Research Note

A Comparative Study of IDA and ETA Methods on Steel Moment Frames Using Different Scalar Intensity Measures

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ABSTRACT

Endurance Time Analysis (ETA) method is a time-history based dynamic pushover procedure in which structures are evaluated using predesigned intensifying acceleration functions from linear elastic range to collapse point. In this paper, ETA is compared with well-established incremental dynamic analysis (IDA) for high-rise steel moment frames. Different scalar intensity measures (IMs) are used to figure out the most efficient one, which reduces the dispersion of the results in both methods. It was observed that ETA could estimate the general trend of IDA curves while it needs a few numbers of analyses. In addition, based on the results, the peak ground velocity and the spectral acceleration are the best IMs for comparing the results of IDA and ETA methods in steel moment frames.

Keywords:
Endurance time analysis; Incremental dynamic analysis; Steel moment frames; Scalar intensity measure

1. Introduction

Performance based earthquake engineering (PBEE) is widely used in recent years as a new method that can provide a quantitative basis for seismic assessment of the structures. The implementation of PBEE depends on the ability to estimate the probability that engineering demand parameter (EDP), such as maximum inter-story drift ratio (θ_{max}) or member force exceeds a specific value. The probability of exceeding EDP from the specific value depends on both randomness in input ground motion and mechanical properties of the material. Ground motion potential with respect to structural performance is usually characterized by a parameter named intensity measure (IM). The well-established method that has been developed to meet the needs of PBEE is incremental dynamic analysis (IDA) [1-3].

Although IDA method can describe the seismic behavior of a structure much precisely, necessity for large number of nonlinear analysis is its main disadvantage. Therefore, developing a new analysis method seems to be important. Endurance time analysis (ETA) method was introduced by Estekanchi et al. [4] where heuristic method was used in order to generate the intensifying seismic inputs called Endurance Time Acceleration Functions (ETAFs). ETA is a special method that is capable to estimate various EDP from low to high seismic intensity levels only by single analysis. Application of ETA method has been investigated on various types of structures before such as steel moment and braced frames [5-6], concrete dams [7], steel tanks [8], and offshore structures [9]. Emamjome and Estekanchi compared the results of IDA with ETA method for a set of single- and multi- degree-of-freedom

(SDOF, MDOF) structures [10]. They modeled several SDOF systems with different periods and yield force as well as some low-rise and mid-rise steel frames and concluded that ETA curve can predict IDA results with reasonably good accuracy before the collapse point. Hariri-Ardebili et al. [11] compared ETA and IDA for steel frames in terms of interstory drift ratio and base shear. They found that ETA can predict the 50%-IDA curve with acceptable accuracy. On the other hand, there are many researches on the role of the appropriate scalar and vector-based IM in PBEE of structures [12-14].

In the present study, the recently developed analysis method, ETA, is compared with well-established IDA method using different scalar intensity measures as an intermediate parameter. Four steel moment-resisting frames with different story numbers were used as case studies. Plastic hinge model was used for simulation of the nonlinear behavior of the beam-columns. This model has a tri-linear backbone curve considering strength loss with a post-yield stiffness equal to 3% of the initial elastic stiffness. Responses of the structures in terms of θ_{max} were compared for both IDA and ETA methods considering the role of the scalar intensity measures.

2. Concept of IDA and ETA

IDA method involves performing a bunch of nonlinear dynamic analyses on the calibrated model of the structure using a suite of ground motion records, each scaled to several IM levels designed to force the structure all the way from elastic response to final global dynamic instability [2]. Maximum response of the structure under the desired IM is then calculated and plotted in IM-EDP coordinate system. From the IDA curves, limit-states can be defined. The final results of IDA curves are then combined with the conventional seismic hazard curve in order to calculate mean annual frequency of exceeding a certain damage limit-state capacity.

The inherent concept of ETA method is very similar to IDA in which it tries to provide the equivalent results using a simpler way. As definition, ETA is a simple dynamic pushover test to estimate EDPs at various IMs by subjecting them to some predesigned intensifying excitations called ETAFs instead of the real ground motions. ETAFs are intensifying functions because they should evaluate the performance of the structure at various seismic intensity levels.

ETA concept is derived from the treadmill exercise test used by cardiologists in order to evaluate the cardiovascular system condition of human beings. In this test, the subject, i.e. human, is asked to run on the treadmill while the speed and slope is increased gradually. Time passing increases energy consumption by the subject (sum of the kinetic and potential energies), until the abnormal biological signs are observed. Finally, the level of health in the subject is judged based on the length of the time he/she can endure from the start of the test. The same concept can be used for the structures using hypothetical shaking table experiment. Here, the prototype model of the structure is going to be evaluated according to its seismic resistance performance. The structural model of the frame is fixed on a shake-table and the test begins by subjecting the structures to an increasing acceleration function, ETAF. As the time passes, the amplitude of the vibrations is increased in the shake-table. EDPs are monitored up to the point where the structure collapses. The time duration from the start of the test or the analysis to the collapse point is called the "Endurance Time" [4]. Recently, the similar concept was developed for offshore structures in which the performance of the considered offshore platform is evaluated under intensifying wave train function [8]. The biological treadmill exercise test, seismic excitation of the frames and the sea-wave excitation of the offshore platforms are shown conceptually in Figure (1).

In ETA method, time history of the EDP is recorded during the analysis. The maximum absolute value of the EDP is calculated for the total duration of the analysis that is the basis of the Endurance Time Curve (ETC). Theoretically, ETC represents a special diagram in which the vertical axis refers to the maximum absolute values of selected EDP during time interval from zero to *t*, and the horizontal axis shows the time.

Second generation of ETAFs are used in the present study, which are produced using the average response spectrum of the real ground motions. The procedure for generation of ETAF can be found in reference [15] in detail. The base target time for these series of ETAFs had been set to 10s. Therefore, response spectrum of the ETAFs in the first

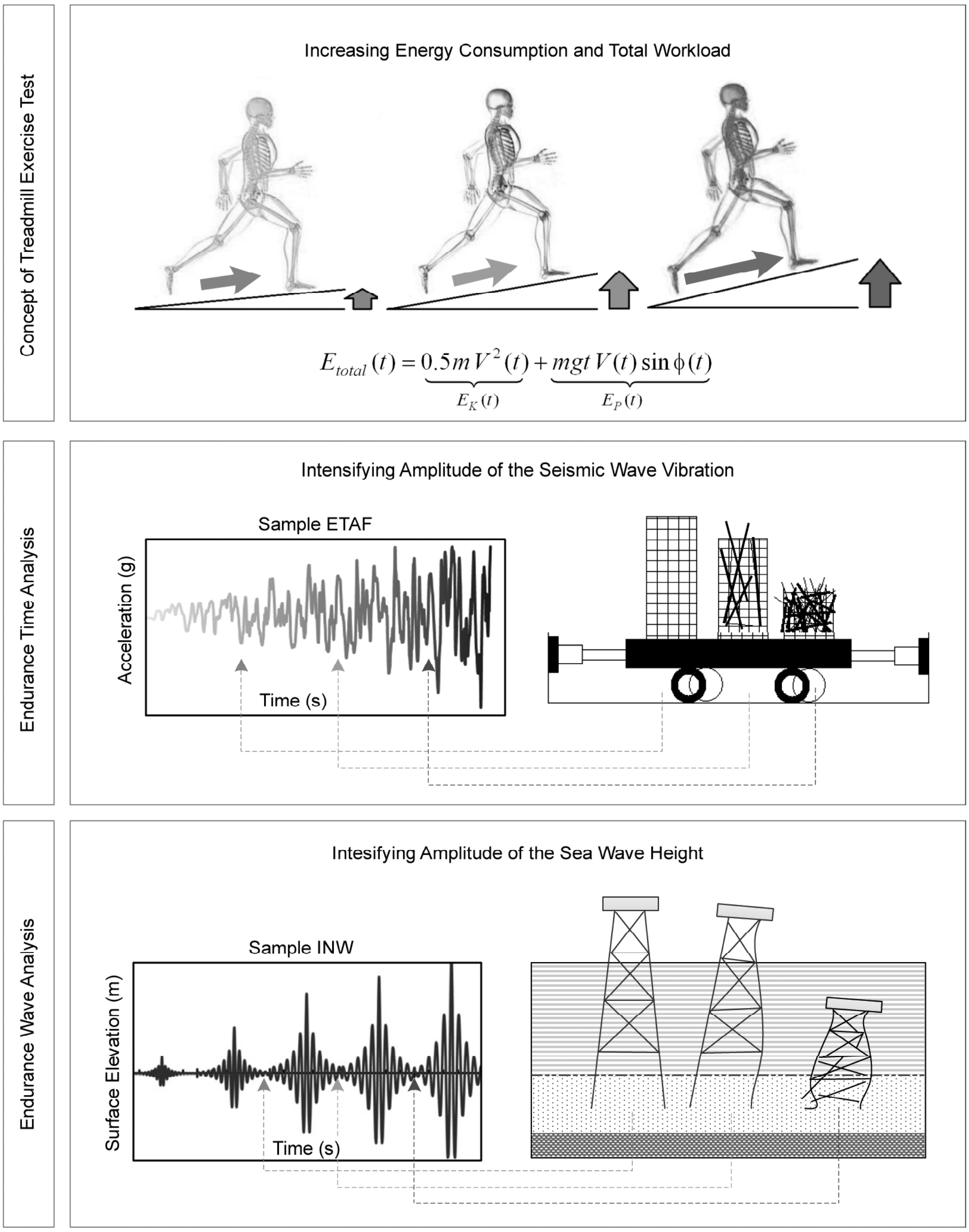

Figure 1. Concept of the treadmill exercise test; endurance time analysis; and endurance wave analysis methods.

10s, matches reasonably well with the average response spectrum of the GM1 set. The response spectrum of acceleration functions remains proportional to the base target spectra at all times [11].

3. Numerical Models

A group of steel moment-resisting frames with different number of stories was designed as case studies. This set consists of 2D regular frames with 9, 11, 13 and 15 stories and three bays designed based on UBC97 design code [16]. The section properties of all frames and their characteristics are summarized in Table (1). Yield stress is considered to be 240MPa and ultimate stress is 400MPa. It is noteworthy that the frames designed as ordinary moment-resisting frame and also in order to consider the stiffness effect of in-filled frames and non-structural components, stronger sections were considered rather than designed sections [17]. Plastic hinge approach was used for modeling nonlinear behavior of frames in this study. Plastic-hinge model for beam-columns has a tri-linear backbone curve considering strength loss with a post-yield stiffness equal to 3% of the initial

Table 1. Section properties and characteristics of the frames.

Stories	15	IPB 360	IPE 360						
	14	IPB 360	IPE 360						
	13	IPB 360	IPE 360	IPB 360	IPE 360				
	12	IPB 360	IPE 400	IPB 360	IPE 360				
	11	IPB 360	IPE 400	IPB 360	IPE 360	IPB 360	IPE 360		
	10	IPB 400	IPE 400	IPB 360	IPE 400	IPB 360	IPE 360		
	9	IPB 400	IPE 450	IPB 360	IPE 400	IPB 360	IPE 360	IPB 360	IPE 360
	8	IPB 450	IPE 450	IPB 400	IPE 400	IPB 360	IPE 400	IPB 360	IPE 360
	7	IPB 450	IPE 450	IPB 400	IPE 450	IPB 360	IPE 400	IPB 360	IPE 360
	6	IPB 550	IPE 500	IPB 450	IPE 450	IPB 400	IPE 400	IPB 360	IPE 400
	5	IPB 600	IPE 500	IPB 450	IPE 450	IPB 400	IPE 450	IPB 360	IPE 400
	4	IPB 600	IPE 500	IPB 550	IPE 500	IPB 450	IPE 450	IPB 400	IPE 400
	3	IPB 700	IPE 500	IPB 600	IPE 500	IPB 450	IPE 450	IPB 400	IPE 450
	2	IPB 800	IPE 500	IPB 600	IPE 500	IPB 550	IPE 500	IPB 450	IPE 450
	1	IPB 900	IPE 500	IPB 700	IPE 500	IPB 600	IPE 500	IPB 450	IPE 450
Model		Column	Beam	Column	Beam	Column	Beam	Column	Beam
		15 Story		**13 Story**		**11 Story**		**9 Story**	
Fundamental Period (s)		**1.70**		**1.80**		**1.62**		**1.38**	

elastic stiffness. To apply these material models to the structures, PERFORM beam-column element with nonlinear lumped plasticity was utilized [18]. Only one (horizontal) component of the ground motions has been considered in present study, while dynamic soil-structure interaction has been neglected. P-Δ effects have been included in the analysis. A viscous damping of 5%, as customary for these types of frames, has been applied to the analyses.

4. Comparison of IDA and ETA

Increasing nature of ETAFs raises the question of how the results of ETA method should be compared with IDA. To make it possible, the time parameter in ETA method should convert to an appropriate equivalent parameter in IDA. IM plays the role of the intermediate parameter to compare the results of IDA with ETA. As mentioned before, there are many IMs that can be used, but it is important to find the most appropriate one for both ground motions and ETAFs. It should be mentioned that the results of IDA method is sensitive to characteristics of the selected input motions; however, these characteristics are also considered in generation of ETAFs [11, 15]. Thus, as far as the selected ground motions for IDA method are used to generate the corresponding ETAFs, the responses of ETA and IDA can be compared.

Peak ground acceleration (PGA) has been traditionally used as a possible IM since hazard maps and attenuation relations are usually available in terms of PGA. Spectral acceleration at the first-mode period of vibration, $S_a(T_1)$, is another well-known IM. $S_a(T_1)$ is an effective IM, but among records with the same value of $S_a(T_1)$, there is still significant variability in the level of structural response in a MDOF system [19]. In order to avoid the major shortcomings of $S_a(T_1)$, an improved two-parameter scalar IM that accounts for the period lengthening was proposed by Cordova et al. [20] as $(S_a(T_1))^{1-\alpha}(S_a(cT_1))^{\alpha}$ where c and α are two parameters estimated by the researchers as 2 and 0.5 respectively [21]. Arias intensity (AI) is another intermediate parameter that can be used as a possible IM. The importance of the peak ground velocity (PGV) as an IM was discussed by Akkar and Ozen [22].

In the present paper, seven IMs were used in order to compare the results of IDA and ETA methods in which θ_{max} was used as EDP in all cases. These intensity measures are: PGA, PGV, peak ground displacement (PGD), AI, cumulative absolute velocity (CAV), $S_a(T_1)$, and finally $S_a(T_1 \& 2T_1)$ as proposed by Cordova et al. [20].

5. Results

This section presents the results of IDA and ETA method and compares responses of the structural frames using different types of the scalar IMs. In all cases, θ_{max} was selected as the EDP while seven different definitions of the IMs were used for comparison purpose. Some of these IMs were previously examined by other researchers, as mentioned in previous sections, and their efficiency was proved for steel frames. However, in this paper, we are going to compare the results of IDA and ETA methods to find the most appropriate IM in which the results of two methods are consistent.

Figure (2) shows the comparison of IDA and ETA curves using PGA as IM. For all frames, there is great consistency between mean ETA curve and the median IDA curve for PGA less than 1.0 g. For higher θ_{max}, the mean ETAF curve shows higher PGA than ground motions. Figure (3) compares the two methods using PGV as IM. Not only the record-to-record variability reduces, but also the mean ETA curve completely matches with 50% IDA curve for all ranges of the θ_{max}. In spite of the Figure (2) where one of the records had abnormally high PGA at the collapse point, using PGV regulates all the records in the same range. Figure (4) presents the responses of two methods using PGD as IM. As it can be seen, the record-to-record variability in displacement response of IDA method is more than both PGA and PGV. In addition, mean ETA curve estimates higher PGD almost for all range of the θ_{max}. For this IM, the mean ETA curve varies mainly between 50% and 16% IDA curves. Comparing PGA, PGV, and PGD as possible IMs reveals that for very small θ_{max}, the first one, PGA, can be better IM while in the case of the large deformations using the second one, PGV, is a better choice.

Figure (5) compares IDA and ETA curves considering AI as IM. Arias intensity is an important measure of the strength of the ground motion. Whereas the most common scalar ground motion measures such as PGA, PGV or $S_a(T_1)$ reflect a specific aspect of the ground motion, AI as a scalar measure is able to capture and represent multiple attributes of the overall ground motion. AI reflects the energy of the ground motion signal and the influence of the entire duration of the ground motion. According to Travasarou et al. [23], there is a strong correlation between AI and structural damage in

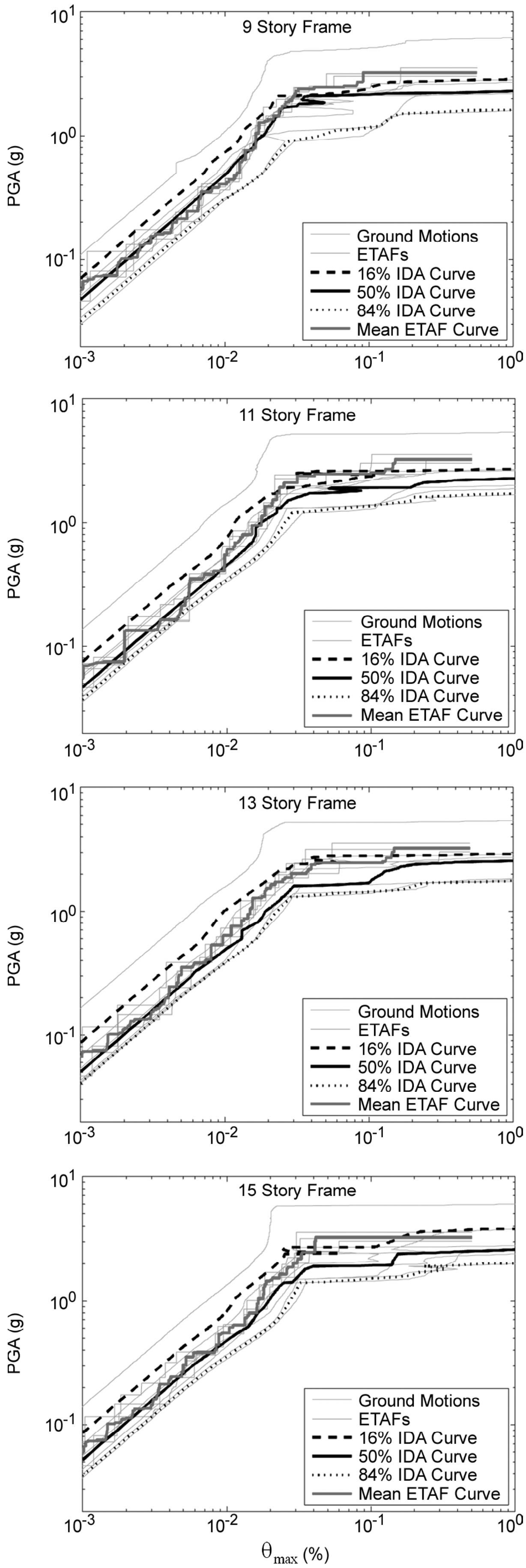

Figure 2. IDA and ETA curves; and the summarized curves considering PGA as IM .

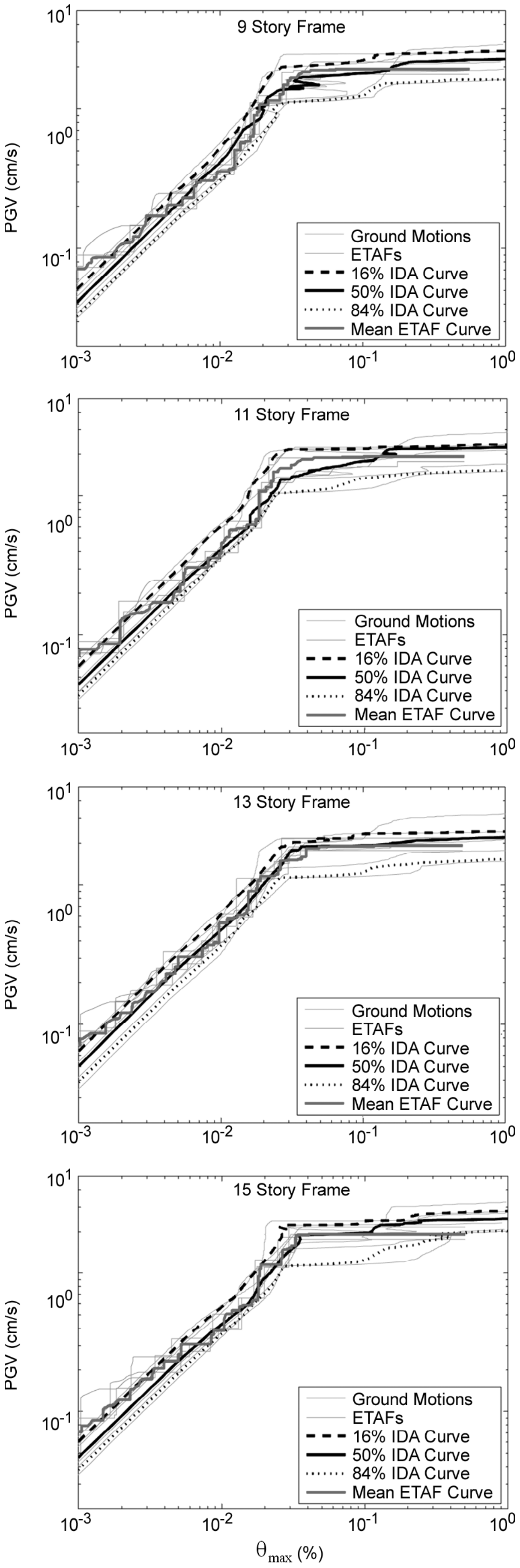

Figure 3. IDA and ETA curves; and the summarized curves considering PGV as IM .

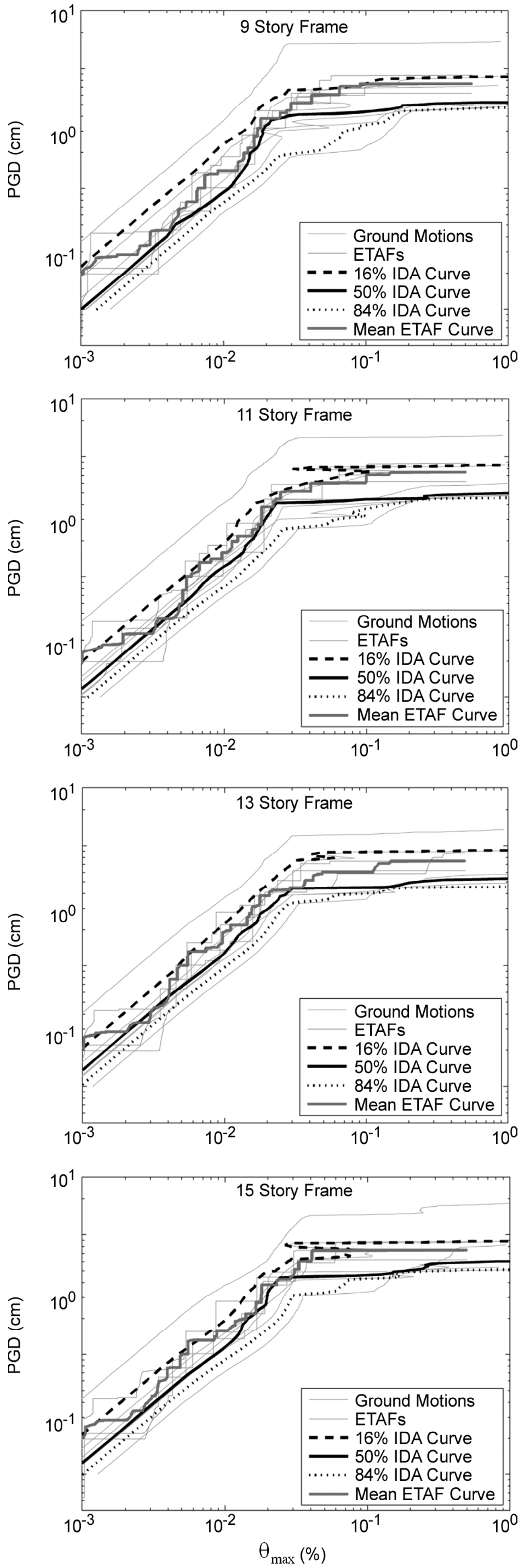

Figure 4. IDA and ETA curves; and the summarized curves considering PGD as IM .

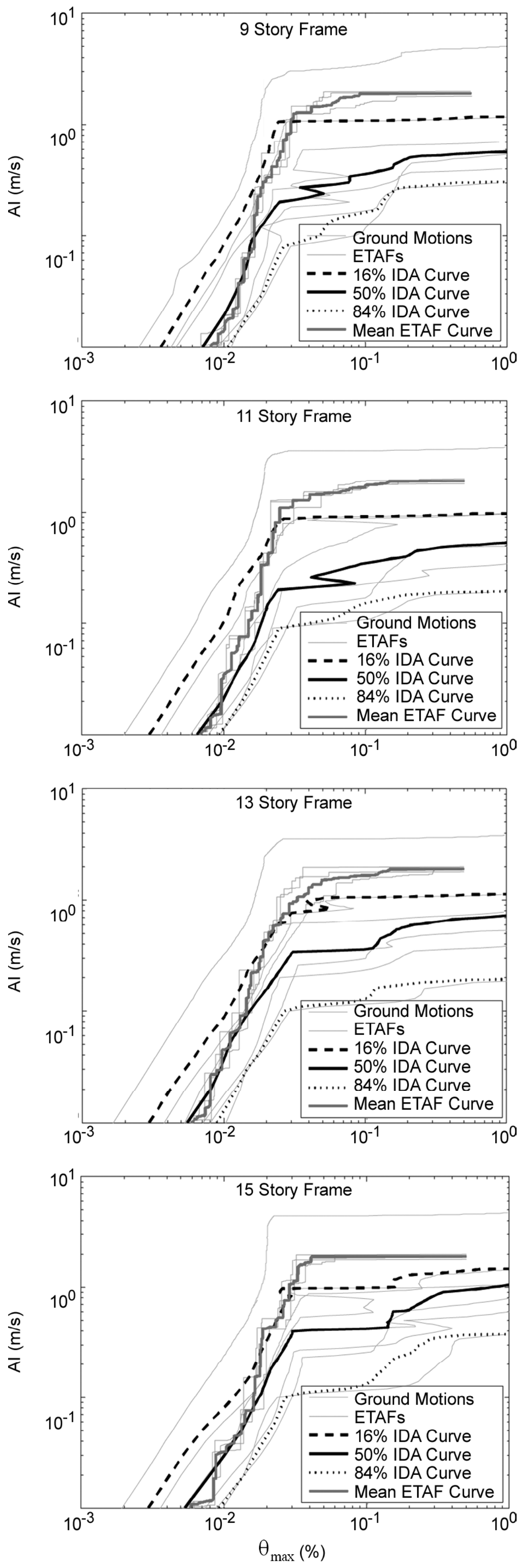

Figure 5. IDA and ETA curves; and the summarized curves considering AI as IM .

short-period structures. In the present study, the period range of the case studies are [1.38 s, 1.80 s], so it is expected to have less correlation especially in higher intensity levels. Based on Figure (5), there is a considerable dispersion between the results of IDA method showing that the basic characteristics of the GM1 set differ highly in terms of the ground motion energy with respect to its duration. In all cases, the mean ETA curve fails at higher AIs, shows that the selected frames require either higher energy under the ETAFs or a set of long duration ETAFs rather than the current ones.

Figure (6) shows the results of IDA and ETA method using CAV as IM. CAV is sum of the absolute value of the acceleration time series at each time period. CAV includes the cumulative effects of ground motion duration, which is a key advantage of this parameter. Based on Figure (6), the slope of the mean ETA curve is steeper than the median IDA curve. For the θ_{max} less than 0.01%, the value of CAV for ETAFs is less than ground motions, but for higher θ_{max} it is vice versa. For the collapse point, the value of CAV resulted from mean ETAFs is almost the same as the 16% IDA curve.

Figure (7) shows IDA and ETA curves using $S_a(T_1)$ as IM. As it can be seen, there is a great consistency between the mean ETA and median IDA curves for both pre-collapse zone and collapse point. Dispersion of the single-IDA curves for this IM is less than others. The average spectral acceleration at the collapse point is about 2.0 g for 9-story frame and 1.5 g for 15 story frame. Figure (8) shows the similar curves using Cordova et al. [20] improved IM. Results are very close to those obtained from Figure (7); however, due to using the higher period effects, the collapse spectral acceleration were reduced in all frames.

6. Conclusion

In the present paper, ETA method was compared with IDA in seismic analysis of moment-resisting frames using different scalar intensity measure parameters. In all cases, material and geometric nonlinearities were considered in transient analyses. Seven scalar intensity measures were used to compare IDA and ETA performance curves. It was found that PGV, $S_a(T_1)$ and improved version of spectral acceleration i.e. $S_a(T_1 \,\&\, 2T_1)$, are the most

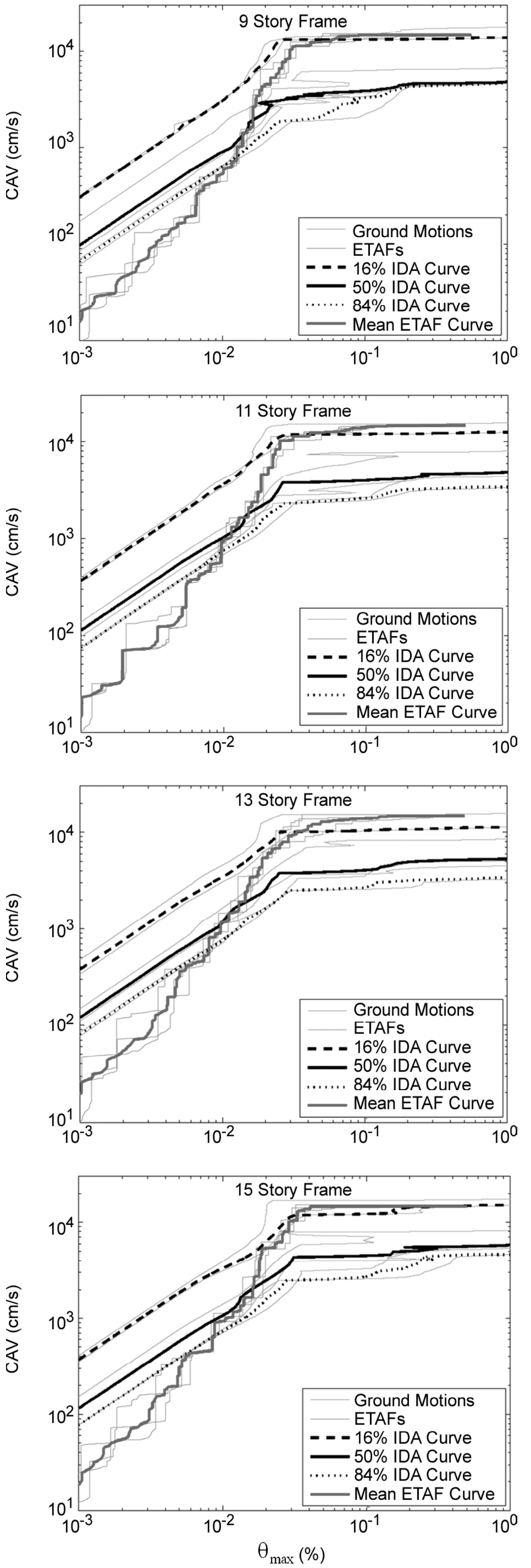

Figure 6. IDA and ETA curves; and the summarized curves considering CAV as IM.

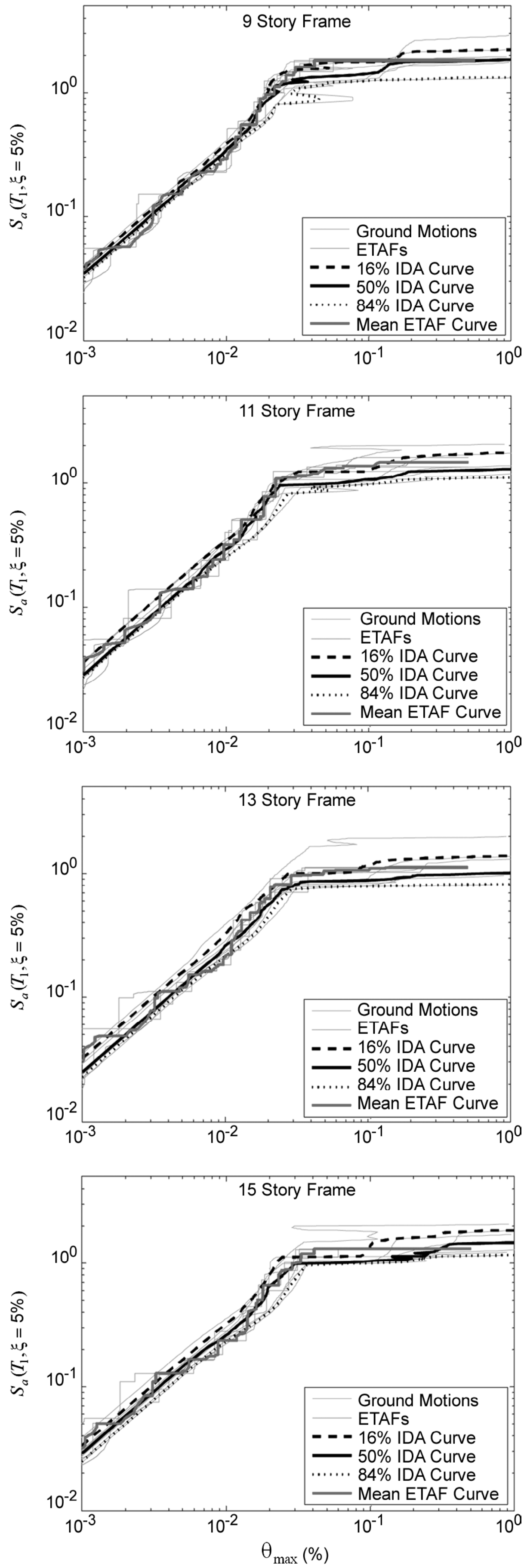

Figure 7. IDA and ETA curves; and the summarized curves considering $S_a(T_1)$ as IM.

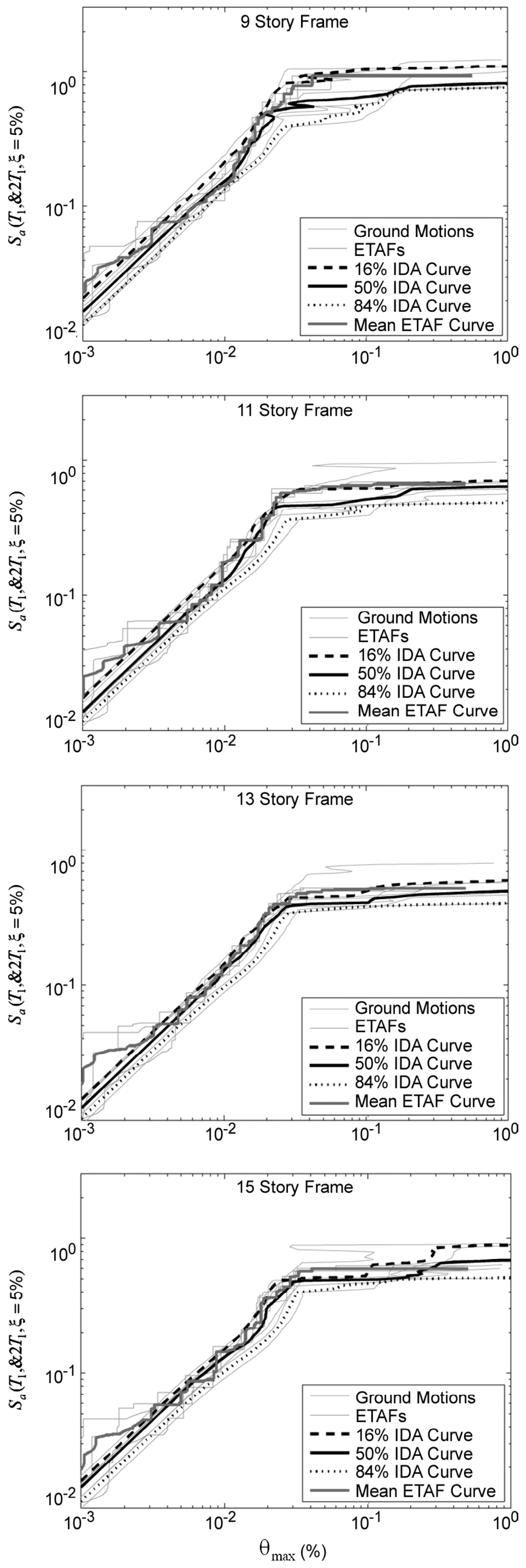

Figure 8. IDA and ETA curves; and the summarized curves considering $S_a(T_1 \& 2T_1)$ as IM.

appropriate IMs in order to compare ETA and IDA curves. Using these IMs, the mean ETA curve fluctuates around the median IDA curve almost for all range of EDP. PGA is another IM that provides good results for the lower intensity levels; however, in higher levels, there are some differences between two summarized IDA and ETA curves. AI and CAV are two other IMs that are able to account not only the intensity of the input motion but also its duration effects. The slope of the mean ETA curve is too steeper than the median IDA curve when the IM is AI or CAV. For the present case studies, there are considerable differences between IDA and ETA curves, and it seems that these two parameters are not suitable for the high-rise steel moment-resisting frames.

In general, ETA curves are step-like, and it is better to compare the smoothed ETA curve with those obtained from IDA method. The most interesting ability of ETA method is providing the structural responses with fewer analyses than IDA. In the current study, about 180 nonlinear analyses were used for each frame to capture the full behavior, elastic region to collapse, while only three nonlinear analyses were used in ETA method. Therefore, using ETA method decreases computational efforts considerably in comparison with the comprehensive IDA method while the accuracy of the results is almost the same. It should be mentioned that ETA method is not able to capture the record-to-record variety of the input ground motions and only predicts the mean responses of the structure under the base target response spectrum.

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Nomenclature

ETA: Endurance Time Analysis

IDA: Incremental Dynamic Analysis

PBEE: Performance Based Earthquake Engineering

IM: Intensity Measure

EDP: Engineering Demand Parameter

ETAF: Endurance Time Acceleration Function

θ_{max} : Maximum Inter-story Drift Ratio

SDOF: Single-degree-of-freedom

MDOF: Multi-degree-of-freedom

PGA: Peak Ground Acceleration

PGV: Peak Ground Velocity

PGD: Peak Ground Displacement

$S_a(T_1)$: Spectral Acceleration at the First-Mode period of Vibration

AI: Arias Intensity

CAV: Cumulative Absolute Velocity