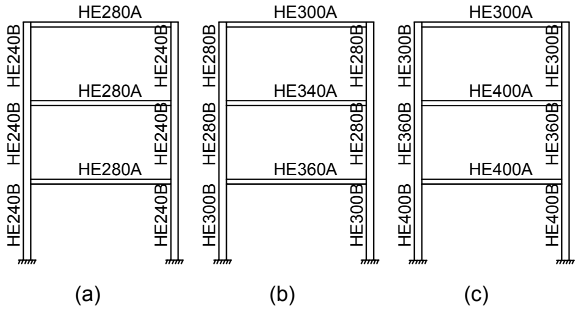

Fig. 9 An example of the investigated frames, designed with variable lateral loadings
(a) Weak; (b) Ordinary; (c) Strong

Table 1 Some properties of the investigated models

Frame	No.[1]	No.[2]	MPM (%)	PFV (s)
FMS01B1RGW	1	1	100.0	0.89
FMS01B1RGO	1	1	100.0	0.76
FMS01B1RGS	1	1	100.0	0.54
FMF03B1RGW	3	1	84.7	1.28
FMF03B1RGO	3	1	82.4	0.92
FMF03B1RGS	3	1	79.2	0.72
FMF03B1IGO	3	1	80.5	0.93
FMS03B1RGO	3	1	90.4	1.03
FMS03B1IGO	3	1	87.5	1.12
FMS03B3RGW	3	3	88.3	1.30
FMS03B3RGO	3	3	85.6	0.97
FMS03B3RGS	3	3	85.6	0.69
FMS07B1RGW	7	1	80.9	2.03
FMS07B1RGS	7	1	80.4	1.48
FMS07B1RGO	7	1	80.4	1.08
FMS07B3RGW	7	3	80.8	2.07
FMS07B3RGS	7	3	80.7	1.51
FMS07B3RGO	7	3	80.3	1.07
FMS12B3RGO	12	3	78.2	2.16
FMS12B3RGS	12	3	75.0	1.44

Frame naming convention: All frames start with letters FM; The third letter indicates base fixity (S: simple; F: fixed); Next two digits are the number of stories followed by letter B and the number of bays; Next two letters indicate regularity (RG: regular; IG: irregular); The last letter indicates design basis (O: ordinary design; W: weak design; S: strong design). No.[1]: Number of stories; No.[2]: Number of bays; MPM: Mass participation mode 1; PFV: Period of free vibration

concentrate on vulnerable points of nonlinear static pushover.

Nonlinear characteristics were defined for each model. Hinges with nonlinear characteristics were defined at the ends of beams and columns. Since it is possible that plastic hinges are formed at the middle of the beams under the gravity load effects, nonlinear hinges were further defined at the middle of beams. Nonlinear properties dependent on sections were defined based on FEMA 356 (Fig. 10).

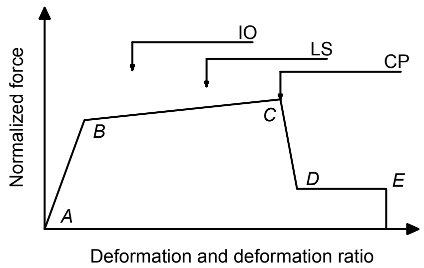

Fig. 10 Nonlinear properties for nonlinear analysis based on FEMA 356

IO: Immediate occupancy; LS: Life safety; CP: Collapse prevention. *A*, *B*, *C*, *D*, and *E* are points of variations in nonlinearity properties

In this study, the average of the results of seven time history analyses was used as the basis for comparing the results. The acceleration records were selected based on the dynamic properties which were compatible with soil type 2 of the Iranian Code. The scale was chosen so that the acceleration response spectrum of each acceleration record had the best compatibility with the design spectrum of the studied model at its fundamental period (FEMA 440, 2005). Table 2 shows the earthquakes considered.

Table 2 Description of the ground motions study

Earthquake name	Magnitude (Ms)	PGA (cm/s^2)	Record name
Landers	7.5	167.8	LADSP000
Loma Prieta	7.1	494.5	LPSTG000
Loma Prieta	7.1	349.1	LPGIL067
Loma Prieta	7.1	433.1	LPLOB000
Loma Prieta	7.1	239.4	LPAND270
Morgan Hill	6.1	280.4	MHG06090
Northridge	6.8	504.2	NRORR360

PGA: Peak ground acceleration

7 Analysis of results

The NSP method clearly identified the weak, ordinary, and strong frames. The ET diagrams were also capable of differentiating between these frames (Figs. 11 and 12).

Fig. 11 shows that the static pushover method has clearly differentiated between the frames. The ET

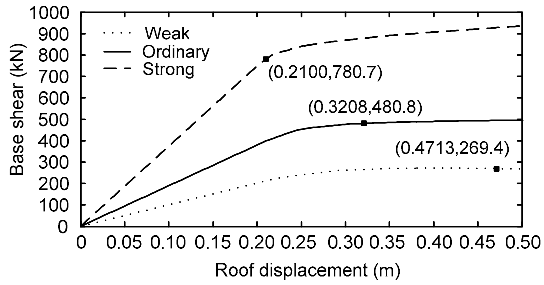

Fig. 11 Pushover diagrams for weak, ordinary, and strong seven-story frames

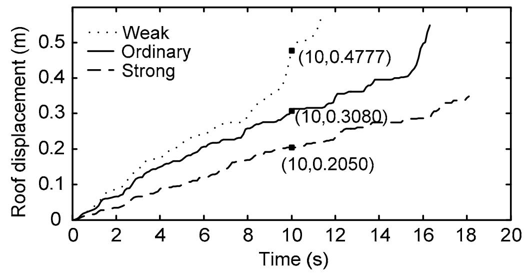

Fig. 12 ET diagrams of weak, ordinary, and strong seven-story frames

diagrams show that the strong frames were capable of resisting the ET acceleration records for longer than the weak frames. Furthermore, the stronger frames experienced less simultaneous displacement (Fig. 12). As a result, the ET diagrams were able to distinguish between the frames either by displacements during a particular time or by the length of the time they could tolerate the ET acceleration records. The target displacements are also shown in Figs. 11 and 12. There was no considerable difference between the target displacements calculated by these two methods. The estimation of the target displacement using the ET or the NSP method was similar. The stronger frames experienced fewer displacements, as expected. In Fig. 13 the target displacements of the frames are plotted against the time history results of seven acceleration records.

Fig. 13 shows that both methods were capable of estimating the target displacements and comparing frames. Other important issues are how well these two methods perform in representing the nonlinear behavior of a structure and how they monitor the vulnerable points of a structure. In this study, the above issues were investigated using the number of plastic hinges at the target displacement as a criterion.

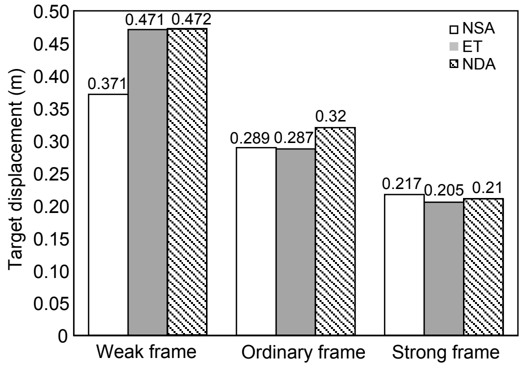

Fig. 13 Target displacements of the two methods compared to time history analysis results of seven acceleration records of NDA

Fig. 14 shows the distribution of plastic hinges in the three-story and three-span model in which the columns on the third story experienced more nonlinear deformation at target displacement than did other elements, although the ductility ratio in each hinge did not exceed 3. The maximum plastic rotations, which occurred at the middle columns of the third story, were about 0.0129, 0.105, and 0.126 rad in NDA, ET, and NSP analyses, respectively. Fig. 14 indicates that ET was comparable to NSP and NDA in predicting the distribution of plastic hinges in a frame. Note that the results of NSP relate to average of the two analyses in which the direction of the lateral

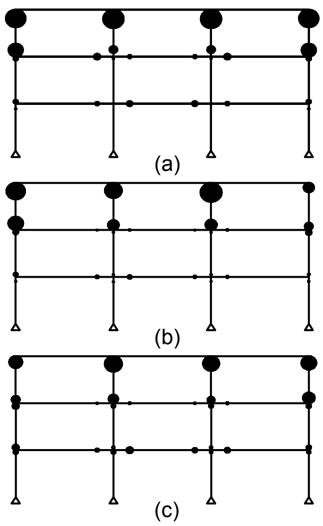

Fig. 14 Distribution of plastic hinges at target displacement in which the amount of plastic rotation is scaled by a radius of circles and the maximum rotation is 0.0129 rad
(a) NSP; (b) NDA; (c) ET

load changed. The maximum rotation of each hinge is depicted in Fig. 14.

The effect of mass irregularity was investigated in the three-story frames. Two of these frames had regular mass distribution on the floors while the other had a roof with twice as much mass as the lower floor.

The pushover diagrams of the two frames (Fig. 15) were very similar and their target displacements were indistinguishable. This is attributed to the similarity of their natural frequencies. However, the ET method has clearly identified these two frames. It also shows different results for the target displacements and unlike the NSP analysis, has led to higher target displacements for the symmetric structure compared with those for the asymmetric mass structure. The time history analysis has further verified the results of the ET method (Figs. 16 and 17).

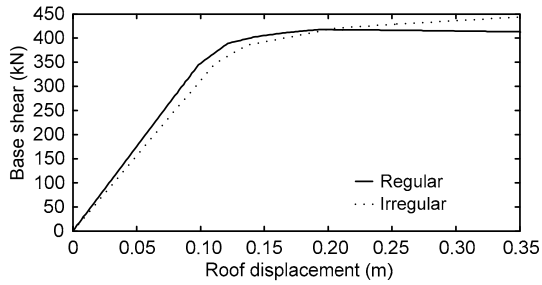

Fig. 15 Pushover diagrams for two regular and irregular mass frames

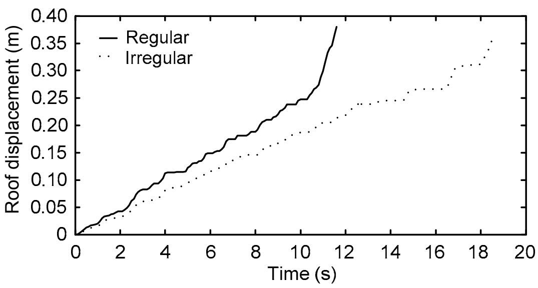

Fig. 16 ET diagrams for two regular and irregular mass frames

Another set of six regular mass frames with four stories was investigated. The findings indicated that the ET method leads to better results for target displacement compared to the static pushover method. ET diagrams also distinguished two similar frames with different damping ratios. Six different damping ratios ranging from 1% to 50% were chosen. NSP led to the same pushover diagrams in all cases.

In other words, because of the static identity of the NSP method, damping cannot be applied in equations directly but needs to be applied by correction of the design spectrum. Figs. 18 and 19 show results of similar one-story frames with different damping ratios in NSP.

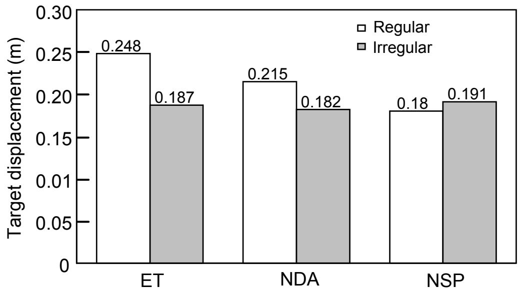

Fig. 17 Target displacements of two methods compared to time history analysis results of seven acceleration records of NDA

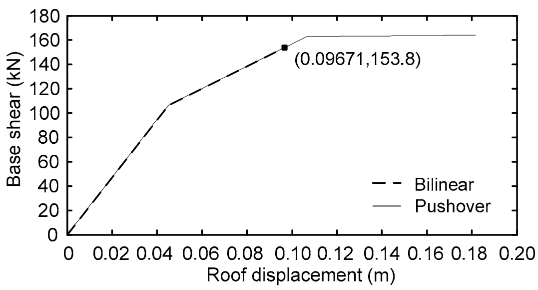

Fig. 18 Pushover diagram and the corresponding bilinear diagram for a one-story frame with 1% damping

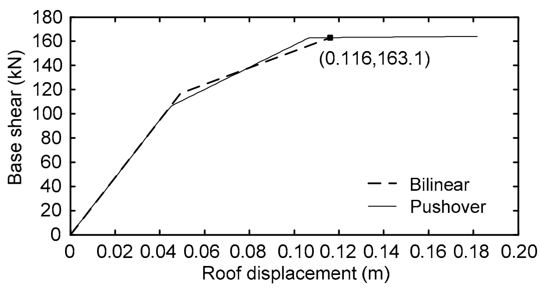

Fig. 19 Pushover diagram and the corresponding bilinear diagram for a one-story frame with 5% damping

The ET method has the advantage of applying the damping effects directly. Fig. 20 shows the ET diagrams for six one-story frames which differed only in their damping ratios.

Fig. 21 indicates the estimated target displacements of both methods, accompanied by time history results with seven acceleration records. The results imply that both methods provided estimates close to the average of the seven acceleration records. However, if a story had a different damping ratio or dampers were installed in a particular story, the NSP method did not lead to reasonable results, while the ET method could resolve these problems.

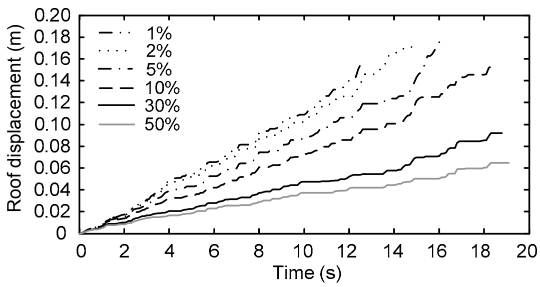

Fig. 20 ET diagrams for one-story frames with different damping ratios

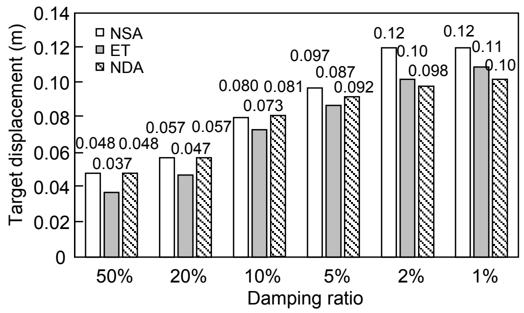

Fig. 21 Target displacements of both methods compared to time history analysis results of seven acceleration records of NDA

Where the time history analysis did not converge, the nonlinear ET method could not reach the target time, and thus could also not extract a target displacement. Although this specific example indicates the weak performance of these models, these frames were ignored in the results.

To compare the ET and the NSP methods, two graphs for the target displacements were plotted. The best fitting line relative to the results was drawn and the slope of the line showed reasonable consistency between the two methods. In addition, the correlation coefficient, R^2, was calculated as 0.929 (Fig. 22). Similar diagrams were plotted for the results based on the NDA method to investigate the results more thoroughly (Fig. 23). In these figures, the best-fitting line passing through the points is also shown. The closeness of the slope of the line to 1 indicates better agreement between the ET method and the time history results. Furthermore, the closeness of the correlation coefficient to 1 indicates less dispersion in the results. The equation of the regressed line to the ET results was $y=1.202x-0.0188$ and its corresponding correlation coefficient was $R^2=0.9568$. The regressed line of the other method was $y=1.2769x-0.0316$ and its correlation coefficient was $R^2=0.907$. These equations signified satisfactory estimates of both methods although the ET method led to slightly better results. An error function from the time history results can be defined which calculates the root mean square error of each method from time history analysis. This error was 0.0338 for the ET method and 0.0483 for the NSP analysis.

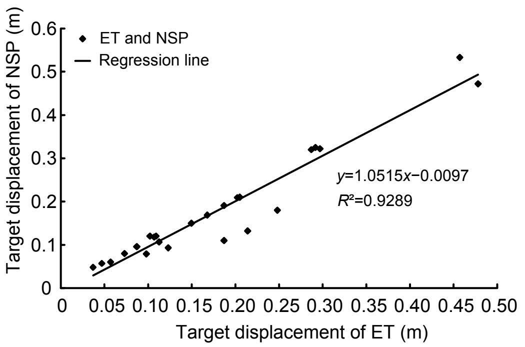

Fig. 22 Target displacements related to ET and NSP analyses

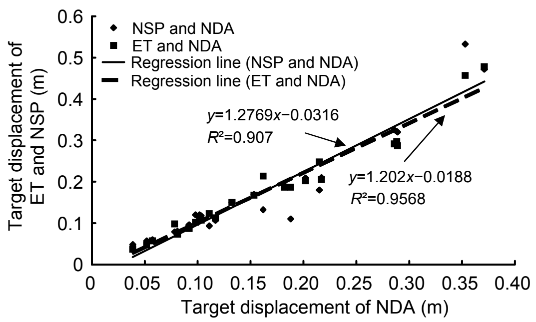

Fig. 23 Target displacements of both methods vs. time history results from seven acceleration records

Generally, the dynamic nature of the ET method was advantageous in producing realistic estimates of the target displacements and the distribution of the plastic hinges.

8 Conclusions

In this paper, the consistency of results associated with the ET method was studied by comparing the results from this type of analysis with the results from NSP and NDA. Based on the results of this research, the following conclusions were drawn:

1. In general, the results from ET analysis were consistent with those from NSP and NDA. The results of the ET method were more consistent with the results of the ground motion analysis compared to those of the NSP method. This means that the ET method provides a more exact estimation of the behavior of structures compared to NSP analysis.

2. The results of the distribution of plastic hinges indicated that the ET method is capable of predicting the distribution of plastic deformation in structures. More accurate investigations of plastic rotations and local nonlinear deformations are being carried out and will be reported later.

3. The ET method was successful in predicting the effects of irregularity in seismic response. In one example, the displacement demand of the roof of a regular structure was considerably less than that of a similar frame with some mass irregularity. In this frame, the NSP method exhibited higher target displacements for the regular frame, while the ET method led to consistent results when compared to the time history outcomes.

4. The ET method can differentiate structures with different damping ratios appropriately, while in static pushover analysis the inclusion of damping effects is not straight forward. NSP analysis takes into account the effect of damping by applying an overall correction in the design spectrum and cannot be readily applied to the problem of a structure with dampers installed at different specific locations. The effect of damping is considered directly in the ET method.

5. The ET method overestimated the nonlinear response of frames in this paper. This can be attributed to the template design spectrum used in the production of the ETA20a series of the ET acceleration functions that corresponded to the design spectrum of the stiff soil condition in INBC (2005). This spectrum was largely on the safe side in the long period range, affecting nonlinear results in this region. More realistic template spectrums should be

employed to improve the accuracy of the results of this type of analysis.

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