Application of Endurance Time Method in Structural Optimization of the Dampers for Seismic Design

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SUMMARY:
Optimization techniques help a designer to find the best solutions in order to maximize benefits derivation from the available resources. The optimization design of structure by using damper, including the optimization of damper characteristics and its position in structure, is an important task since mentioned parameters have fundamental effect on the structural energy absorption. The main goal of this paper is the evaluation of steel moment-resisting frames strengthened using dampers by Incremental Dynamic Analysis (IDA) and Endurance Time (ET) analysis. To reach this goal a sample set of steel moment-resisting frames (3 and 7-story) are designed. It is clearly observed that structural responses resulted from ET analysis are compatible with those obtained from IDA. Optimization results of dampers characteristics and their positions in the structures obtained by ET analysis are similar to the results of IDA in most cases.

Keywords: *Structural optimization, Damper Devices, Endurance time analysis, Steel moment-resisting frame, Incremental dynamic analysis*

1. INTRODUCTION

Analytical and experimental studies show that by using dampers in structures the structural damping is increased notably and damages to the structures due to strong earthquakes can be reduced significantly. Optimum design of structures with damper, including optimization of dampers' parameters and optimization of dampers' location in the structure, is a major task, because rational parameters and proper location of dampers will lead to most effective energy dissipation (Estekanchi et al., 2011).

Endurance time method is basically a dynamic pushover method that tries to predict seismic response of structures by analyzing their performance when subjected to predesigned intensifying acceleration functions (Riahi and Estekanchi, 2010). If ET acceleration functions can assemble the major characteristics of real ground motions with different intensities, they can provide a good estimate of the real response of the structures to be used in performance based engineering (Estekanchi et al., 2011). Therefore this method can be used to check the performance of different systems and find the one with the best performance. In this research, this capability is used to optimize the amount of the damping devices and their locations and the results are compared with the results of incremental dynamic analysis (Vamvatsikos and Cornell, 2002).

2. ET ACCELERATION FUNCTIONS AND SPECTRUM MATCHED RECORDS

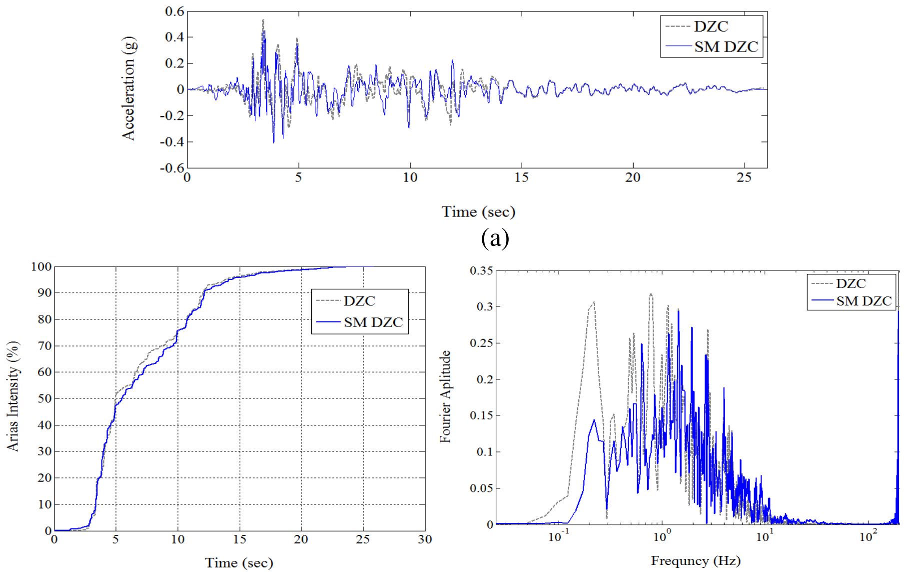
A major factor in the success of the endurance time method is in the availability of suitable intensifying excitation functions. Previous studies show that usable intensifying excitations (i.e.

acceleration functions in this study) can actually be designed (Estekanchi and Basim, 2011). Acceleration functions are designed in such a way that each window from zero to time t produces a response spectrum that is proportional to the template spectrum with proportionality factor that is linearly increasing with time and equal to unity at particular time called t_{Target}. To achieve this goal, the target acceleration response of ET acceleration function can be defined as in Eqn. 2.1:

$$S_{aT}(T,t) = \frac{t}{t_{Target}} S_{aC}(T) \tag{2.1}$$

Where $S_{aT}(T,t)$ is the target acceleration response spectrum at time t and period of vibration T. $S_{aC}(T)$ is the template acceleration response spectrum. Acceleration functions used in this study (ETA40g or series g) have been optimized in such a way that, the response spectrum of SDOF system with 5% damping for the window from zero to 10 (t_{Target}) seconds of ETA40g is fit to design spectral acceleration of the ASCE-07 (2005) code for soil type C with Ss=1.5, S1=0.6, Fa=1.0, Fv=1.3 and TL=8. The response of SDOF system to the acceleration function series ETA40g with a window from zero to any other time has a linear relation with ASCE-07 spectrum. For example for time 5 sec or 15 sec the spectrum will be equal to 0.5 or 1.5 times to ASCE-07 spectrum. Optimization of these acceleration functions is for 200 periods in 0 to 5 seconds plus 20 points from period = 6 to period = 50 seconds. The whole time of these acceleration functions is 40.96 seconds.

Seven near fault ground motions (series OGM) were selected from the series of fourteen near-field pulse records subset listed in FEMA P695 (2009). The specifications of the ground motions of this set are shown in Table 1. The records have been spectrum matched to the same design earthquake spectrum ASEC-07 that acceleration functions ETA40g are optimized to fit. The spectrum matching procedure is applied in time domain using wavelet method. The wavelet used in this study is reverse impulse presented by Abrahamson (1992). After using impulse reverse wavelet for prevention of non-zero displacement and velocity at the end of the time series a linearly base line correction has been applied to the spectrum matched results. This procedure has the advantage that the shape and frequency content of time series after spectrum matching are almost the same before (Hancock et al., 2006). Fig. 1. shows the arias intensity, fourier amplitude and acceleration time history of record DZC befor and after of spectrum matching. Fig. 2. shows the mean response acceleration of acceleration functions ETA40g at t = 10 and 15 seconds, OGM set with scale factor 1 and 1.5 and spectrum match set (GM) with scale factor 1 and 1.5. The obtained coefficients for GM set and ET acceleration functions proportionate with the performance levels are shown in Table 2 .



(a)

(b) (c)

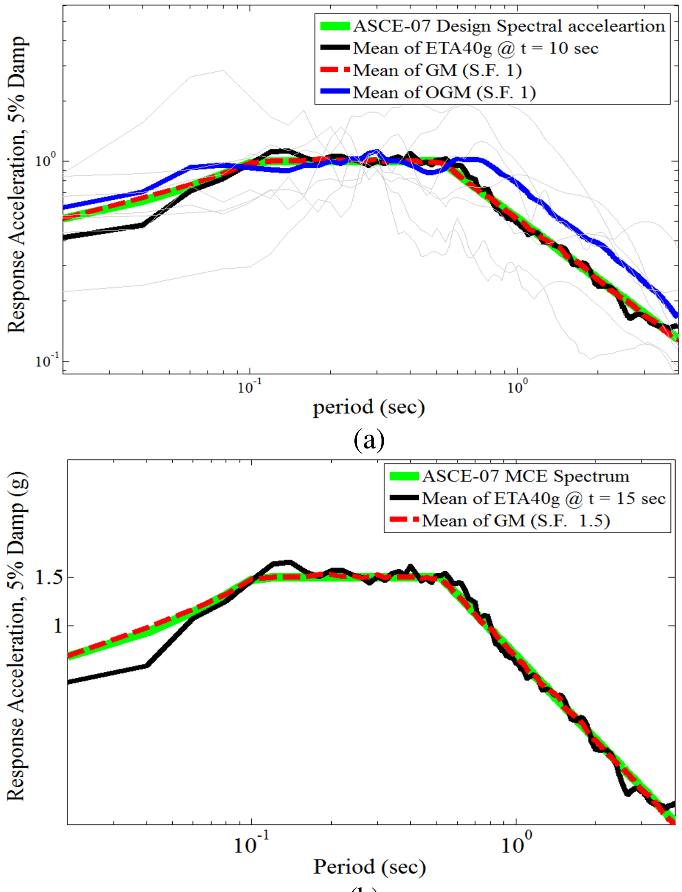
Figure 1. a) apparent shape, b) Arias intensity and c) Fourier amplitude of record DZC before and after spectrum matching.

Table 1. Description of the GM set of ground motions used in this study.

Date	Name	Magnitude (Ms)	Station Name	PGA (g)	Component (degree)	Epicentral (km)	Abbreviation
1999	Duzce, Turkey	7.1	Duzce	0.52	270	1.6	DZC
1992	Erzican, Turkey	6.7	Erzincan	0.49	N-S	9	ERZ
1979	Imperial Valley-06	6.5	El Centro Array #6	0.44	230	27.5	H-E
1999	Kocaeli, Turkey	7.5	Izmit	0.22	90	5.3	IZT
1992	Landers	7.3	Lucerne	0.79	0	44	LCN
1992	Cape Mendocino	7	Petrolia	0.63	90	4.5	PET
1994	Northridge-01	6.7	Rinaldi Receiving Sta	0.87	228	10.9	RRS

Table 2. Scale factors for GM1 and ET time in 3 hazard levels.

Performance levels	Scale factor	ET time (sec)	Maximum interstory drift ratio (MIDR)
BSE-1 (Basic safety earthquake 1) ASCE-07 design earthquake (L.S.)	1.00	10	2.5%
BSE-2 (Basic safety earthquake 2) ASCE-07 maximum considered earthquake (C.P.)	1.50	15	5%
BSE-UD (user defined level)	1.50	15	2.5%



(a)

(b)

Figure 2. Response spectrum acceleration a) of ETA40g at time 10 sec, GM and OGM sets with scale factor 1 b) of ETA40g at time 15 sec, GM set with scale factor 1.5.

3. STRUCTURAL MODELS AND VISCOUS DAMPERS

In this study eight flexural steel frames are considered. The generic frames are adopted from the models developed by Estekanchi et al. (2010). The design of these structures for gravity loads is carried out according to allowable stress method of AISC-ASD89 code (1989). The geometry of some of these models is depicted in Fig. 3. The height of all stories is 3.2 meters and the length of each span is 6 meters. All supports are fixed and the joints are all rigid. The beams and columns are HE profiles. HEA profiles are used for the beams and the columns are selected from HEB profiles. Loading is set according to Iranian National Building Code (INBC) section 6. The behavior of the steel material is considered as elastoplastic with yielding stress of Fy=235.44MPa, elastic modulus of E=206 GPa and post-yield stiffness equal to 3% of the initial elastic stiffness. This material model is applied in the analysis using OPENSEES beam-column elements with nonlinear distributed plasticity (OpenSees, 2011). Four of this models completely modeled by fiber and for of them with letter SSD have zero length element at the joints. These frames have been designed based on one half of the codified base shear. It was expected that the maximum interstory drift ratio (MIDR) of these frames under ground motion exceeds the levels of performance of ASCE41-06, but it was not, except frame FM07B3RGW-SSD. So the performance criterion of BSE-UD is considered to be 2.5% instead of 5% (BSE-2) and both results are shown. The specifications of frames are shown in Table 3.

Viscous dampers are widely used in mechanical systems. The force induced in viscous damper depends on velocity; therefore, the maximum damper force in an earthquake is always π/2 out of phase with respect to displacement, and the maximum speed occurs at the time that the displacement is zero. This is an advantage for these kinds of dampers because when the structure endures great internal forces due to displacements created by earthquakes, they induce least extra forces on the structure. To model viscous dampers as bracing, viscous material available in OPENSEES is used. The induced stress in this material is acquired from this equation:

$$\sigma = C_0|\dot{\epsilon}|^{\alpha}\, sign(\dot{\epsilon}) \tag{3.1}$$

Where σ represents the induced stress in the material, $\dot{\epsilon}$ strain rate, C_0 damping ratio and α damping exponent.

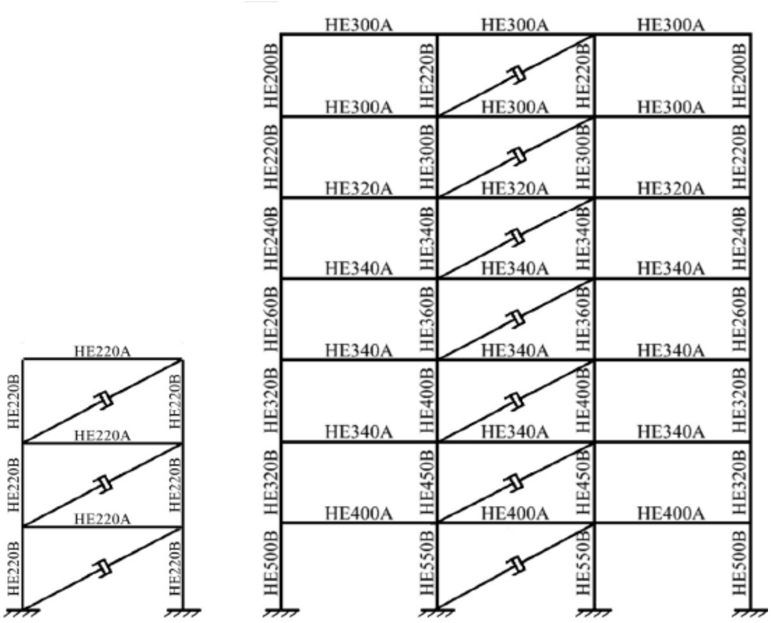


Figure 3. Schematic of steel frames under investigation.

Table 3. Specification of the frames.

Frames	Number of stories	Number of bays	Total mass (kNs^2/m)	Period of free (sec) vibration
FM03B1RGW	3	1	81.47	1.20
FM03B1RGW-SSD	3	1	81.47	1.17
FM03B3RGW	3	3	244.40	1.25
FM03B3RGW-SSD	3	3	244.40	1.16
FM07B1RGW	7	1	190.09	2.03
FM07B1RGW-SSD	7	1	190.09	1.97
FM07B3RGW	7	3	570.28	2.05
FM07B3RGW-SSD	7	3	570.28	1.87

4. ANALYSIS AND OPTIMIZATION PROCEDURE

The problem is going to find optimized damper coefficients in each story so that the MIDR of the frame in two level of ASCE-07 satisfy the limit levels of ASCE41-06 (MIDR = 2.5% for design earthquake and MIDR = 2.5 or 5% for maximum considered earthquake (MCE)). At first step some value should be assigned to the dampers and in the next step OPENSEES is running and then it’s got to be check that MIDR has satisfied the ASCE41-06 levels or not. So this problem needs an optimization procedure. It seems that the genetic algorithm is a good optimization procedure for this problem. In genetic algorithm a primary population is randomly generated then after generation the fitness function will be check. The good population will be remain with a cross over rate and remain are killed. After that a new population will be generated from the good ones. For prevention of stick answer in a local space, the algorithm is doing a mutation. In this specific problem the fitness function is defined sum of damping coefficients in all stories. Primary population is generated randomly between 0 to 4000 (kN.sec/m). Before checking fitness function the constraint (MIDR should have an acceptable difference with ASCE or user defined Limit) should be controlled. If primary population satisfy the constraint the algorithm can go on, if not the population should change. Because of negligible changes in MIDR under primary population, the algorithm may never converge. The convergences criteria may be defined the algorithm after a specified number of iteration or converge in damping coefficient. After generation organisms (coefficient) the structure is analyzed under ETA40g. Then ET curve corresponding to MIDR is drown. MIDR correspond to time 10 sec is equivalent to MIDR for design earthquake (Life Safety (LS)), and at time 15 sec is equivalent to MCE (Collapse Prevention (CP)). After checking both MIDR of LS and CP levels with ASCE limits, if feasible solution is obtained then genetic algorithm tries to find optimal solution. Else new population of organisms should be reproduced.

5. ANALYSIS AND OPTIMIZATION RESULTS

5.1. ET acceleration functions and ground motions

The response spectrum of seven records and ETA40g are exactly match to the ASCE-07 spectrum (target spectrum). So any scale factor multiplied by the records produce a spectrum that is scale factor times to target spectrum. The performance criterion for BSE-1 level is considered to be LS (2.5% MIDR) and for BSE-2 level is considered to be CP. So for controlling MIDR at BSE-1 level, the scale factor is 1 and for controlling BSE-2 level the scale factor is 1.5 respectively. In the endurance time method particularly for ETA40g the dynamic analysis is going to the last time of the acceleration function that is here 40.96. Then the ET curve is drown correspond to MIDR. MIDR at time 10 sec should be compared with BSE-1 level and at time 15 sec should be compared with BSE-2 level.

5.2. ET analysis and optimization

In this research, according to the code, the design objectives ‘p’ and ‘k’ are assigned as the rehabilitation objectives. Therefore, the structure should satisfy the CP performance level in BSE-2 hazard level and LS level in BSE-1 hazard level. This would be the basic safety objective or BSO. According to ASCE41-06, the allowable transient interstory drift ratio is 5% for the CP level or 2.5% for those structures that without damper satisfy the limits levels and 2.5% for the LS level. By drawing the performance curve similar to the curve in Fig. 4 and comparing with the allowable limits of the code, the vulnerability of each structure can be distinguished (Riahi and Estekanchi, 2010). In this stage using the genetic algorithm with the purpose of reaching the acceptable performance stated in the code, which is equivalent to make the performance curve (ET curve) below the allowable limit of the code presented in Fig. 6 to Fig. 8, the required damping for each structure is evaluated (Fig. 5). For example, for the frame FM03RGW, the required damping in the second story is more than the other stories. The damper in this story has the most influence on the structure behavior and for the frame FM07RGW just the first story has influence in drift controlling.

The performance curves of the structures before and after the rehabilitation are compared in Fig. 6 to Fig. 8. As shown, the performance curve of the structure after rehabilitation (damper installation) is quite close to allowable limit of the code and the smoothed curve has contacted it at a point, this indicates the optimal use of structure capacity.

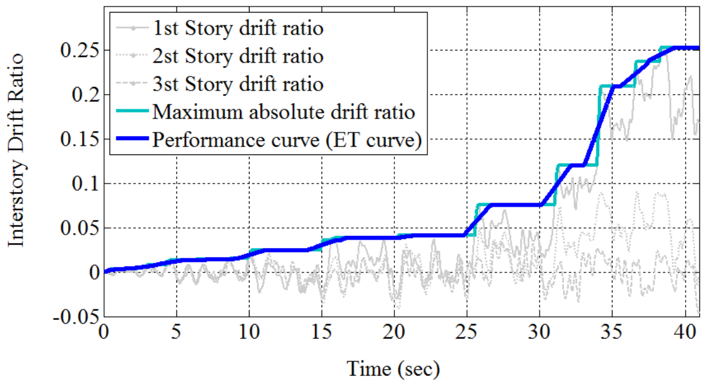


Figure 4. Generating performance curve (ET curve) for FM03B1RGW based on interstory drift ratio.

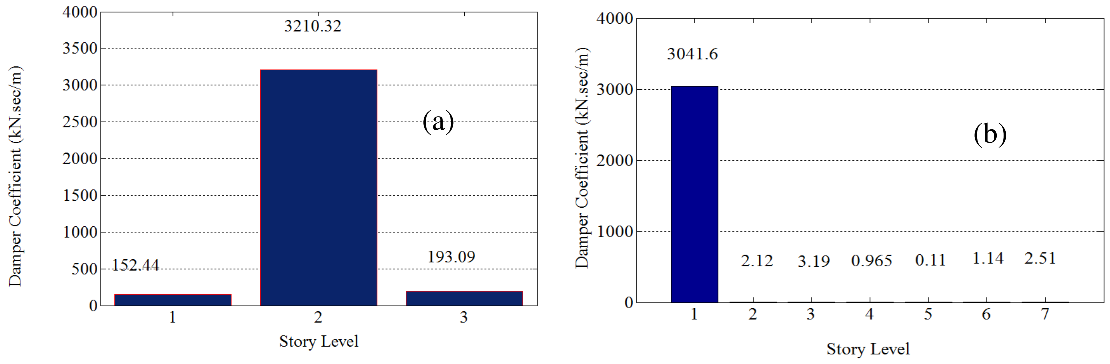


Figure 5. Optimum damper distribution for (a) FM03b3RGW b) FM07B1RGW

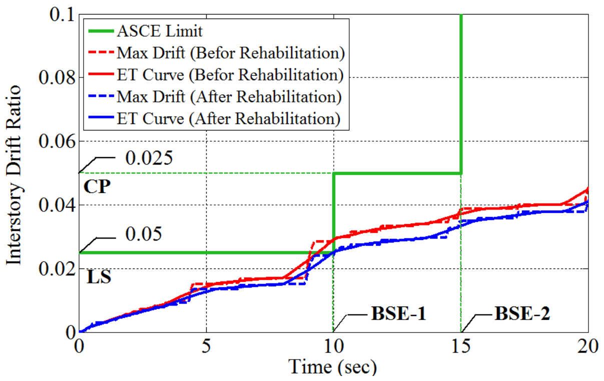


Figure 6. Performance curve (ET curve) for FM03b1RGW before and after rehabilitation.

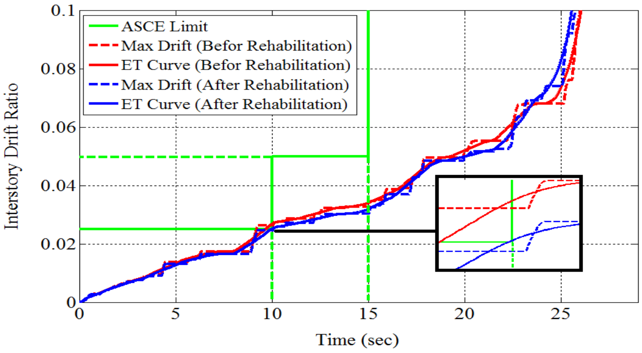


Figure 7. Performance curve (ET curve) for FM03b1RGW-SSD before and after rehabilitation.

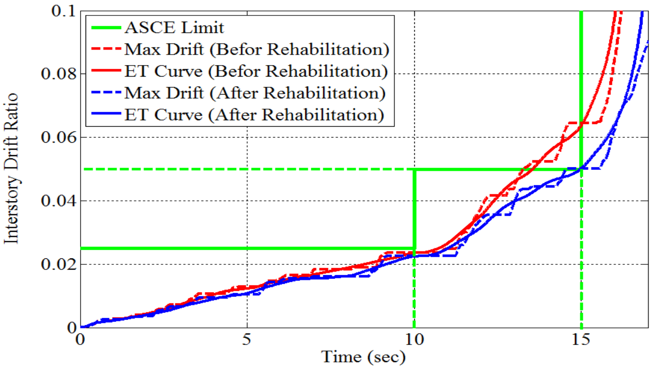
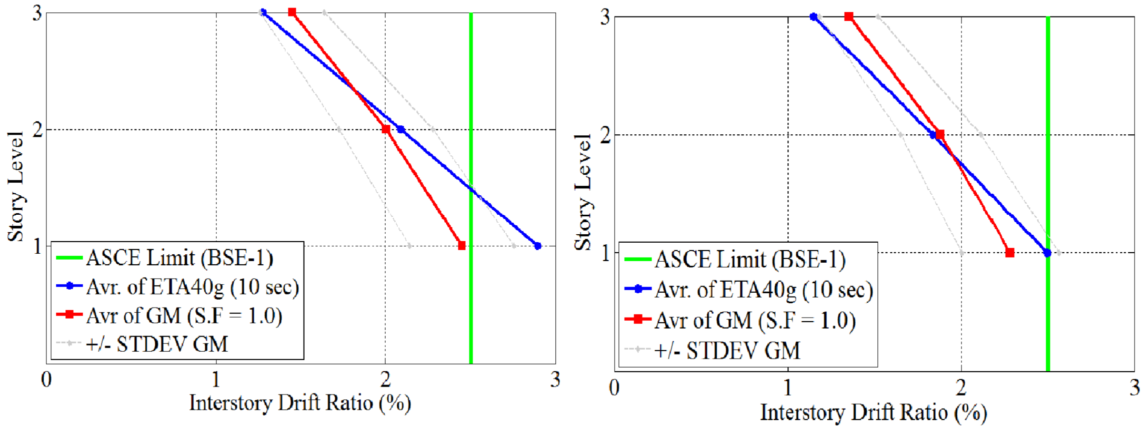


Figure 8. curve (ET curve) for FM07b3RGW-SSD before and after rehabilitation.

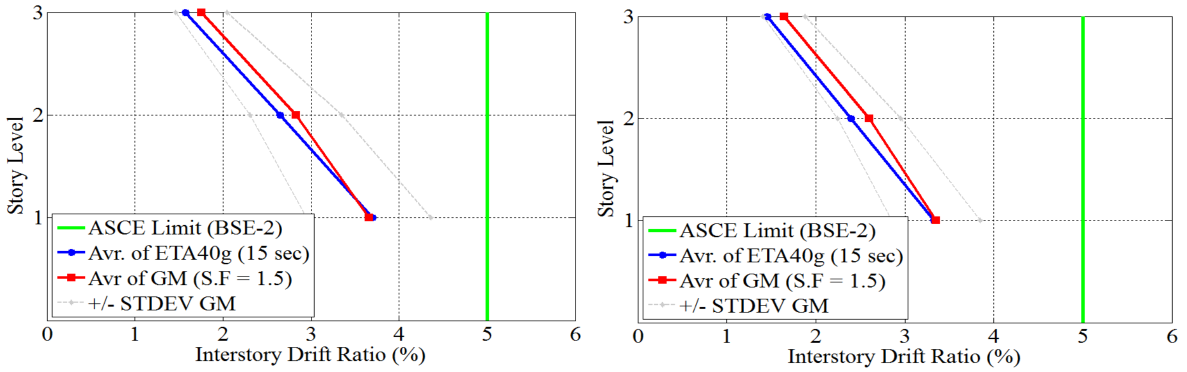
5.3. Verification and comparative study

In order to investigate the structure behavior under earthquake records and to compare them with the ET method estimation, the average response of the structure to seven earthquake records and also the response of the structure to the ET acceleration function before and after the rehabilitation in the frames are compared in Fig. 9 to Fig. 13.



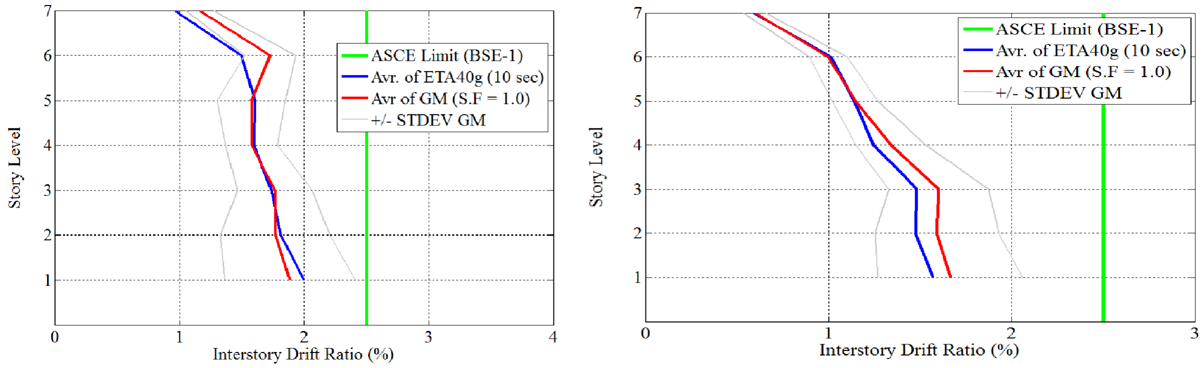
(a) (b)

Figure 9. Average interstory drift ratios of frame FM03B1RGW under GM set of ground motions and ET estimation in BSE-1 a) before rehabilitation b) after rehabilitation



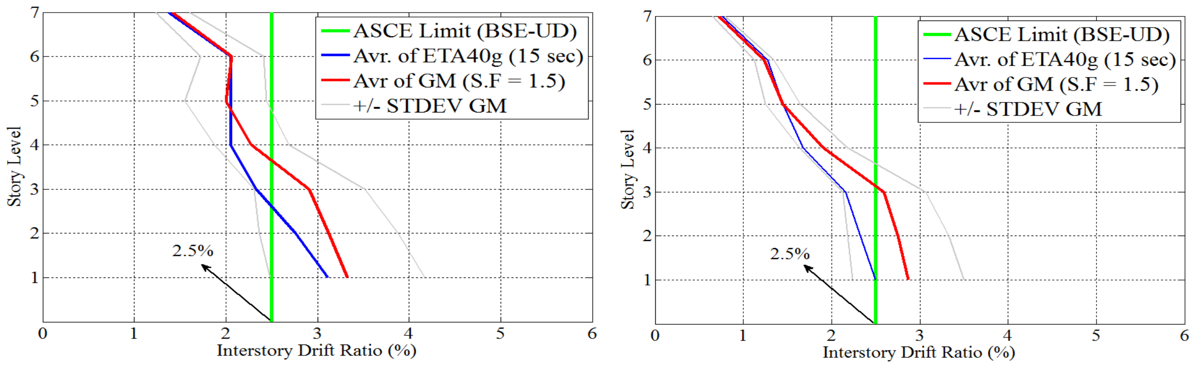
(a) (b)

Figure 10. Average interstory drift ratios of frame FM03B1RGW under GM set of ground motions and ET estimation in BSE-2 a) before rehabilitation b) after rehabilitation.



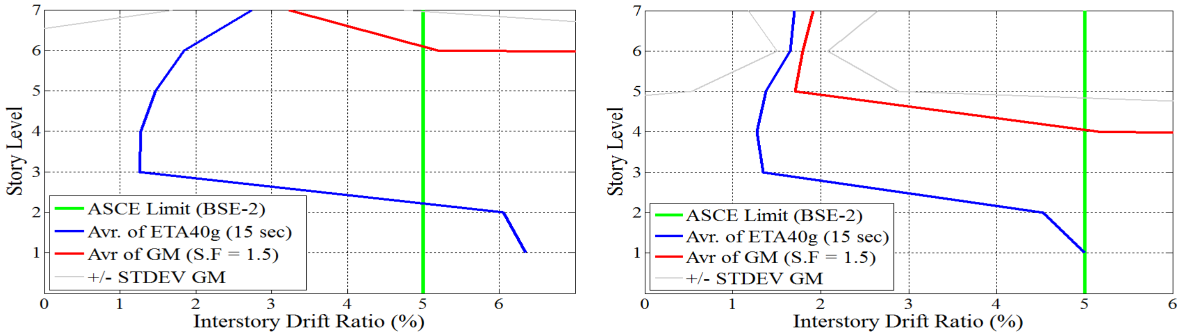
(a) (b)

Figure 11. Average interstory drift ratios of frame FM07B1RGW under GM set of ground motions and ET estimation in BSE-1 a) before rehabilitation b) after rehabilitation



(a) (b)

Figure 12. Average interstory drift ratios of frame FM07B1RGW under GM set of ground motions and ET estimation in 2.5% limit a) before rehabilitation b) after rehabilitation



(a) (b)

Figure 13. Average interstory drift ratios of frame FM07B3RGW-SSD under GM set of ground motions and ET estimation in BSE-2 a) before rehabilitation b) after rehabilitation

ETA40g acceleration functions contrariwise GM set of ground motion show that before rehabilitation MIDR of all frames except FM07B3RGW-SSD exceeds BSE-1 and with optimum damper it goes to close to the BSE-1 limit. However also after rehabilitation MIDR under GM set, it is less than before and this decrease is almost equal to the one from endurance time. But in the frame FM07B1RGW-SSD MIDR under GM set both before and after rehabilitation exceeds BSE-2 limit and in both 3th story has a large interstory drift ratio and it is because of RRS record. The third story plays the soft story role for the frame under RRS record and ET method could not predict it.

7. SUMMARY AND CONCLUSIONS

In ET method, a range of equivalent intensities can be covered in a single numerical or experimental simulation, thus significantly reducing the computational demand as compared to classical nonlinear response-history analyses. In this research, the ET method is used to tackle the problem of optimal damper placement in short steel frames. Four steel moment frames with nonlinear material and four with zero length element for joints are considered and the ET method is used to estimate the structural response at different hazard levels. The earthquake records are spectrum matched to the ASCE-07 design spectrum. Using the genetic algorithm, the optimal damper placement in order to reach the target performance in three levels of LS, CP and user defined in all eight structures was investigated. The results of time-history analyses under seven spectrum matched earthquake records in some hazard levels confirm the optimization results and in some does not. In each eight models after rehabilitation, the structure satisfied the performance requirements of the code for acceleration functions.

ET method can be considered an effective procedure in performance based optimum design of structures hugely reducing the required computational effort. This reduction of the number of required time-history analyses is accompanied by some loss of accuracy, suggesting classical procedures to be used for final verification of the design. Thus, the ET method can play a role in making the response-history analysis performance based seismic optimization a practical design alternative.

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