Evaluation of reliability and sensitivity analysis of steel moment-resisting frames based on endurance time method

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SUMMARY:
Sensitivity analysis is becoming increasingly widespread in many fields of engineering and it is essential for engineers to make decisions under conditions of uncertainty. This paper investigates the seismic reliability and sensitivity analysis of Endurance Time (ET) method by considering steel moment resisting framed buildings. Different approaches for evaluating the effects of uncertainties are described here. Samples of regular three, seven and twelve storey steel moment resisting frames are designed. Reliability and sensitivity analysis is accomplished by the incremental dynamic analysis. Then results compared with the results of endurance time analysis. Also building fragility curves, which demonstrate the critical probabilities at increasingly intensity of ground motions, are illustrated. The results obtained indicate that ET analysis can clearly identify the uncertainties of the performance of the structure with a satisfied accuracy. Therefore this method can be used as a suitable tool for estimating uncertainties of the steel moment-resisting frames responses.

Keywords: *Sensitivity Analysis, Endurance Time Method, Reliability Analysis, Engineering Demand Parameters*

1. INTRODUCTION

A primary goal of seismic provisions in building codes is to protect life safety through prevention of structural collapse. To achieve this goal major factors which results in uncertainties of the structural responses should be recognized. Uncertainty is generally costly in earthquake engineering because of the large amount of the parameters that should be considered for its calculation. Endurance time method is basically a dynamic procedure that tries to predict seismic performance of structures by analyzing their resilience when subjected to predesigned intensifying dynamic excitations (Riahi and Estekanchi, 2010). In this method, numerical or experimental models of structures are subjected to specially design intensifying dynamic accelerations. Major structural responses, such as displacements, drift ratios, stresses, plastic rotations or other appropriate Engineering Demand Parameters (EDPs) are monitored as the intensity of dynamic excitation is increased. The time duration from the start of the excitation the limit point considering an EDP of interest is called the endurance time with respect to that EDP. Since the intensity of the excitation is increasing with time, a longer endurance time means that the structure has been subjected to a higher equivalent intensity before the intended EDP exceeds its maximum limit value. Thus, if the intensity of ET acceleration can be properly correlated to the intensity of equivalent ground motion, a longer endurance time can be interpreted as a sign of better fitness for tolerating seismic loading. Obviously, the term of endurance time can be defined relative to any desired criteria such as reaching certain story drift limit or maximum design stress ratio that are not necessarily related to collapse or limit state of the structure as used in explaining the concept of ET method. In practical applications of ET procedure, the entire response history of the structure rather than the maximum endurance time is considered for assessing its performance (Estekanchi et al., 2011).

2. STRUCTURES AND GROUND MOTIONS USED IN THIS STUDY

In order to estimate the sensitivity of collapse fragility curves to variations in system and component parameters, we use moment-resisting frames with number of stories, *N*, equal to 3, 7, 12 and consists of 1-bay & 3-bay with span equal to 6 m and story heights of 3.2 m. The same mass is used at all floor levels. Fig. 1. shows a schematic representation of the 3-story 1-bay frame.

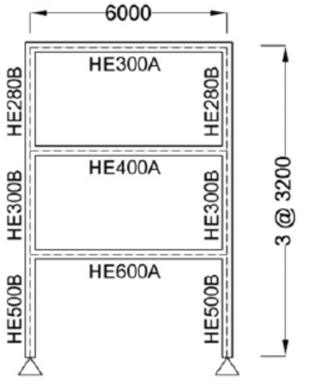


Figure 1. Schematic representation of the 3-story 1-bay

The frames are two-dimensional and are modeled with elastic elements and rotational springs. The material model is intended to reproduce the hysteretic behavior of structures in which lateral stiffness and lateral strength decrease when subjected to cyclic reversals (SSD model). In this model, the amount of strength and stiffness degradation is a function of the hysteretic energy dissipated (Shafei et al., 2011; Rahnama and Krawinkler, 1993). The parameters of SSD model is adopted from the steel model used by Ibarra and Krawinkler (2005). The strain-hardening ratio (ratio between post-yield tangent and initial elastic tangent) of this model is 0.03. The post-capping stiffness coefficient is assumed to be 0.03. Ductility capacity (δc/δy) that refers to the ratio of the displacement at which peak strength is attained (δc) over the yield displacement (δy) is assumed to be 2.75. Cyclic deterioration parameter refers to the ratio of the hysteretic energy-dissipation capacity over twice the elastic strain energy at yielding (Fy × δy). This parameter is assumed to be 130 for SSD model. Fig. 2 (Ibarra and Krawinkler, 2005) shows the necessary parameters for defining the SSD modelThis approach permits incorporation of most of the important parameters that strongly affect structural behavior. Sensitivity of the maximum roof displacement and maximum interstory drift ratio to uncertain design parameters was studied. Uncertain design parameters considered in this study were elastic modulus of the steel, post-capping stiffness coefficient, strain-hardening ratio and ductility capacity.

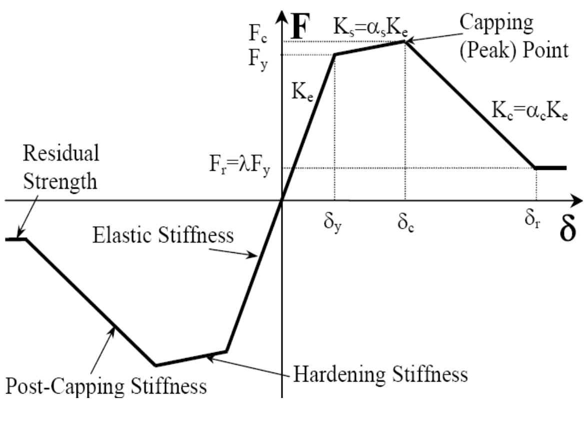


Figure 2. Necessary parameters for defining the SSD model (Ibarra and Krawinkler, 2005).

3. SENSITIVITY ANALYSIS

To evaluate the behavior of models a sensitivity study was performed by perturbing each of the random parameters (Vamvatsikos and Cornell, 2002). The sensitivity of each parameter is evaluated using Incremental Dynamic Analysis (IDA). IDA is a powerful analysis method that can provide accurate estimates of the complete range of the model's response, from elastic to yielding, then to nonlinear inelastic and finally to global dynamic instability (Vamvatsikos and Fragiadakis, 2010). The selection of earthquake ground motions with an appropriate earthquake ground motion intensity measure is an important issue, hence, in order to investigate the sensitivity of engineering demand parameters, a set of earthquake ground motions are selected. This set is used for performing IDA (Table 1).

Table1. The suite of twenty two ground motion records used in this study.

EQ Index	Mag.	Year	Event	Station Name
1	6.7	1994	Northridge	Beverly Hills
2	6.7	1994	Northridge	Canyon Country
3	7.1	1999	Duzce, Turkey	Bolu
4	7.1	1999	Hector Mine	Hector
5	6.5	1979	Imperial Valley	Delta
6	6.5	1979	Imperial Valley	El Centro Array #11
7	6.9	1995	Kobe, Japan	Nishi-Akashi
8	6.9	1995	Kobe, Japan	Shin-Osaka
9	7.5	1999	Kocaeli, Turkey	Duzce
10	7.5	1999	Kocaeli, Turkey	Arcelik
11	7.3	1992	Landers	Yermo Fire Station
12	7.3	1992	Landers	Coolwater
13	6.9	1989	Loma Prieta	Capitola
14	6.9	1989	Loma Prieta	Gilroy Array #3
15	7.4	1990	Manjil, Iran	Abbar
16	6.5	1987	Superstition	El Centro Imp.
17	6.5	1987	Superstition	Poe Road (temp)
18	7.0	1992	Cape Mendocino	Rio Dell Overpass – FF
19	7.6	1999	Chi-Chi, Taiwan	CHY101
20	7.6	1999	Chi-Chi, Taiwan	TCU045
21	6.6	1971	San Fernando	LA - Hollywood Stor
22	6.5	1976	Friuli, Italy	Tolmezzo

The process for obtaining the collapse capacity for a 3-story 1-bay frame (FM03B1) subjected to a set of 22 ground motions is illustrated in Fig 3. It is assumed that the collapse capacity is a lognormal variable and the cumulative distribution function of collapse capacities defines the "collapse fragility curve" which is shown in Fig 3. Similar curves are shown for 7-story 1-bay frame (FM07B1) in Fig. 4.

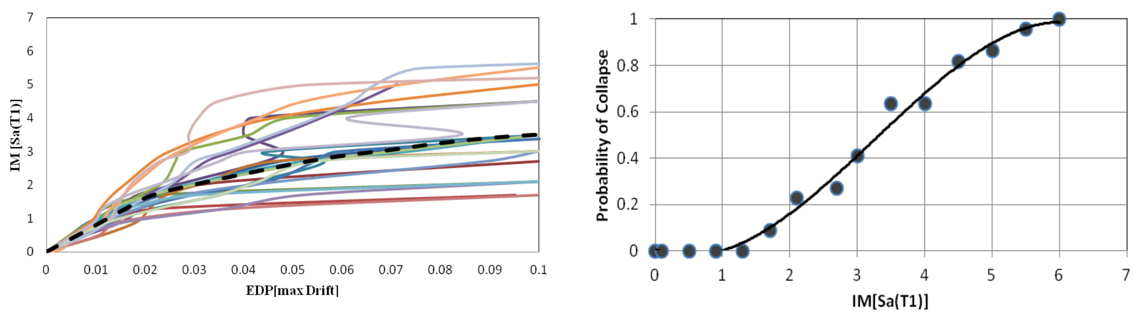


Figure 3. Collapse fragility curve using IDAs-FM03B1: a) IM-EDP plot, b) Collapse fragility curve

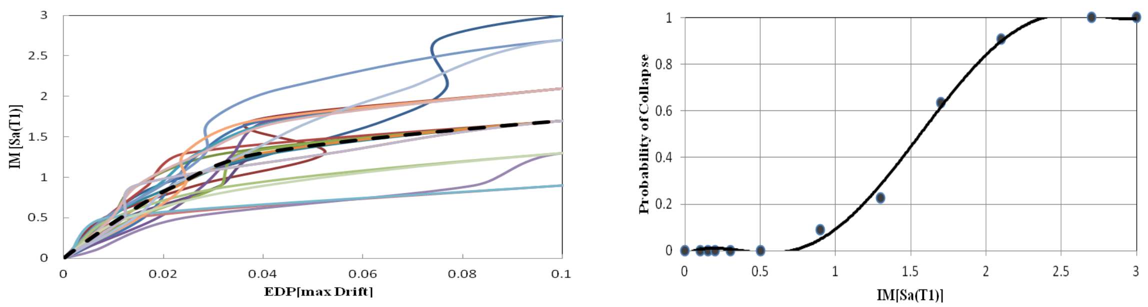
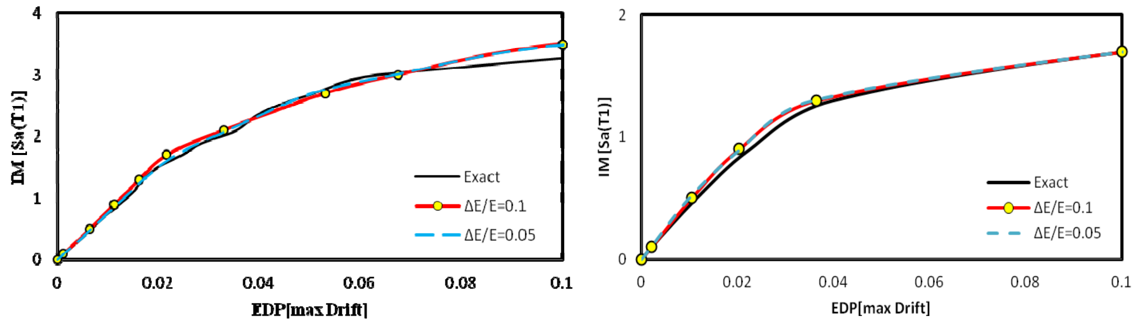
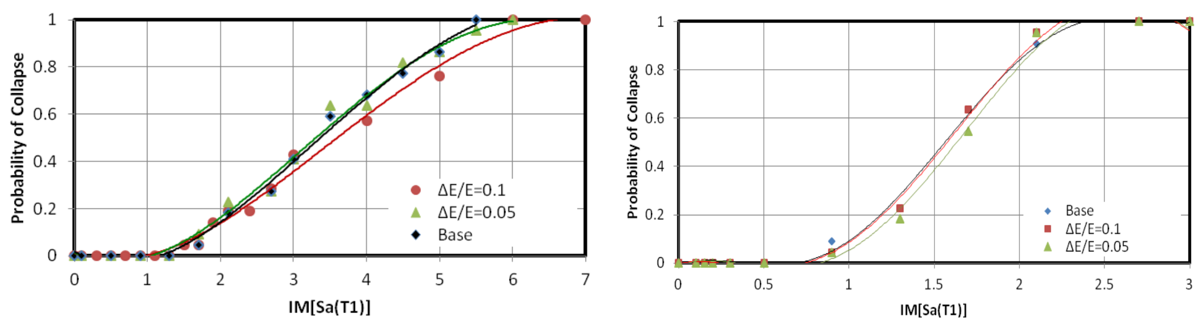


Figure 4. Collapse fragility curve using IDAs-FM07B1: a) IM-EDP plot, b) Collapse fragility curve



(a) (b)

Figure 5. Sensitivity of Maximum Interstory Drift ratio to modulus of elasticity: a) FM03B1, b) FM07B1



(a) (b)

Figure 6. Sensitivity of Collapse fragility Curve to modulus of elasticity: a) FM03B1, b) FM07B1

Sensitivity of maximum interstory drift ratio to modulus of elasticity is shown in Fig. 5 for FM03B1 and FM07B1 frames. As it can be seen, the results for ΔE/E=0.1 and 0.05 are matched together and also there is a little difference between these results and the results without uncertainty (base state). The fragility curves for FM03B1 and FM07B1 frames considering uncertainties of modulus of elasticity are shown in Fig. 6. This figure shows that in the base state the probability of collapse at Sa=4 is 70 % while at ΔE/E=0.1 the probability of collapse is 60%. In other words in this frame, small changes of modulus of elasticity can reduce the probability of failure about 10%. But in FM07B1 frame, it is vice-versa. For example at Sa=1.5 the probability of collapse for Base and ΔE/E=0.05 is 40% and 42% respectively. Therefore E parameter for FM03B1 frame is important because with a slight change the probability of collapse decrease 10% while for FM07B1frame the change is just about 2%. In general, elastic modulus of the steel is one of important parameter that greatly affects the collapse potential of moment-resisting frames.

The sensitivity of Maximum Interstory Drift Ratio (MIDR) to post-capping stiffness coefficient (α_c), strain-hardening ratio (α_s) and ductility capacity (δc/δy) for each frame is shown in Figs.7, 8 & 9.

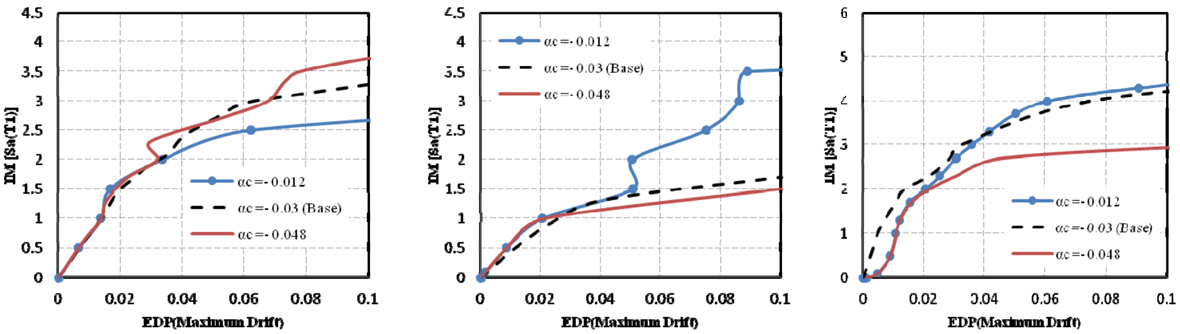
According to these figures, it is clear that the sensitivity of MIDR to increasing or decreasing the parameters is different:

1. The sensitivity of MIDR to increasing or decreasing of αc (Fig. 7): the FM03B1 frame is more sensitive to increasing of αc. It means the difference between αc = -0.012 and αc=-0.03 is more against the αc = -0.048. Therefore it seems that the best value for αc is -0.048. But in the FMO7B1 frame αc = -0.012 have a most positive impact on the structural performance while for αc = -0.048 there is not much differences. It is interesting that for FM12B3 frame the situation is reverse. It means that αc = -0.048 have a negative impact and αc = -0.012 is not much different in the structural performance.

2. The sensitivity of MIDR to increasing or decreasing of αs (Fig. 8): For this parameter the FM03B1 frame is the most sensitive one among others. In general the effect of changing αs on the MIDR is not significant for taller frames (FM07B1 & FM12B3 frames).

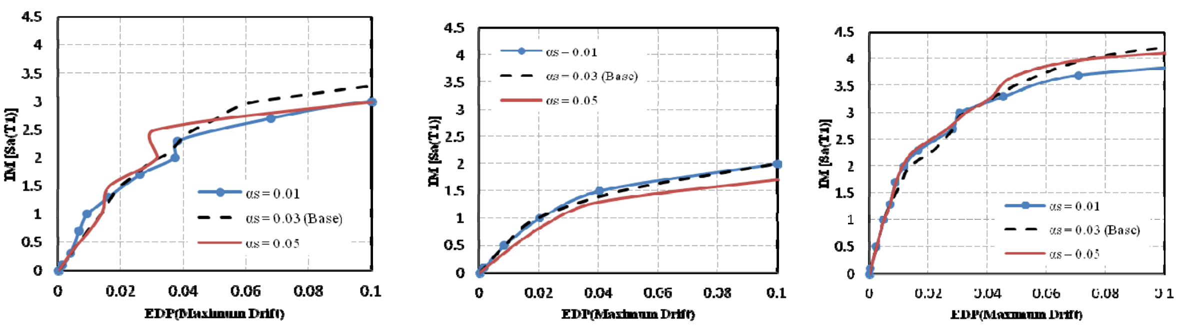
3. The sensitivity of MIDR to increasing or decreasing of δc/δy (Fig. 9): It is completely clear that the frames are more sensitive to δc/δy versus αs. For three frames we can say that δc/δy=3.5 have the best effect on the response of structures.

In general, it is noticed that the importance of parameters are not the same. αc is more sensitive in determining the response than the αs & δc/δy.



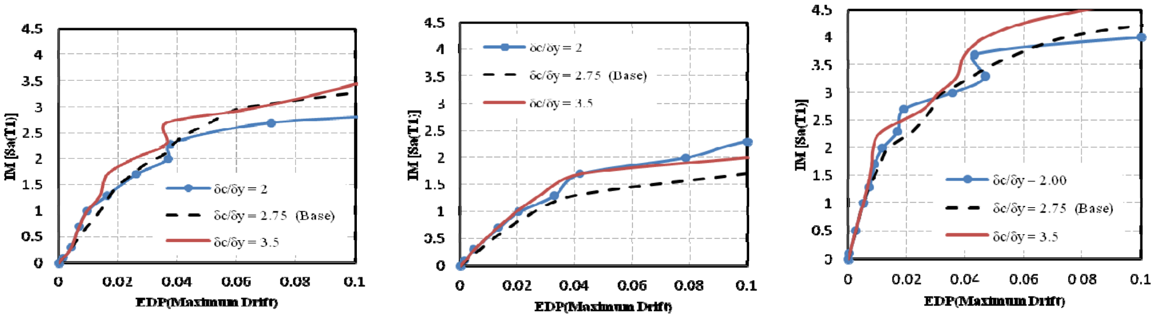
(a) (b) (c)

Figure 7. Sensitivity of Maximum Interstory Drift to α_c: a) FM03B1, b) FM07B1 and c) FM12B3.



(a) (b) (c)

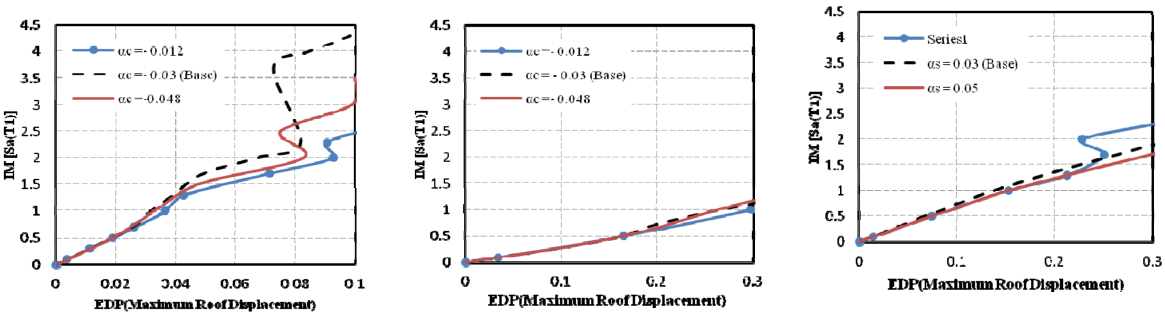
Figure 8. Sensitivity of Maximum Interstory Drift to α_s: a) FM03B1, b) FM07B1 and c) FM12B3.



(a) (b) (c)

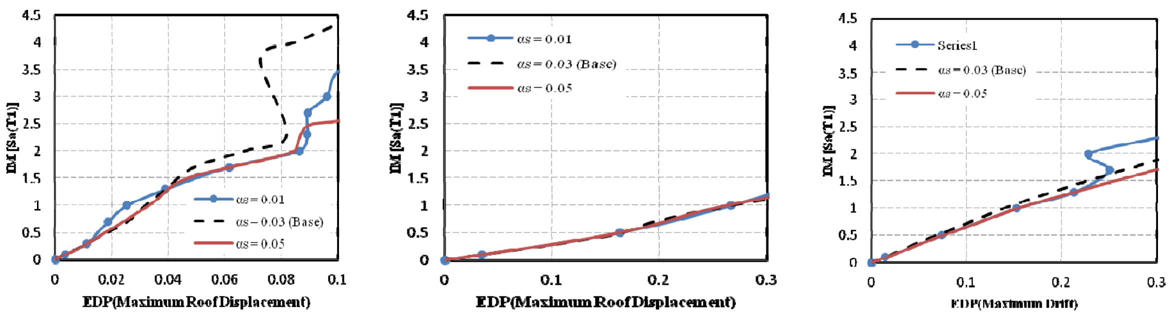
Figure 9. Sensitivity of Maximum Interstory Drift to δc/δy: a) FM03B1, b) FM07B1 and c) FM12B3.

Like the previous state, the sensitivity of maximum roof displacement (MRD) to α_c, δc/δy & α_s is obtained (Figs. 10, 11 and 12). It is completely clear that MRD is sensitive to the parameters although the sensitivity for each parameter is different. In this state, the MRD of FM03B1 frame is the most sensitive one among other frames. Figs. 10, 11 and 12 show a rather minor influence of the changes of α_c, α_s and δc/δy on the system performance of 7 and 12 story frames but FM03B1 frame is more sensitive to these parameters. In general the sensitivity of MRD is less than MIDR.



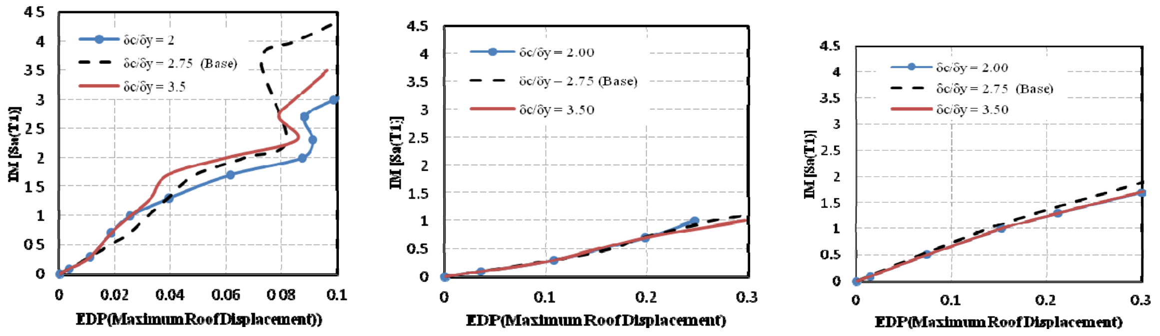
(a) (b) (c)

Figure 10. Sensitivity of Maximum Roof Displacement to αs: a) FM03B1, b) FM07B1 and c) FM12B3



(a) (b) (c)

Figure 11. Sensitivity of Maximum Roof Displacement to αs: a) FM03B1, b) FM07B1 and c) FM12B3



(a) **(b)** **(c)**

Figure 12. Sensitivity of Maximum Roof Displacement to δc/δy: a) FM03B1, b) FM07B1 and c) FM12B3.

4. ENDURANCE TIME METHOD

In the endurance time method, structures are subjected to a specially designed intensifying ground acceleration function and their performance is judged based on their response at various excitation levels. In this paper a set of three acceleration functions have been produced using the ET concept by applying optimization techniques (ETA20e01, ETA20e02& ETA20e03) (Fig. 13). The analysis was conducted using the OpenSees software. To obtain the equivalent time in ET analysis, the average response spectrum of the scaled accelerograms is calculated. The value of this average response spectrum is found at T_i (fundamental period) of each frame ($S_{a,\ Ave}$). Furthermore the value of the target response spectrum used for the generation of ET acceleration functions at T_i is calculated ($S_{a,\ ET}$). Finally the equivalent time is obtained by Eqn. 4.1.

$$t_{eq} = \frac{S_{a,AVE}}{S_{a,ET}} \times 10 \tag{4.1}$$

Constant 10 is used in this equation because the response spectrum of ET acceleration functions at t = 10 s (i.e. the target time in these records) matches the target response spectrum.

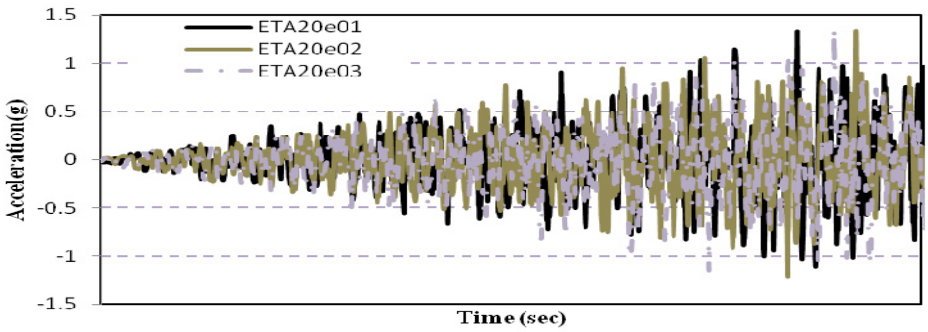
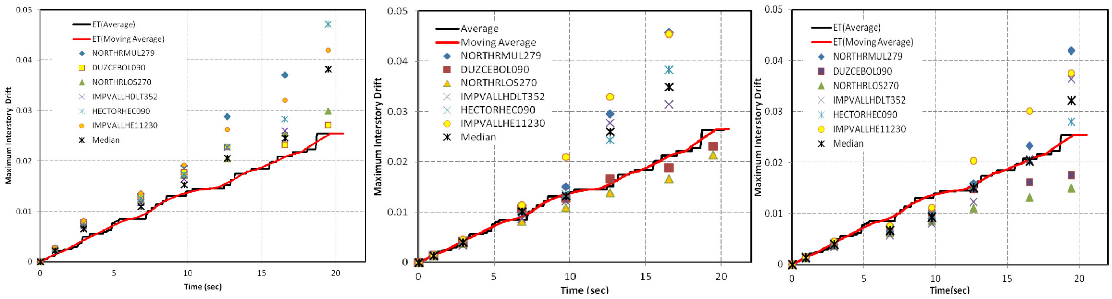


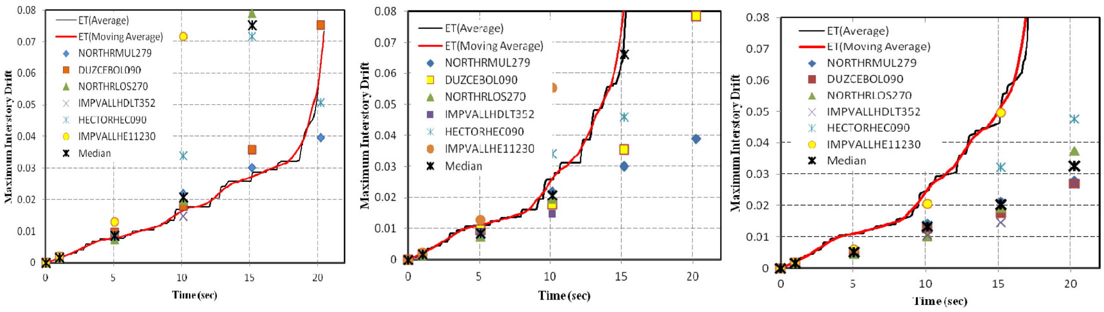
Figure 13. Acceleration for ET

As it will be explained, at first the sensitivity of MIDR & MRD to the defined parameters were obtained using ET acceleration functions and then the results are compared with previous results. These comparisons are shown in Figs. 14, 15 and 16. This figures show the average of sensitivity of MIDR to consider changing of the parameters. As it can be observed, the ET results are sensitive to changing the parameters. In the below Figures we have average and moving average graphs. As mentioned earlier, we had 3 acceleration functions. The average graph defines the response of system when subjected to average of this 3 acceleration functions and the moving average graph defines the moving average response of systems with a radius of 100 points. According to the below figures, approximately at all of them in the linear state the ET and IDA results have a good match. The best results of ET are for α_c because they are less scattered. Also it can be said that the results of different accelerograms are so much scattered and their uncertainties is more significant than hysteretic characteristics of the frames.



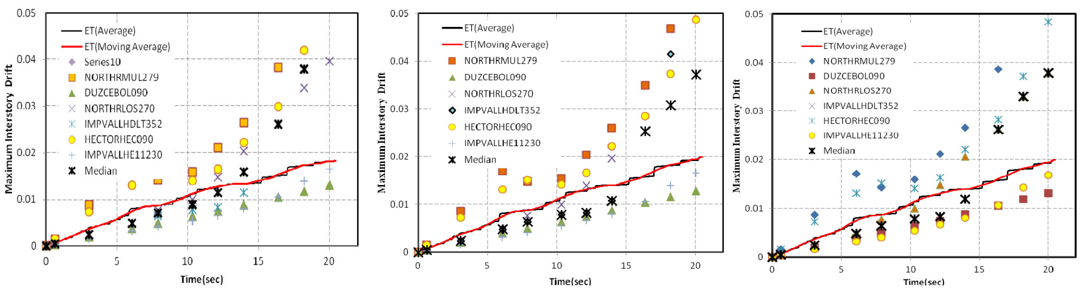
a b c

Figure 14. Maximum Interstory Drift Consider of changing αc: a) FM03B1, b) FM07B1 and c) FM12B3.



a b c

Figure 15. Maximum Interstory Drift Consider of changing αs: a) FM03B1, b) FM07B1 and c) FM12B3.



a b c

Figure 16. Maximum Interstory Drift Consider of changing δc/δy: a) FM03B1, b) FM07B1 and c) FM12B3.

5. SUMMARY AND COCLUSIONS

The effect of three parameters of fracturing beam-column connections on the global seismic performance were investigated for a 3, 7 and 12 storey steel moment-resisting frame using both incremental dynamic analysis and endurance time methods. Then these results are compared together. Results show that:

1. The estimates of connection hysteretic behavior that is essential to building performance are affected by the uncertainties of the structural parameters and the uncertainties in ground motions but the second one is more important.

2. The results obtained indicate that ET analysis can clearly identify the uncertainties of the performance of the structure but in some cases with high amount of nonlinearity the results are not consistent and more studies should be done to find the exact reason. But still this method can be used as a suitable tool for estimating uncertainties of the steel moment-resisting frames responses.

3. Modeling uncertainties have greater impact when the relationship between model parameters and structural response is highly nonlinear.

4. These results point more generally to the importance of uncertainties in responses of structures and show simplified variations may have a large effect on calculated risks. The accuracy of simplifying assumptions should be considered with care when the results will impact important decisions.

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