Endurance Time Method: Exercise Test for Seismic Assessment of Structures

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ABSTRACT:
Endurance Time (ET) method is a new time-history based dynamic pushover procedure in which structures are subjected to a gradually intensifying acceleration functions and their performance is assessed based on the length of the time interval that they can satisfy required performance objectives. This relatively simple test procedure can be useful in preliminary design stage of various structures where the performance parameters are hard to estimate with reasonable accuracy using simplified procedures such as static pushover. The procedure can also be useful when comparing the relative performance of two different structures or design alternatives for the same structure. In this paper, some fundamental concepts of ET method are explained and the accuracy, potentials and limitations of this procedure in linear and nonlinear seismic analysis of SDOF and MDOF systems are investigated. Numerical procedures for generating ET acceleration functions that are compatible with real ground motions are explained. Some case studies are provided. It is concluded that while current ET acceleration functions generate reasonably accurate results that are compatible with conventional time-history analysis in linear and nonlinear cases, improved acceleration functions need to be produced in order to utilize full potentials of the method.

KEYWORDS:
Endurance Time method, Incremental dynamic analysis, Dynamic pushover, Nonlinear dynamic analysis

1. INTRODUCTION

Structural codes and design guidelines are moving towards adoption of performance-based design approaches [1]. In performance-based engineering (PBE), structures should be capable of satisfying various performance objectives, under a spectrum of design ground motions ranging from minor to severe. Advances in computational technology have stimulated the application of numerically intensive analysis and design procedures in the field of earthquake engineering. Using such procedures can lead the engineers to apply PBE in the design of structures by reducing the amount of uncertainties.

Endurance Time method is basically a simple dynamic pushover test that tries to predict Damage Measure (DM) of structures at different Intensity Measures (IM) by subjecting them to some predesigned intensifying dynamic excitations [2]. Because of the increasing demand of the ET acceleration function, structures gradually go through elastic to yielding and nonlinear inelastic phases, finally leading to global dynamic instability [3]. In this paper, the concept of ET criteria is first described. Optimization techniques used for the generation of ET acceleration functions that are compatible with real ground motions are explained. Compliance and level of accuracy of this method in nonlinear seismic analysis of SDOF structures is investigated. The accuracy of ET method in predicting the response of MDOF structures is investigated by using a set of steel frames. Finally application of ET method for assessment of more complicated systems is explained. It is shown that ET analysis estimates the results of nonlinear time history analysis with reasonable accuracy.

2. ET METHOD CONCEPT

The concept of ET method can be explained by considering a hypothetical shaking table test as follows. Three different structures are assumed to be fixed to a shaking table. The experiment starts by applying an intensifying acceleration function to the structures as shown in Figure 1. As the amplitude of excitation increases, structures start to show different levels of deformations. Let's assume that structure A in Figure 1 is the first one to collapse. This is followed by collapse of structures C and B respectively as shown in Figure 1. Based on this test, structure A that endured least, is judged to have worst performance and structure B that endured longest is considered to be the best performer. If these are considered to be the prototypes of three different designs for the same intended structure, then design B is considered to be the best one. Moreover, if the excitations function is somehow calibrated to conform to requirements of some design codes for different levels of IM, different acceptable endurance times can be specified for practical design application. Therefore ET method can be implemented into an overall performance-based design procedure with multiple performance objectives quantitatively described as various parameters under different intensity of ground motions.

The concept of endurance time is very similar to the exercise test used by cardiologists in order to evaluate the condition of the cardiovascular systems of athletes and patients [4]. In this test, the patient whose general endurance is to be evaluated is asked to run on a treadmill. The treadmill is set to the standard starting speed and slope. As the test continues, the speed and slope of the treadmill is increased as a predefined function of time. Vital biological measurements, such as blood pressure, heart beat rate and other physical parameters are continuously monitored and the test is commenced until abnormal conditions are observed or the patient is exhausted. From the total running time, an estimate of the patient's condition can be made. The interesting point about the exercise test is how a relatively simple procedure is used for assessing the condition of a complex system. In ET method, it is intended to use a conceptually similar procedure for measuring the fitness of structures to endure the dynamic demands imposed on them by earthquakes [5].

The most important issues in successful implementation of the procedure is determination of a suitable acceleration function so that the results from ET analysis can be correlated reliably well with the response of structures subjected to real earthquakes. For this purpose, the concept of response spectra has been taken advantage of in ET method [5,6]. Optimization techniques are used in order to create ET acceleration functions with the property of having a response spectra that proportionally intensifies with time while remaining compatible to a pre-specified template response spectra curve as far as possible (Equation 2.1). This means that the response spectrum of any window of the acceleration function from $t_0=0$ to $t_1=t$ resembles that of the target spectrum with a scale factor that is proportional with time (t) [5]. In previous studies, the problem was formulated as an unconstrained optimization problem in the time domain, as follows:

$$\text{Minimize } F(a_g) = \int_0^{T_{\max}} \int_0^{t_{\max}} \{[S_a(T,t) - S_{aT}(T,t)]^2 + \alpha[S_u(T,t) - S_{uT}(T,t)]^2\} dt\, dT \qquad (2.1)$$

where a_g is the ET acceleration function being sought, $S_{aT}(T,t)$ and $S_{uT}(T,t)$ are the target acceleration response and displacement response at time t respectively, $S_a(T,t)$ and $S_u(T,t)$ are the acceleration response and displacement response of acceleration function at time t respectively, α is a weight parameter set to 1.0 in this study and T is the period of free vibration. Optimization was run considering the 2^{11} data points at 0.01 second time step as optimization variables. 200 different periods, distributed in the range of 0 to 5 seconds, and 20 different periods, distributed in the range of 6 to 50 seconds were assumed in the numerical optimization described by Equation (2.1). 20 long periods are used to remove the effect of incompatibility in the long period range between ET analysis results and real earthquake responses.

ET acceleration functions that have been used in this research are designed in such a way that their response spectrum remains proportional to that of the average of seven real earthquakes recorded on a stiff soil condition (Table 1) [3]. These records are selected from 20 earthquake ground motions recorded on site class C, as defined by the NEHRP, because their response spectra were more compatible with the response spectrum of the Iranian National Building Code (INBC) standard 2800 [7,8]. These 7 accelerograms are scaled in such a way that the area under the pseudo acceleration spectrum of them equals the area under INBC standard 2800 spectrum. Finally average of pseudo acceleration spectrum of these scaled accelerograms is obtained and smoothed. The smoothed spectrum is used as the target spectrum in generating ET acceleration functions. Six acceleration functions are created for this study (ETA20e01-03 and ETA20f01-03).

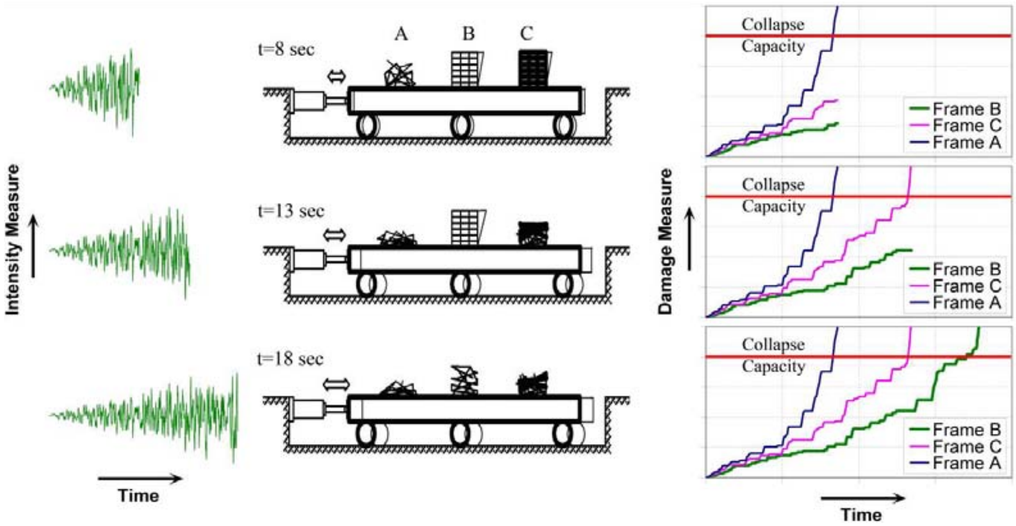

Figure 1. Schematic representation of Endurance Time method analysis in distinguishing different structures.

Table 1. Description of 7 ground motions used in this study.

Date	Earthquake Name	Magnitude (Ms)	Station Number	Component (deg)	PGA (cm/s^2)	Abbreviation
06/28/92	Landers	7.5	12149	0	167.8	LADSP000
10/17/89	Loma Prieta	7.1	58065	0	494.5	LPSTG000
10/17/89	Loma Prieta	7.1	47006	67	349.1	LPGIL067
10/17/89	Loma Prieta	7.1	58135	360	433.1	LPLOB000
10/17/89	Loma Prieta	7.1	1652	270	239.4	LPAND270
04/24/84	Morgan Hill	6.1	57383	90	280.4	MHG06090
01/17/94	Northridge	6.8	24278	360	504.2	NRORR360

3. Application of ET method in Nonlinear Seismic Analysis of SDOF Systems

If ET acceleration functions are to be used successfully as a tool for relative performance measurement, they should be capable of predicting displacements of nonlinear systems with reasonable accuracy and consistency. As it was mentioned before ET acceleration functions used in this study tries to be a representative of the average of 7 real ground motions. In Figure 2 comparison of average of total acceleration spectra of ETA20e series acceleration functions and 7 real ground motions is shown. This comparison is done at different time of ET acceleration functions. It is important to note that the ET response spectra remains proportional to the target spectra from seven real earthquakes at all times, e.g., it is 0.5 and 1.5 times the target spectra at t=5 sec and t=15 sec respectively. Displacement response also follows the same trend with some increased scattering.

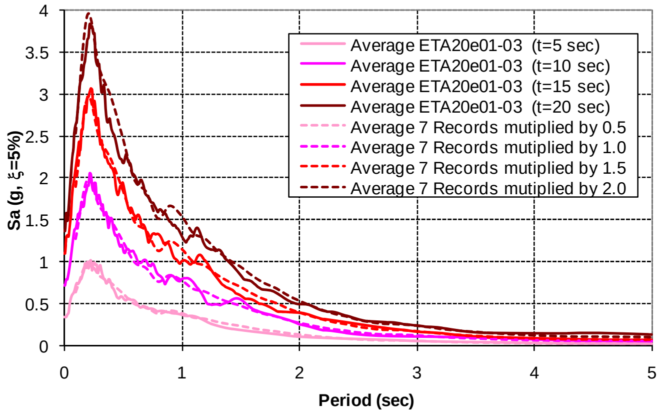

Figure 2. Comparison of total acceleration spectra of ETA20e series acceleration functions at different time and 7 real ground motions.

To evaluate the results of ET acceleration functions for nonlinear SDOF systems, an elastic perfectly plastic (EPP) model is used. This model has been used widely in previous investigations and therefore it represents a benchmark to study the effect of hysteretic behaviour. Nonlinearity is introduced to the model by the means of normalized lateral strength. In this study the lateral strength is normalized by the strength ratio R, which is defined by equation 3.1.

$$R = \frac{mS_a}{F_y} \tag{3.1}$$

where m is the mass of the SDOF oscillator, S_a is the spectral acceleration ordinate corresponding to the initial period of the system and F_y represents the lateral strength required to maintain the system elasticity. In Figure 3 average of total acceleration spectra for 7 scaled accelerograms are compared with the average of total acceleration spectra for ETA20f series for different R values. Results demonstrate the reasonable compatibility between the acceleration functions and 7 scaled accelerograms. In Figure 4 the displacement response of ETA20f series and real ground motions are compared for R=5. There are some differences between the results of ET acceleration functions and real records but a distinct trend cannot be observed. For example for R=2 displacements of real earthquakes in long periods are more than ET method estimation but for R=5 this conclusion is not valid. The dispersion of the results of ET acceleration functions is larger than the real ground motions.

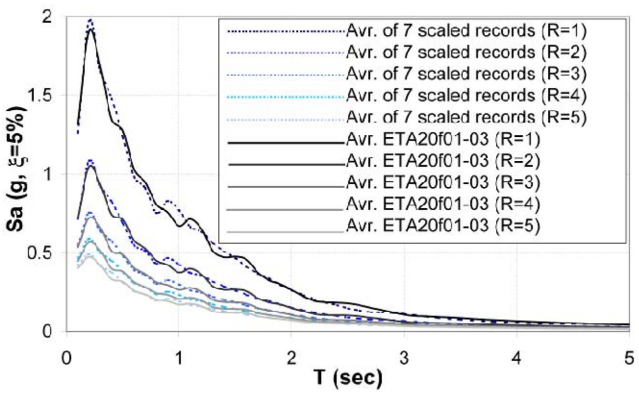

Figure 3. Comparison of of total acceleration spectra for 7 accelerograms and ETA20f series for different R values.

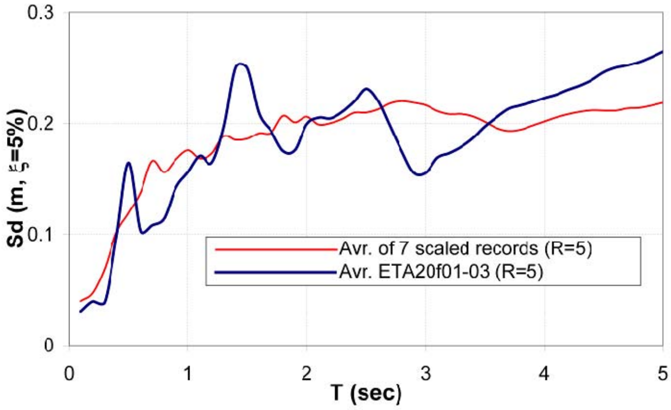

Figure 4. Comparison of displacement spectra for 7 accelerograms and ETA20f series (R=5).

A fixed viscous damping ratio (ξ=5%) is used in generating acceleration functions in this research. The response spectrum of a ground motion record is typically highly depending on the assumed level of damping. By applying 4 different levels for damping ratios, the consistency of ET method in estimating the response of SDOF systems with different damping ratios is investigated. Damping ratios are assumed to be 5, 10, 20 and 50 percents. The results of 7 scaled accelerograms and 3 acceleration functions are compatible in linear range for different damping ratios. In linear range displacement values are decreased by increasing damping ratios. However by increasing the nonlinearity of the systems (Figure 5), ET acceleration functions underestimate the response in almost every point of periods for larger damping ratios.

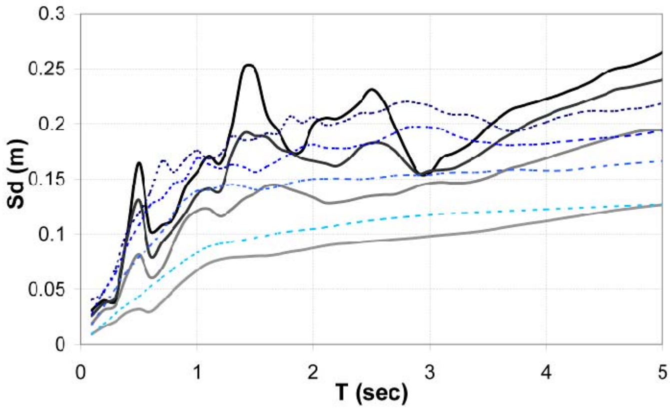

Figure 5. Comparison of displacement spectra for 7 accelerograms and ETA20f series for different damping ratios (ξ=5%, 10%, 20%, 50%) (R=5).

4. Application of ET method in Nonlinear Seismic Analysis of MDOF Systems

In order to implement ET method for seismic analysis of MDOF systems, a set of steel moment frames with different number of stories and bays was used. This set consists of two-dimensional regular generic frames with 3, 7 and 12 stories (Table 2). For comparison of behavior of the well designed frames with improper designed frames, each frame is designed in three kinds. Standard frames have been designed according to the recommendations of the INBC for a high seismicity area [8]. Weak frames have been designed assuming one half of the codified base shear as the design lateral load. Strong frames have been designed for twice the standard lateral load. The results obtained from ET analysis of the frames are compared with the results obtained from nonlinear time history analysis of the frames using 7 real ground motions mentioned before. It should be noted that these accelerograms are scaled based on the usual method used in the seismic codes

An important question is how the results of ET method can be compared with other methods. Because in ET method time is correlated to IM, an equivalent time should be fined in it that can be a representative of IM of any other method. In this research first−mode spectral acceleration (S_a) is used as IM to obtain the equivalent time. To compare the results of a set of records with the results of ET analysis the average of the first−mode spectral acceleration of the records ($S_{a,Ave}$) should be calculated. Furthermore the value of the smooth response spectrum used for the generation of ET acceleration functions at the first−mode period (T_i) is calculated ($S_{a,ET}$). Finally the equivalent time is obtained by Equation 4.1.

$$t_{eq} = \frac{S_{a,Ave}}{S_{a,ET}} \times 10 \quad (4.1)$$

Constant 10 is used in this equation because the response spectrum of ET acceleration function at t=10 second matches the target smooth response spectrum. Based on this Equation for each structure an equivalent time can be computed (Table 2).

Table 2. Specifications of the frames.

Frames	Number of Stories	Number of Bays	Mass participation Mode 1	Period of free vibration (sec)	Design base shear (KN)	*Equivalent time (sec)*
FM03B1RGW	3	1	90.98%	1.20	59.7	10.79
FM03B1RGS	3	1	88.03%	0.89	116.32	10.26
FM03B1RGO	3	1	85.15%	0.60	244.92	9.63
FM03B3RGW	3	3	88.57%	1.25	179.3	10.96
FM03B3RGS	3	3	85.71%	0.89	362.17	10.36
FM03B3RGO	3	3	85.64%	0.61	729.26	9.48
FM07B1RGW	7	1	81.18%	2.03	101.38	13.13
FM07B1RGS	7	1	80.60%	1.43	204.78	11.47
FM07B1RGO	7	1	80.56%	0.99	414.92	10.64
FM07B3RGW	7	3	81.25%	2.05	302.34	13.51
FM07B3RGS	7	3	80.92%	1.44	609.77	11.67
FM07B3RGO	7	3	80.40%	0.97	1233.41	10.57
FM12B3RGW	12	3	79.32%	2.89	399.2	15.36
FM12B3RGS	12	3	78.43%	2.05	804.38	13.28
FM12B3RGO	12	3	75.17%	1.30	1631.52	11.16

The average of maximum interstory drift ratios for ET acceleration functions through time are presented for FM03B3RG frames in Figure 6. In this figure EPP material model is used to introduce nonlinearity to the structures. Equivalent times of the frames for comparison the results with the results of nonlinear response history analysis are also shown in the figure. It should be noted that ET analysis results are usually presented by increasing curves where the y coordinate at each time value t, corresponds to the maximum absolute value of the required parameter in the time interval [0, t] as given in Equation 4.2.

$$\Omega(f(t)) \equiv Max(Abs(f(\tau):\tau \in [0,t]) \quad (4.2)$$

Where Ω is the Max-Abs operator as defined above and *f(t)* is the response history such as base shear, interstory drift, damage index or other parameter of interest [9]. Figure 6 shows that at the first time of the excitation the structure behaves linearly till it reaches a certain point that the first plastic hinge is created. After that by increasing the intensity of the acceleration function through time, the structure experiences more deformations until it reaches the collapse limit. For example FM03B3RGW frame experiences significantly high displacements after 10 second and the analysis does not converge after t=16 second for two of acceleration functions. Maximum interstory drift ratios and corresponding base shears obtained from nonlinear response history analysis and ET analysis of the frames with elastic-plastic material model with 3% strain hardening are compared in Table 3. In most of the frames, estimations of ET analysis for maximum interstory drift ratio are less than nonlinear response history analysis results. The difference between the results is more in weaker frames which experience more nonlinearity in their analysis. This is due to the fact that the dispersion of the results of nonlinear response history analysis for the frames that experience more nonlinearity is high. But in ET analysis the dispersion of the results is not significant.

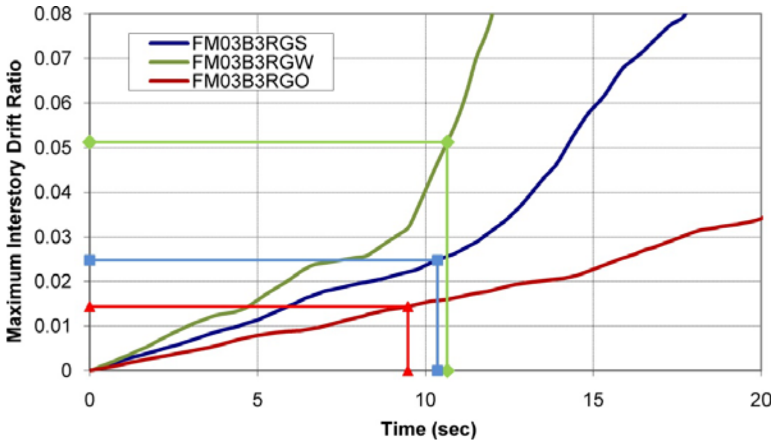

Figure 5. ET maximum interstory drift ratio curves for FM03B3RG frames and values of t_{eq} of nonlinear response history analysis.

Table 3. Comparison between the results of nonlinear response history analysis and ET analysis for different frames.

Frames	Maximum interstory drift ratio			Base shear (KN)		
	Nonlinear time history analysis	*ET analysis*	*Differences*	*Nonlinear time history analysis*	*ET analysis*	*Differences*
FM03B1RGW	0.0340	0.0312	-8.1%	227.6	230.8	1.4%
FM03B1RGS	0.0219	0.0216	-1.3%	339.4	355.4	4.7%
FM03B1RGO	0.0140	0.0144	3.0%	523.9	568.3	8.5%
FM03B3RGW	0.0349	0.0300	-14.0%	590.5	588.9	-0.3%
FM03B3RGS	0.0247	0.0222	-9.9%	964.0	1019.9	5.8%
FM03B3RGO	0.0147	0.0140	-4.4%	1538.9	1579.8	2.7%
FM07B1RGW	0.0250	0.0235	-6.1%	294.8	305.6	3.7%
FM07B1RGS	0.0206	0.0204	-0.6%	470.7	466.0	-1.0%
FM07B1RGO	0.0146	0.0137	-6.0%	779.1	779.6	0.1%
FM07B3RGW	0.0357	0.0326	-8.7%	790.7	795.9	0.7%
FM07B3RGS	0.0211	0.0194	-8.0%	1338.8	1322.6	-1.2%
FM07B3RGO	0.0149	0.0141	-4.8%	2261.4	2295.8	1.5%
FM12B3RGW	0.0257	0.0219	-15.0%	1036.0	1067.4	3.0%
FM12B3RGS	0.0223	0.0189	-15.6%	1545.8	1619.9	4.8%
FM12B3RGO	0.0151	0.0136	-10.0%	2917.5	3225.1	10.5%

5. Application of ET method in more complicated cases

To examine the potential of ET method in distinguishing structures with better performance, a more involved assessment problem is discussed in this section. A 3 stories frame is selected for this analysis. EPP material model is considered for modeling nonlinearity. The question to be answered is the story level that a damper with the damping constant of 2000 KN.sec/m should be installed to result in the best performance. Because ET analysis and Incremental Dynamic Analysis (IDA) analysis are in common, similar curve to an IDA curve can be drawn by the results of ET analysis [10]. These similar curves resulted from ET analysis and IDA curves resulted from IDA analyses of 7 accelerograms are depicted in Figure 6. As it can be seen although that the results of IDA analysis and ET analysis have some differences but ET analysis can predict the best system through different systems even for complicated cases. Like previous sections the estimation of ET analysis for DM at a same level of IM is smaller than what is obtained from time history analysis of real ground motions.

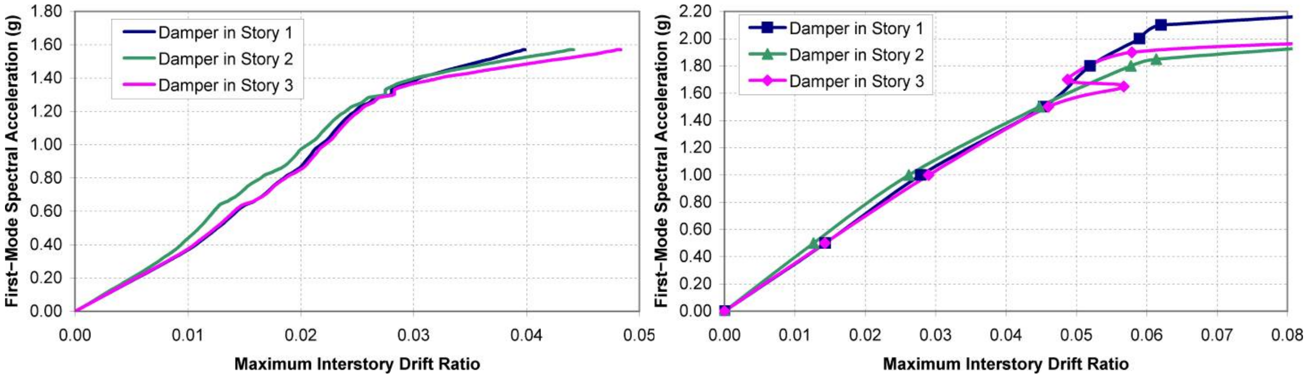

Figure 6. IDA curves resulted for three locations of damper in a three stories frame: a) ET analysis, b) IDA analysis.

6. CONCLUSIONS

- Displacement responses of SDOF systems from ET acceleration functions, optimized to be compatible with real ground motions, match well with responses from real ground motions in linear and nonlinear ranges with reasonable accuracy. Highest differences between the results were observed in short period range (T=0 to T=1 second).
- In most of the frames, estimations of ET analysis for maximum interstory drift ratio are less than nonlinear response history analysis results. The difference between the results is more in weaker frames which experience more nonlinearity in their analysis. The consistency of the base shears obtained by two methods is acceptable. The dispersion of the results of nonlinear response history analysis for the frames that experience more nonlinearity is high. In ET analysis the dispersion of the results is not significant.
- It is shown that although the results of ET analysis are not exactly consistent with the results of real ground motions analysis but ET method can find the structure with better performance even in the case of complicated structures. Therefore ET method can be a useful tool to apply in PBSE.

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