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# Evaluation of Response Modification Factor, Strength and Stiffness Deterioration Effects by Endurance Time Method

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**Abstract:** Most recent seismic codes include response modification factor in the definition of equivalent lateral forces that are used for the design of earthquake resistant buildings. The response modification factor, used to reduce the linear elastic design spectrum to account for energy dissipation capacity of structure, is the central feature of force-based seismic design. The main goal of this paper is the assessment of Endurance Time (ET) method results accuracy in the evaluation of response modification factors and estimation of strength and stiffness deterioration effects on them according to frame performance evaluation. To reach this goal a sample set of steel moment-resisting frames (3, 7 and 12-story) are designed and ET results are compared to Incremental Dynamic Analysis (IDA) ones as an evaluation base. In order to model deteriorating connections, frames are also modeled using concentrated plastic springs. ET analysis is a new dynamic pushover procedure in which structures are subjected to gradually intensifying acceleration functions and their performances are assessed based on their responses. It is observed that although the results of ET analysis are not exactly consistent with the results of IDA, the ET analysis can reasonably assess the response modification factors and strength and stiffness effects in most cases. Also, considering the great amount of computational efforts that should be done for evaluating response modification factors and the effects of strength and stiffness on them by IDA analysis, ET analysis can evaluate them and the performances of structures with less analysis.

## 1. Introduction

It is not only uneconomical to design and strengthen a building to remain in elastic range (undamaged) but it also is troublesome to predict the response of all structures applied to various earthquake types loading. Therefore, a number of structural seismic damages which does not result in the collapse are accepted in design principles of current seismic codes. Through the design of the structural components in a ductile manner, collapse can be avoided. The capability of a structure to dissipate energy through inelastic behavior is reflected by the response modification factor, $R$. In other words this factor was often referred to as a general “ductility” factor and plays a key role in earthquake resistant design principals.

The Endurance Time (ET) method is a time-history based dynamic procedure for seismic design of structures that has recently been introduced (e.g., Estekanchi, Vafai and Sadeghazar 2004). This is an inevitable fact in any fields of science that a new recommended method should be evaluated in different aspects comprehensively and ET method should not be excluded. In other words, ET analysis should be assessed in presenting the fundamental aspects of the hysteretic behaviour of different structural systems undergoing inelastic response under severe earthquake events. The main goal of this paper is to evaluate the response modification factors in addition to strength and stiffness deterioration effects on these factors for some 2D moment resisting steel frames by application of the FEMA P695 collapse safety assessment methodology (e.g., FEMA. 2009). Additionally, the basics of the ET procedure are briefly reviewed, its potential applications are discussed and the obtained results of ET analysis in this regard have been compared to those of IDA analyses. It has been shown that even though the ET method is a time-history based analysis, its concept and application are quite intuitive and straightforward. This method has the capability to predict demand and capacity of the structures in regions ranging from elasticity to global dynamic instability. Also its results are compatible with the results of IDA analyses. Some of the major problems of ET method are discussed and some techniques to remove them are presented.

## 2. Basic Concepts of ET Method

In ET method, structures are subjected to gradually intensifying acceleration functions and their reliabilities and performances are assessed during time till they collapse or meet the accepted failure criteria. In order to reach a successful implementation of ET analysis, generation of appropriate acceleration functions are a fundamental issue. Acquired results of the employed acceleration functions should properly be correlated with the real responses of structures subjected to earthquakes. In this study, ET acceleration functions are produced in such a way that an ET acceleration function response spectrum is intensifying linearly with time (e.g., Riahi, Estekanchi, and Vafai 2009). In other words, the response spectrum of any detachments of ET acceleration function is compatible with target response spectrum with a scale which is proportional with time. ET analysis is done with three acceleration functions sets, including ETA20e, ETA20f and ETA20g. Each of these sets consists of three acceleration functions. The target response spectrum used for generation of ETA20e and ETA20f sets is the average response spectrum of 7 records (e.g., Riahi and Estekanchi 2007, FEMA 2005). Figure 1 shows one of the acceleration functions of ETA20f set. The response spectra of ETA20f set at different times of the duration are depicted in Figure 2. This figure shows how these response spectra vary linearly through time. The time duration of ETA20e and ETA20f sets is 20.48 seconds. For some cases the structures cannot reach their collapse levels with these sets. For this reason ETA20g set with time duration of 40.96 seconds is also used in this study. The target response spectrum used for generation of this set is the ASCE-07 response spectrum for high seismic regions (e.g., ASCE 2005).

## 3. FEMA P695 Collapse Safety Assessment Methodology

FEMA P695 recommends a methodology in order to quantify building system performance and response parameters to use in seismic design (e.g., FEMA 2009). In this methodology, a lateral load resistant system is designed by using specific response modification factors and its performance is evaluated according to the acceptability of collapse margin ratio. This acceptability is assessed through comparison of adjusted collapse margin ratio; the adjustment is done to consider the effect of spectral shape, with acceptable values.

The FEMA P695 methodology can be summarized in four major following steps:

1) Design provisions are identified. Structures are designed according to them considering all design requirements in order to define structural details and characteristics which determine collapse performance.
2) Considering the sources of uncertainty including test data, modeling, design requirements and record to record collapse uncertainty.
3) Nonlinear static (pushover) and dynamic (response history) analyses for a set of ground motions of all archetype models are performed to simulate the seismic responses of structures. To obtain period-based ductility, $\mu_T$, a nonlinear static pushover analysis is done for each structure. Nonlinear dynamic analyses are performed to assess median collapse capacities, $\hat{S}_{CT}$, and collapse margin ratios.
4) The structural performances which satisfy following two criteria are accepted:

a. The average value of adjusted collapse margin ratio for each performance group exceeds *ACMR*10%.
b. Individual values of adjusted collapse margin ratio for each structure within a performance group exceeds *ACMR*20%.

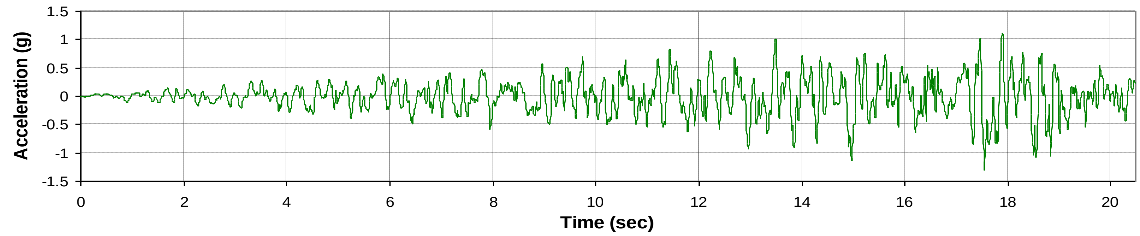


Figure 1: ETA20f01 acceleration function

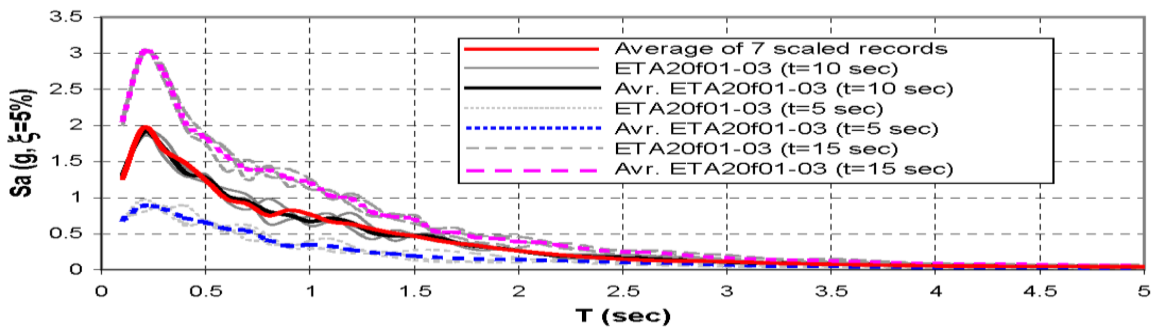


Figure 2: Total acceleration spectra of ETA20f series acceleration functions at different time

## 4. Design provisions and archetype configurations

A set of 3-bay steel moment-resisting frame is studied that comprises two-dimensional regular frames with 3, 7 and 12 stories, Table 2. These frames were designed according to AISC-ASD design code (e.g., AISC 1989).The span and story heights of these frames are equal to 6 and 3.2 meters respectively. To evaluate and compare the structures with diverse loading bearing capacity, frames are designed with three different base shears, named “Standard”, “Underdesigned” and “Overdesigned”. The standard frames are designed according to BHRC design base shear for a high seismicity area, the names of these frames ends with the letter S. The weak and over strength ones are designed according to half and twice of this amount and their names ends with letters W and O respectively (e.g., BHRC 2005). A response modification factor of R=6 is used for the design of the frames and interstory drift was limited to 0.005 in the design procedure. As a basic analysis an elastic perfectly plastic material is considered in this study. P-Δ effects have been included in the nonlinear analysis. Damping ratio is assumed to be 0.03 of the critical value.

In accordance with FEMA P695 and ASCE 7, seismic design category is considered to be Dmax which its characteristics are shown in Table 1 (SMs is the maximum considered earthquake spectral response acceleration for short periods and SM1 is that at 1s adjusted for site class effects).

To assess the strength and stiffness deterioration effects on the response modification factor values, two kinds of models are prepared for each frame, a SeismoStruct distributed nonlinear beam-column element implemented with displacement-based finite element formulation (e.g., SeismoSoft 2007) and an elastic beam-column element in which all inelastic behaviour is concentrated plastic hinge rotational springs at the member ends. The stiffness and strain-hardening coefficient of rotational springs and elastic beam-column elements are determined in accordance with Ibarra and Krawinkler models (e.g., Ibarra and

Krawinkler 2005) and the hysteretic curve with pinching was modeled by modified Richard-Abbott hysteresis loop, programmed and implemented by Nogueiro (Nogueiro, Silva, Bento and Simoes 2005).

Table 1: Summary of Dmax Characteristics

| Seismic Design Category | Maximun Considered Earthquake | | Transition Period |
|---|---|---|---|
| | SMS (g) | SM1 (g) | Ts (sec) |
| Dmax | 1.5 | 0.9 | 0.6 |

Table 2: Frames Basic Properties

| Frames | Number of Stories | Number of Bays | Mass Participation Mode 1 | Fundamental Period (sec) | Design Base Shear (KN) |
|---|---|---|---|---|---|
| FM03B3RGW | 3 | 3 | 88.48% | 1.2 | 179.3 |
| FM03B3RGS | 3 | 3 | 85.68% | 0.88 | 362.17 |
| FM03B3RGO | 3 | 3 | 85.63% | 0.61 | 729.26 |
| FM07B3RGW | 7 | 3 | 80.76% | 1.98 | 302.34 |
| FM07B3RGS | 7 | 3 | 80.59% | 1.41 | 609.77 |
| FM07B3RGO | 7 | 3 | 80.03% | 0.97 | 1233.41 |
| FM012B3RGW | 12 | 3 | 78.93% | 2.72 | 399.2 |
| FM012B3RGS | 12 | 3 | 77.70% | 2.01 | 804.38 |
| FM012B3RGO | 12 | 3 | 74.27% | 1.29 | 1631.52 |

## 5. Comparison of ET method with IDA

Since IDA analysis and ET method have similar concepts, the comparison of their results is considered as an evaluation base for the assessment of ET method results accuracy (e.g., Riahi, Estekanchi, and Seyedain Boroujeni. 2011). Both methods try to estimate the performances of structures by applying different levels of Intensity Measure (IM). While IDA analysis comprises a large number of time history analyses to predict the capacity and demand of a structure, ET method, as an alternative, tries to estimate the results of IDA with less nonlinear analyses for a set of acceleration function.

In order to assess the seismic responses of frames, maximum interstory drift ratio is considered as a proper parameter to evaluate total collapse and dynamic instability of each frame. Therefore, maximum interstory drift ratio and total acceleration of first mode of a structure with 3% damping are considered as Engineering Demand Parameter (EDP) and IM, respectively. IDA is done for 22 far-field ground motions. This set is adopted from FEMA 695 code and are selected from the PEER-NGA database using the specific criteria described there (e.g., FEMA. 2009).

By comparing ET method results with those of IDA, it can be clearly observed that ET method results have less variability so they cannot present the huge differences between the performances of structures subjected to various ground motions with different frequency characteristics, see Figure 3. This coherence in ET method results is due to the fact that ET acceleration functions are created based on the same average response spectrum of the ground motions.

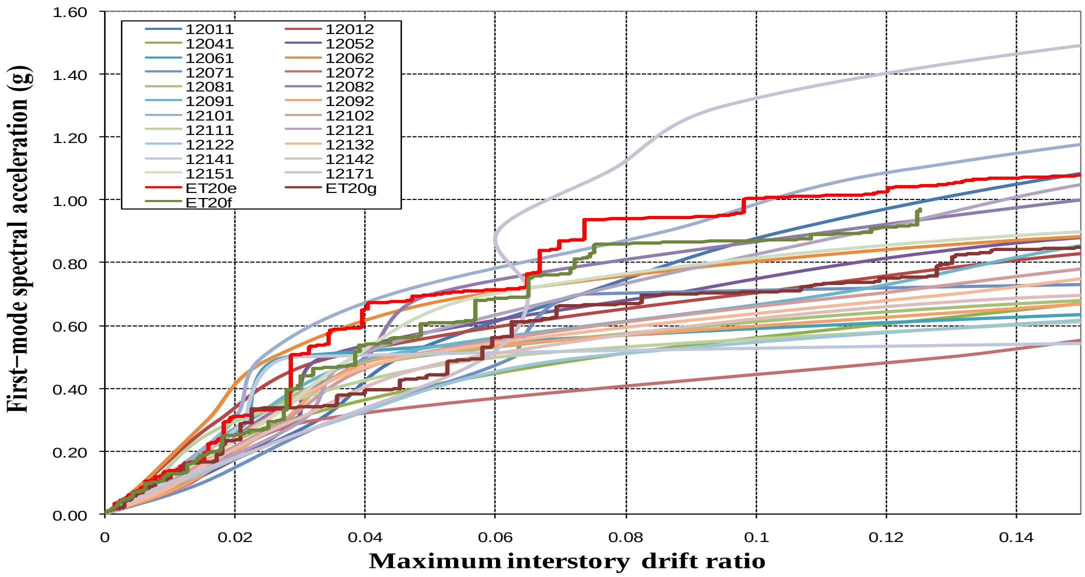

Figure 3: Twenty two IDA curves and three ET curves for FM03B3RGW frame.

In some cases, it is observed that the intensity of acceleration functions (particularly ETA20e and ETA20f) through their durations is not large enough to force some structures experience large deformations till their dynamic instabilities. In this regard, a suitable coefficient should be applied to acceleration functions or ETA20g set with a larger duration and intensity can be used, both of these mentioned methods are used in this study. As an example, in figure 4, ETA20e and ETA20f sets do not force FM07B3RGS frame to reach its collapse limit. In this condition not only is ETA20g set used but also a coefficient equal to 3 is applied to both ETA20f and ETA20e acceleration functions and analyses are repeated.

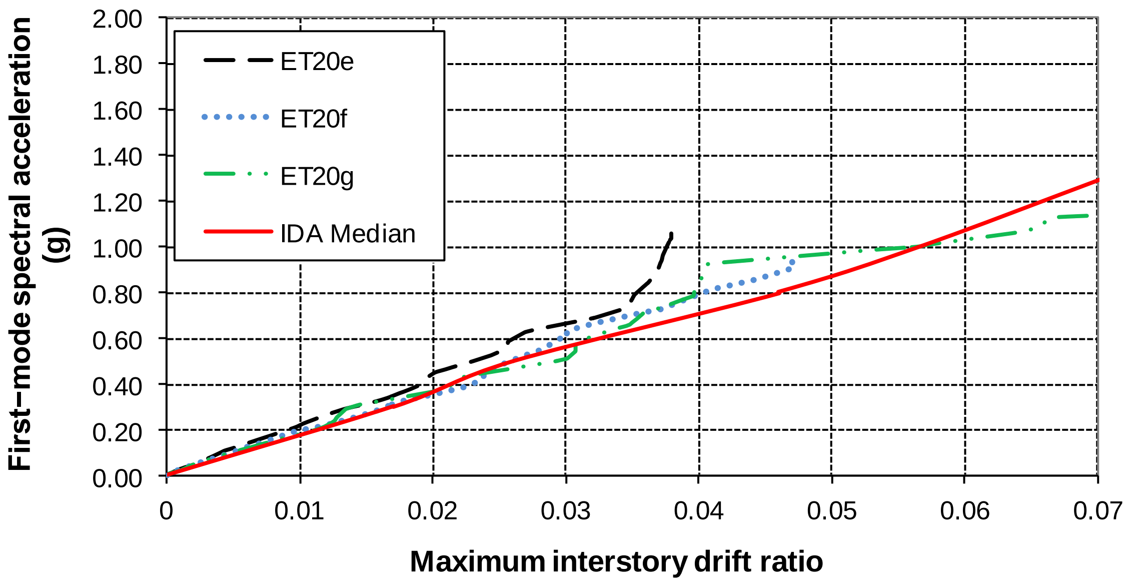

Figure 4: IDA median curve and ET moving average curves for FM07B3RGS frame.

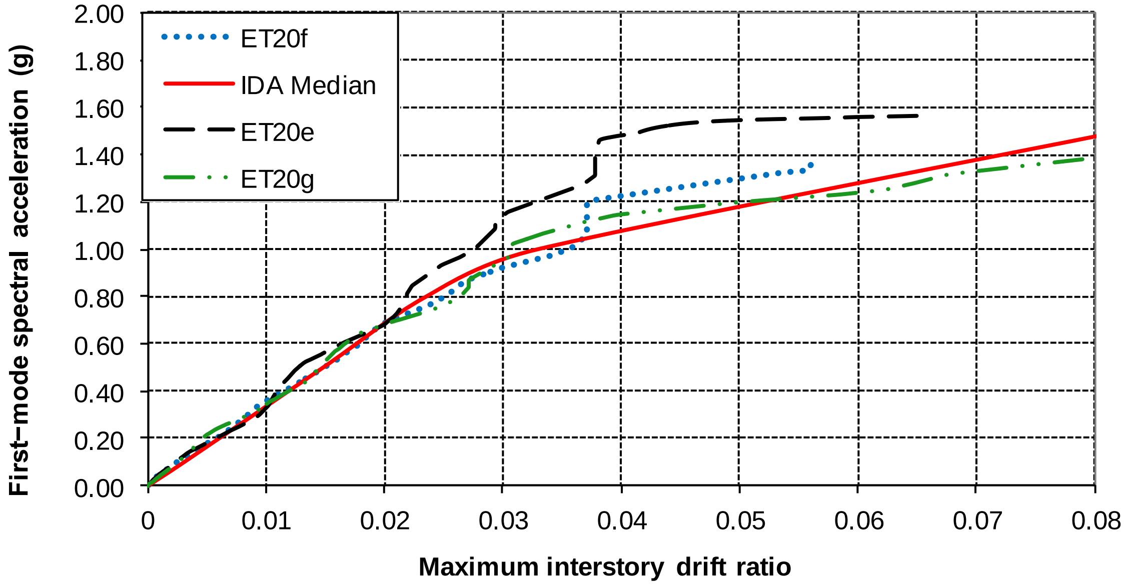


Figure 5: IDA median curve and ET moving average curves for FM07B3RGO frame.

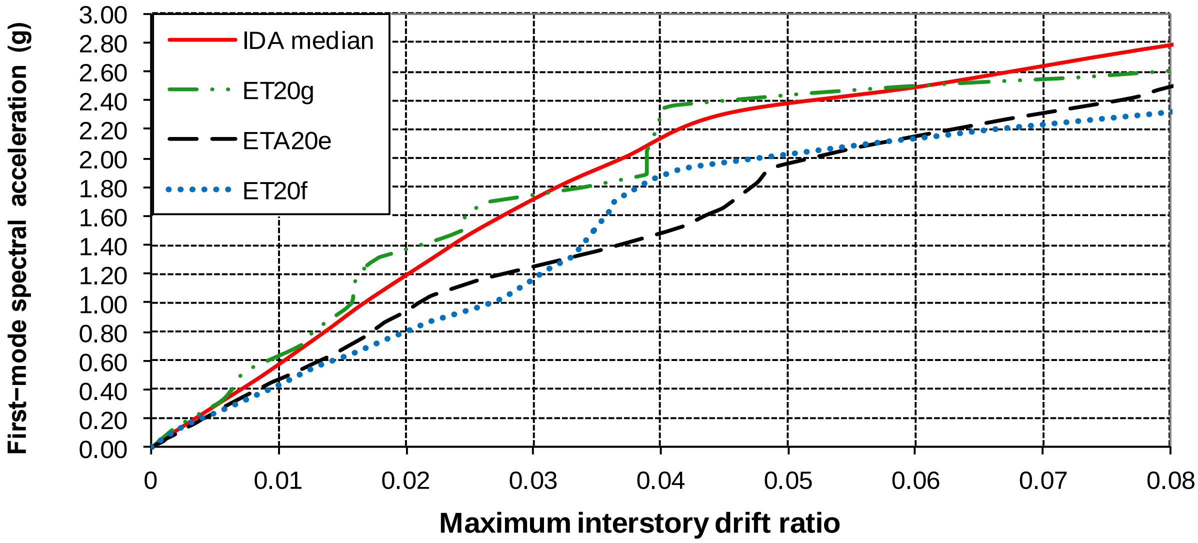


Figure 6: IDA median curve and ET moving average curves for FM03B3RGO frame.

Generally, ETA20g results have shown the most compatibility with IDA ones compared with ETA20f and ETA20e sets and in fact, can predict the trends of IDA results median precisely in most of cases, see Figure 5 and 6.

In order to assess ET method more logically, the average of ETA20g, ETA20e and ETA20f results is also compared with the median of IDA results for 22 considered earthquakes. It can be clearly observed from this comparison that the average of ET results are properly compatible with the median of IDA results and the only inconsiderable differences in this regard are related to 3 and 7-story over strength frames. Therefore, it can be concluded that to evaluate the performances of structures, it is more preferable and accurate to consider the average of three ET sets results instead of each of them separately.

In comparison to IDA curves, three mentioned acceleration functions can predict critical maximum interstory drift ratio properly. As a whole, both methods are presented consistent results in linear part and their general trends are similar to each other even in nonlinear range, see Figure 7 and 8. Major differences referred to the stages that frames undergo dynamic instability.

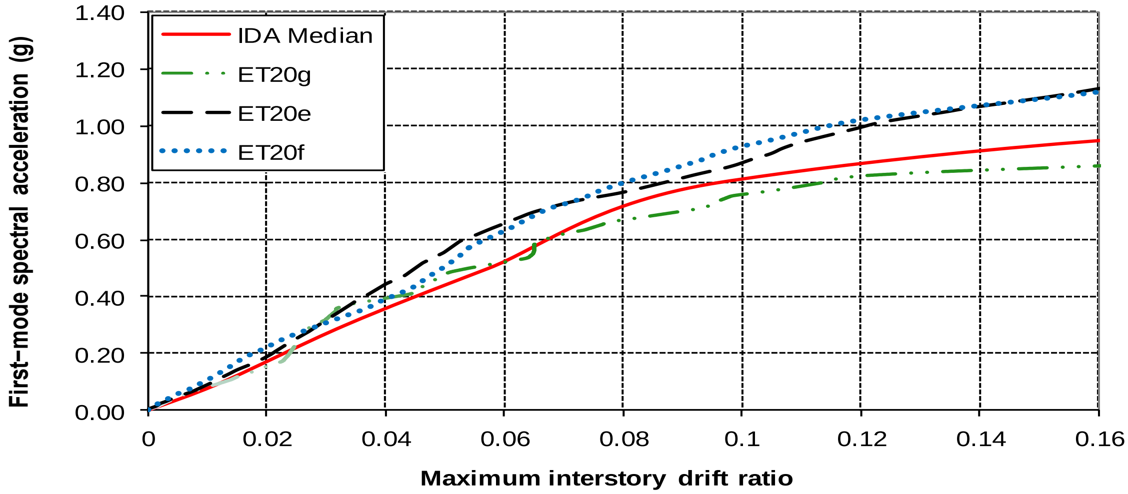


Figure 7: IDA median curve and ET moving average curves for FM07B3RGW frame with springs.

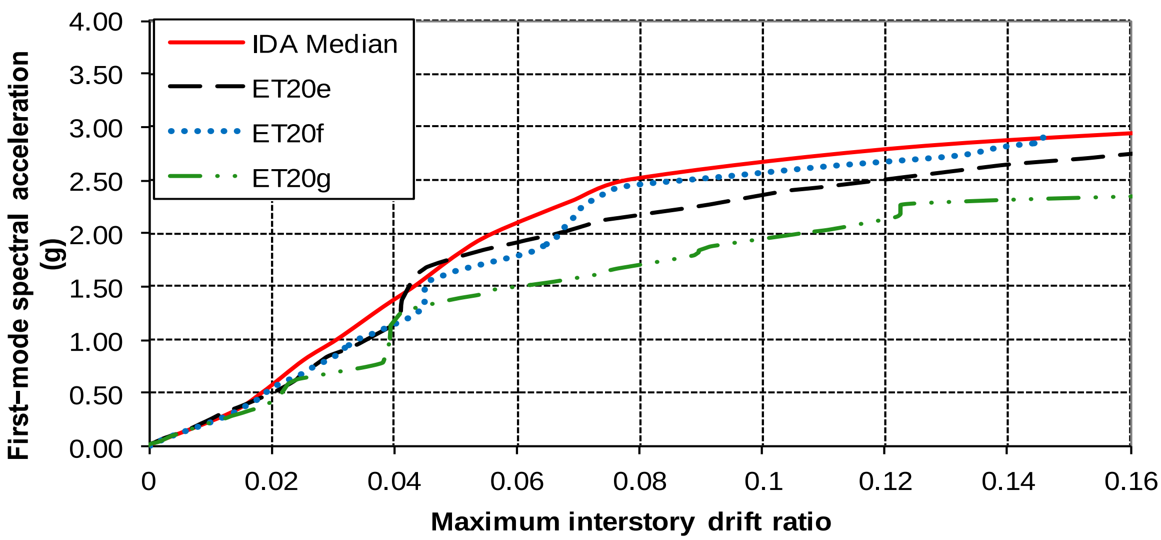


Figure 8: IDA median curve and ET moving average curves for FM07B3RGS frame with springs.

Considering the FEMA P695 methodology, ET method and IDA analysis have presented no incompatible performance evaluation related to standard and over strength frames. Both methods show that all individual standard and over strength frames and their performance groups pass the acceptability check, Table 3. In the case of weak frames, Table 3 shows that although two used analyses have presented consistent and almost close CMRs for 3 and 7-story weak frames, a few incompatibilities have been seen regarding performance evaluation. Mentioned differences is due the fact that ACMRs of weak frames are really close to acceptable ACMRs so only a few differences in their values relative to each other can lead to various and different performance evaluations. Considering 12-story weak frame, ETA20f and ETA20e have presented inconsistent CMRs. The reason of theses incompatibilities is that 12-story weak frame because of its height is more sensible to seismic loads compared with 3 and 7-story weak frames (for example P-Δ effects is more influential in this frame) so this frame enters nonlinear stages sooner and experience more nonlinearity compared with other frames . Since the considerable differences between ET method and IDA results are referred to nonlinear parts, 12-story weak frame have shown inconsistent results. Regarding weak frames, ETA20g and ETA20f sets has presented more conservative results compared with IDA.

In brief, the most consistent CMRs is related to ETA20g set which is presented more conservative results in the case of standard and over strength frames (CMR (ET20g) < CMR (IDA)) while this trend reverses about weak frames, shown in Table 3. In other words ETA20 predict higher collapse capacities regarding weak frames in comparison with IDA while in two other kinds of frames (standard and over strength) predict lower levels of collapse capacities.

In overall, by comparing the obtained values of CMR for both ET method and IDA analysis, it can be seen that they are reasonably close to each other in most of examined frames. It is clear that these methods are different and it is pragmatic to accept reasonable differences among their results.

Table 3: Summary of Collapse Performance Evaluation of Plastic Beam-Column Frames

| Frame ID | Computed Overstrength and Collapse Margin Parameters | | | | | | | | | | Acceptance Check | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CMR | | | | SSF | ACMR | | | | Accept ACMR | Pass/Fail | | | |
| | IDA median | ET20e | ET20f | ET20g | | IDA median | ET20e | ET20f | ET20g | | IDA median | ET20e | ET20f | ET20g |
| FM03B3RGW | 1.07 | 1.32 | 1.21 | 1.20 | 1.41 | 1.50 | 1.86 | 1.71 | 1.69 | 1.62 | Fail | Pass | Pass | Pass |
| FM07B3RGW | 1.17 | 1.12 | 1.52 | 1.32 | 1.42 | 1.66 | 1.59 | 2.16 | 1.87 | 1.62 | Pass | Fail | Pass | Pass |
| FM012B3RGW | 1.60 | 0.66 | 2.24 | 1.84 | 1.61 | 2.58 | 1.06 | 3.60 | 2.97 | 1.62 | Pass | Fail | Pass | Pass |
| Mean of Performance Group | | | | | | 1.91 | 1.51 | 1.93 | 2.18 | 2.09 | Fail | Fail | Fail | Pass |
| FM03B3RGS | 1.96 | 1.52 | 1.64 | 1.47 | 1.44 | 2.82 | 2.18 | 2.37 | 2.11 | 1.62 | Pass | Pass | Pass | Pass |
| FM07B3RGS | 2.66 | 3.43 | 3.65 | 2.38 | 1.58 | 4.21 | 5.42 | 5.77 | 3.76 | 1.62 | Pass | Pass | Pass | Pass |
| FM012B3RGS | 1.90 | 1.79 | 2.77 | 1.74 | 1.61 | 3.06 | 2.88 | 4.46 | 2.80 | 1.62 | Pass | Pass | Pass | Pass |
| Mean of Performance Group | | | | | | 3.36 | 3.49 | 4.20 | 2.89 | 2.09 | Pass | Pass | Pass | Pass |
| FM03B3RGO | 2.51 | 1.96 | 1.44 | 2.17 | 1.36 | 3.41 | 2.66 | 1.96 | 2.95 | 1.62 | Pass | Pass | Pass | Pass |
| FM07B3RGO | 2.16 | 1.65 | 1.43 | 1.29 | 1.46 | 3.15 | 2.41 | 2.09 | 1.89 | 1.62 | Pass | Pass | Pass | Pass |
| FM012B3RGO | 2.29 | 2.32 | 2.65 | 1.86 | 1.41 | 3.23 | 3.27 | 3.74 | 2.63 | 1.62 | Pass | Pass | Pass | Pass |
| Mean of Performance Group | | | | | | 3.26 | 2.78 | 2.60 | 2.49 | 2.09 | Pass | Pass | Pass | Pass |

## 6. Strength and stiffness deterioration effects

To evaluate the effects of strength and stiffness deterioration, 7 records are selected from 20 accelerograms recorded on site class C by the NEHRP and used in FEMA 440 which their response spectra shapes are more compatible with the response spectrum of soil type II of the INBC standard 2800.

Obtained results are clearly shown that plastic beam-column models predict lower collapse capacity margins in all considered frames compared to the models with the rotational springs. These differences in predicted collapse capacity margins are approximately about 50% which is a high percentage. Therefore, it could considerably decrease the accuracy of results in the estimation of collapse margins, see Figure 9.

The comparison of obtained ACMRs with acceptable ones shows that all the 3 and 7-story frames with the rational springs at the ends of their beams meet the FEMA P695 criteria, Table 4, while it can be observed from the Table 3 that weak frames cannot meet the criteria in some cases. It shows that providing models more precisely can lead to better and more accurate response evaluations which definitely result in accurate and different collapse performance evaluation.

Additionally, through the comparison of obtained CMRs, it can clearly observed that the higher frames (7-story frames) have more sensibility to accurate modelling (modelling with rotational springs) and strength and stiffness deterioration effects compared with lower ones (3-story). In other words, the conservations of 7-story simple models (plastic beam-column frames) relative to those with rotational springs are considerably more than the conservation of 3-story simple models (plastic beam-column frames) relative to those with rotational springs. Additionally, in standard frames, it can be seen that the results of ETA20e and ETA20f are not that much sensible to the way of modeling (with spring or without it) while IDA analysis and ETA20g set results are.

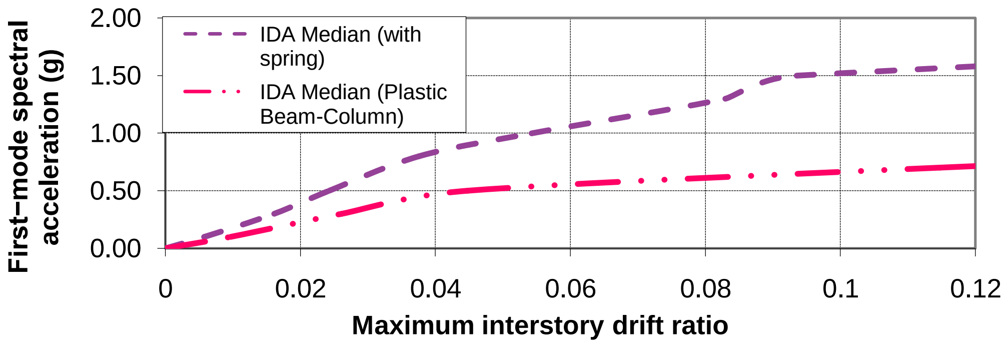


Figure 9: Comparison of IDA median curves for FM03B3RGW frame with plastic beam-column elements and with rotational springs.

Table 4: Summary of Collapse Performance Evaluation of Frames with Rotational Springs

| Frame ID | Computed Overstrength and Collapse Margin Parameters | | | | | | | | | | Acceptance Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CMR | | | | SSF | ACMR | | | | AcceptA CMR | Pass/Fail | | |
| | IDA median | ET20e | ET20f | ET20g | | IDA median | ET20e | ET20f | ET20g | | IDA median | ET20e | ET20f |
| FM03B3RGW | 1.70 | 1.57 | 1.61 | 1.44 | 1.44 | 2.45 | 2.27 | 2.32 | 2.08 | 1.62 | pass | Pass | Pass |
| FM07B3RGW | 1.73 | 1.60 | 2.02 | 1.78 | 1.61 | 2.79 | 2.58 | 3.24 | 2.86 | 1.62 | Pass | Pass | Pass |
| Mean of Performance Group | | | | | | 2.62 | 2.42 | 2.78 | 2.47 | 2.09 | pass | Pass | Pass |
| FM03B3RGS | 2.42 | 1.45 | 2.03 | 1.73 | 1.44 | 3.48 | 2.09 | 2.92 | 2.49 | 1.62 | Pass | Pass | Pass |
| FM07B3RGS | 4.40 | 3.29 | 3.78 | 3.51 | 1.58 | 6.95 | 5.20 | 5.98 | 5.54 | 1.62 | Pass | Pass | Pass |
| Mean of Performance Group | | | | | | 5.22 | 3.64 | 4.45 | 4.02 | 2.09 | Pass | Pass | Pass |
| FM03B3RGO | 2.33 | 3.27 | 2.53 | 3.16 | 1.36 | 3.17 | 4.44 | 3.45 | 4.30 | 1.62 | pass | pass | pass |
| FM07B3RGO | 3.63 | 2.38 | 2.69 | 3.79 | 1.45 | 5.26 | 3.45 | 3.90 | 5.49 | 1.62 | pass | pass | pass |
| Mean of Performance Group | | | | | | 4.22 | 3.95 | 3.67 | 4.89 | 2.09 | pass | pass | pass |

## 7. Conclusion

In the present paper, some 2D moment-resisting steel frames are considered which are modeled in two ways, frames with plastic beam-column elements and models based on concentrated plastic hinge concepts (elastic beam with rotational springs at their ends). The seismic responses and collapse performances of them derived by ET method and IDA evaluated and compared with each other. Following conclusions are the results of this assessment:

1. ET acceleration functions are result in less various structural responses in comparison to real earthquakes used in IDA.

2. Although ET Method is a useful new analysis to predict the performances of structures properly and is capable of presenting compatible results with IDA in primary evaluations and differentiating between structures, in some cases there are still inconsistent results. Therefore, there is a need to investigate all aspects of this method in order to employ it in codes.
3. Although there are no incompatible results in evaluation of response modification factors and strength and stiffness deterioration effects on them, it is clearly observed that in some cases ET method do not present good precision in the estimation of CMR.
4. Frames with rotational springs experience less nonlinearity in comparison to plastic beam-column frames. ET method is more accurate in linear parts and major differences between the ET method results and IDA ones are referred to nonlinear stages so frames with rotational springs have shown less dispersion and differences between two mentioned method results.
5. Accurate modeling and considering strength and stiffness deterioration effects considerably lead to more proper collapse performance evaluation and higher collapse margin ratio.
6. This study employs a few frames and three acceleration functions. In order to do a comprehensive assessment of ET method, more diverse frames with various properties should be examined, more acceleration functions should be generated and the results obtained from them should be checked in future studies.

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