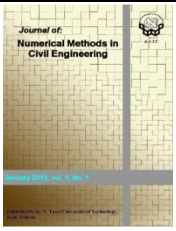

Numerical Methods in Civil Engineering

Employing Nonlinear Response History Analysis of ASCE 7-16 on a Benchmark Tall Building

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ARTICLE INFO

Article history:
Received:
March 2019.
Revised:
July 2019.
Accepted:
August 2019.

Keywords:
nonlinear response history analysis; amplitude scaling; spectral matching; scale factor; performance-based design.

Abstract:

ASCE 7-16 has provided a comprehensive platform for the performance-based design of tall buildings. The core of the procedure is based on nonlinear response history analysis of the structure subjected to recorded or simulated ground motions. This study investigates consistency in the ASCE 7-16 requirements regarding the use of different types of ground motions. For this purpose performance of a benchmark tall building subjected to recorded and different types of spectrally matched ground motions is investigated. Application of ASCE 7-16 procedure, which is also adopted by the Los Angeles Tall Building Structural Design Council (LATBSDC) for amplitude scaling on tall buildings, results in unrealistically large scale factors. As expected, this large scale factor leads to a very conservative estimate of local and global demands by scaled recorded ground motions compared with spectrally matched ones. Recorded ground motions intrinsically cause large variation in engineering demand parameters (EDP), which is significantly magnified by large scale factors. The results are, a large ratio of maximum to mean response and control of the design process by maximum EDPs rather than mean values. Interestingly, capacities associated with maximum EDPs are vaguely defined in the code, partially due to the lack of knowledge on the elements actual response. It is also found that estimates of EDPs by different spectrally matched types of ground motions could be significantly different.

1. Introduction

ASCE 7-16 [1] for the first time puts forward a comprehensive framework for performance-based design of structures. The method is mainly constructed on the basis of nonlinear response history analyses. Analyses could be done by employing recorded or simulated (spectrally matched) ground motions (GMs). Both types of ground motions have their own problems. Finding sufficient number of recorded ground motions with the tectonic regime, site condition and anticipated magnitude, and distance for the site of interest, is not usually a feasible task. In addition to this complication, large scale factors could introduce bias in the evaluation of demand.

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On the other hand, although the use of spectrally matched GMs is allowed by different codes including ASCE 7-16, ASCE 41-17 [2], ASCE 43-05 [3] and LATBSDC [4]; there are different attitudes in the engineering community towards the use of these GMs. As discussed by Al Atik and Abrahamson [5] using spectrally matched ground motions have some plus and minus sides. On the minus side, the target spectrum is an envelope of different ground motions. Therefore, evaluating structural response using spectrally compatible GM could result in an overly conservative estimate of the actual response. Also, on the minus side is a significant reduction in variation of engineering demand parameters (EDP) for spectrally matched GMs compared to recorded ones. On the positive side, due to reduced variation in EDP, it is possible to meaningfully reduce the number of required analyses to obtain a mean estimate of EDPs (if mean controls the design).

Early exploration of spectrally matched GMs revealed that their use could result in unrealistic demand in terms of displacement and energy content (Naeim and Lew [6]).

Bazzurro and Luco [7] pointed out that the use of large-scale factors on recorded GMs could lead to overly conservative estimates of EDPs. They also pointed out that the use of spectrally matched GMs could underestimate the variation of EDPs. Nevertheless, Baker et al. [8] demonstrated that spectral matching preserves the spectral signature of the original GM (seed) and gives essentially the same deformation pattern throughout the structure together with reduced variation in EDPs. Noting that spectral matching could result in unconservative bias in the mean value of EDPs, Seifried and Baker [9] associated this to the dispersion of the response spectrum of spectrally matched GMs at a period about 2.5 times elastic period. Lancieri et al. [10] evaluated the performance of spectral matching methods by applying it on a jagged response spectrum rather than smoothed one. They demonstrated that spectral matching increases residual vibration in the form of longer coda vibration. Analyzing the response of a one degree of freedom system with brittle post-peak response, they also found no bias leading to larger or smaller demands, however, they reported significant variation in the response parameters.

Commonly adopted approaches toward generating spectral matched GMs employ frequency-domain or time-domain based methods. The main idea is modulating the energy content of the ground motions in different ranges of frequency. First-generation of spectral matching methods were developed using frequency-domain methods. The frequency content of seed GM in each frequency is scaled up or down depending on the ratio of target spectrum and spectrum of the seed GM (e.g. Gasparini and Vanmarcke [11]). This is equivalent to adding harmonic components in the entire GM duration to the record that changes nonstationary characteristics of the GM as compared to the seed (Lilhanand and Tseng [12]). In an attempt to overcome this undesired consequence of spectral matching in the frequency domain, different researchers tried spectral modification in the time domain by adding and subtracting improved wavelets.

On the other hand, the ASCE 7-16 requirement for the performance-based design of structures (requirements of chapter 16) is mainly based on the mean value of the response parameters. On the maximum drift, ASCE 7-16 only controls failure in convergence, and there is no explicit requirement on maximum drift. However considering LATBSDC, which could be considered as a natural extension of ASCE 7-16 to tall buildings, there is an explicit maximum drift requirement. For plastic rotation, ASCE 7-16 only requires that demand should not exceed the deformation limit, with no clear definition of what it is or how it could be calculated (the same is true for LATBSDC). In other words, with current knowledge of element behavior, the code's requirements are mainly constructed on the basis of mean capacity and mean demand. Accounting for this and also considering acceptable accuracy of spectrally matched GMs in evaluating the mean value of response parameters, this paper investigates the applicability of these types of ground motions for nonlinear response history analysis as compared to scaled recorded ones.

To investigate how performance assessment is affected by the scaling procedure of ASCE 7-16 and also to evaluate the extent of change in the response due to implementing spectrally matched or amplitude scaled GMs, intensity measures and EDPs are used to compare the performance of different GM types. These parameters are used to obtain a clear view of the problems that could be associated with the use of ASCE 7-16 procedure on tall buildings. Investigating consistency in ASCE 7-16 requirements regarding the use of scaled recorded or spectrally matched ground motions, the response of a tall building, well studied by other researchers, are evaluated for different sets of GMs including a) scaled recorded ground motions, b) for spectrally matched ground motions generated using recorded ground motions of set A as seed, c) for spectrally matched ground motions using seeds generated employing ground motion models, and d) for spectrally matched ground motions generated using filtered white noise as seed. The performance of the structure for different sets is evaluated by considering the variation in intensity measures and, local and global EDPs.

2. The Case Study

The case study is a 46 story building, 42 stories above the ground, and 4 stories at podium levels with perimeter basement walls (Fig. 1). The lateral force resisting system comprises of core walls and perimeter frames. The building is subject to extensive studies by different researchers (e.g. PEER 11/05 [13] and Deger and Wallace [14]).

The structure is designed for linear analysis requirement of ASCE 7-16 using a modal response spectrum and subsequently, design adequacy in passing nonlinear response history analyses requirements of the procedure is investigated. This study uses the same story height, slab thickness, loads and etc. as those of PEER 11/05. Assumed soil type and seismic design category are C and D, and presumed short period (SMS) and 1 sec period (SM1) spectral accelerations are 2.07g and 0.84g, respectively.

ASCE 7-16 compares mean nonlinear deformation demand with ASCE 41-17 rotational limits for collapse prevention. Maximum local deformations are limited in ASCE 7-16 and also LATBSDC to a valid range of modeling, where there is no guide on how to calculate this valid range. This ambiguity could be partly due to the lack of knowledge (Hamburger et al. [15]). LATBSDC limits maximum drift to 1.5 times of allowable mean value, and by extending this logic in this study, it is assumed that the valid range of modeling is 1.5

times of ASCE 41-17 permissible deformations for collapse prevention limit states.

ASCE 7-16 limits mean drift demand to two times of drift limit it uses for conventional design. Considering the risk category of the structure, the drift limit for mean drift demand will be 2x0.02=0.04. LATBSDC limit for mean drift demand is 0.03. ASCE 7-16 has no explicit drift limit for maximum drift demand, it only controls the convergence of the numerical solution. LATBSDC limits maximum demand to 1.5 times its limits for mean drift, i.e. 1.5x0.03=0.045. Accounting for LATBSDC's limitation, a maximum drift limitation of 1.5x0.04=0.06 is considered in the analyses.

The modal response spectrum in linear analysis is done by ETABS [16] and nonlinear response history analysis is carried out using Perform 3D [17]. The design code is ACI 318-14 [18]. Table 1 gives the description of the model structures used in this study and design sections for structural elements are given in Table 2. Except for coupling beams, for other elements, stiffness values suggested by LATBSDC for MCE GM are used.

In Perform 3D nonlinear model, beams of perimeter frames and part of the lateral force-resisting system are modeled using flexural hinges located at the interface of middle elastic beam element and stiffened end zones. Considering ASCE 41-17, the rotational capacity of beams will be 0.04. Columns are also modeled similar to beams with concentrated plastic hinges at element top and bottom sections. In beams and columns, considering the use of elastic material property along the span, LATBSDC’s recommended stiffness values for MCE level ground motions are used to model the effect of cracking.

Shear walls are modeled using fiber sections with expected strength of materials, where confinement is modeled employing Mander et al. [19] model. Recent simulations using different confinement models show better performance of this confinement model in evaluating the nonlinear response of reinforced concrete elements [20]. The discretization of wall elements follows recommendations of Powell [21] accounting for hinge length. Based on ASCE 41-17 plastic hinge length should not exceed story height and half of wall flexural depth.

Coupling beams are modeled with an elastic beam with a nonlinear shear hinge at mid-span. As the 4 nodes membrane element modeling shear wall in the PERFORM 3D does not have rotational degree of freedom, to provide a moment-resisting connection between coupling beam element and wall element, vertical embedded elements as suggested by Powell, are employed. In modeling coupling beams accounting for flexural/shear/extension-slip deformations, flexural stiffness is reduced to 0.2EcIg and allowable chord rotation are considered to be 0.06 (Naish et al. [22]).

3. Ground Motions

Ground motions considered in this study include the following sets

- Set 1: Recorded GMs (**Rec**)
- Sets 2 and 3: Spectrally matched GMs with seeds of recorded GMs of Sets 1 (**Atk** and **Han**). Generated by SeismoMatch [23].
- Set 4: Spectrally matched GMs with seeds generated accounting for regime, distance and magnitude (**Hal**). Generated by SeismoArtif [24].
- Set 5: Spectrally matched GMs with seeds of filtered white noise (**Clo**).

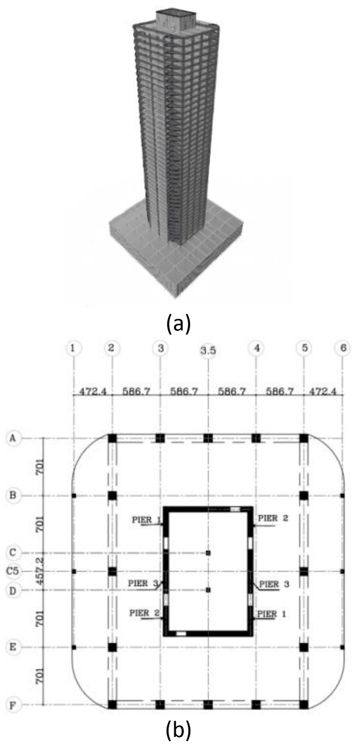


Fig. 1: Example building, a) 3D view, b) plan

Table 1. ASCE 7-16 requirements for NRHA

Modeling Parameter		Requirement
Scaling Method	Recorded GMs	Amplitude scaling to at least 90% of uniform hazard spectrum
	Spect. Matched GMs	Spectral matching to 110% of uniform hazard spectrum
Unacceptable response		Only one GM in suite
Global Acceptance Criteria	Drift	Average: 0.040* Absolute max: no criteria, here it is assumed to be 0.060
Local Acceptance Criteria	Beams	mean≤0.040 / max≤0.060**
	Columns	mean≤0.050 / max≤0.075**
	Walls	mean≤0.020 / max≤0.030**
	Coupling Beams	mean≤0.060 / max≤0.090**
Material Strength		Expected: f'_{ce}=1.5f'_c, f_{ye}=1.25f_y Reinforcements: f_y=414 MPa
		Columns 70 MPa for Found. to Ground Level

		56 MPa for Ground Level to Story 10 42 MPa for Story 11 to Story 26 35 MPa for Story 27 to Roof
		Beams: 35 MPa for All Stories
		Walls and Coupling Beams 56 MPa for Found. to Story 20 42 MPa for Story 21 to Story 30 35 MPa for Story 31 to Roof
Element Stiffness (Flexure/Shear)	Beams	$0.30E_cI_g/0.4E_cI_g$
	Columns	$0.70E_cI_g/0.4E_cI_g$
	Walls	$0.35E_cI_g/0.4E_cI_g$
	Coupling Beams	$0.30E_cI_g/0.4E_cI_g$

* Only for amplitude scaling, drift for one GM could exceed limitation.

** Valid range of response is assumed to be 1.5 times the permissible value for mean

Bin of recorded ground motions (**Rec**) considered in the analyses are given in Table 3 that are far field ground motion used in FEMA P695 [25].

Table 2. Recorded ground motions used in the study.

Record No.	NGA No.	Name
1	286	Irpinia-Italy-01
2	73	San Fernando
3	739	Loma Prieta
4	2601	Chi-CHI-Taiwan-03
5	4455	Montenegro-Yugoslavia
6	125	Friuli Italy-01
7	881	Landers
8	164	Imperial Valley-06
9	4013	San Simeon-CA
10	587	New Zealand-02
11	1111	Kobe-Japan

Amplitude scaling on recorded GMs in ASCE 7-16 is applied on a period range of 0.2T1 to 2T1. ASCE 41-17 has reduced upper bound (Tmax) from 2T1 to 1.5T1 (similar to the previous editions of ASCE 7). Fig. 2 shows the evolution of scale factor with upper bound of period range (Tmax), where scaling factor is evaluated adopting ASCE 7-16 method for a fixed lower bound (0.2T1) and an increasing upper bound rather than a fixed one. The evaluated scaling factor is a (nearly) monotonically increasing function of Tmax. Considering the period range of ASCE 7-16 for scaling in buildings with the first oscillation period above 4 sec gives an unrealistically high scale factor. It should be noted that LATBSDC 2018 also adopted ASCE 7-16 scaling procedure for the performance-based design of tall buildings. For the structure of interest with T1=5.2 sec, based on ASCE 7-16 requirements, Tmax should be 2 times 5.5, i.e., 11 sec, which will lead to an unacceptable scale factor of about 12. Considering this, in the current study, we adopted Tmax=T1, and the scale factor for that will be 6.94. As will be shown later, even this reduced upper bound gives rise to an overly conservative estimates of EDPs (local and global).

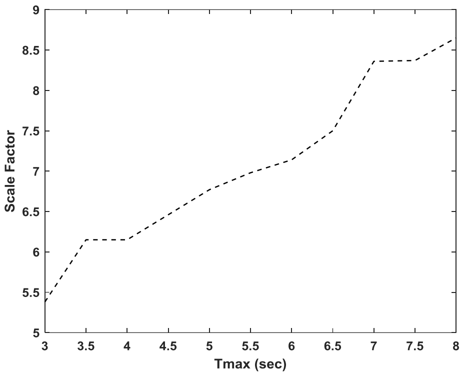


Fig. 2: Evolution of scale factor with Tmax.

All generated GMs are base line corrected using SeismoSignal [26]. GMs denoted by **Atk** are generated using method proposed by Al Atik and Abrahamson working in time domain, which employs tapered cosine wavelets to avoid introduction of long period drift in generated GMs. The method introducing an analytical solution for spectral matching algorithm has improved stability and time efficiency.

GMs denoted by **Han** employs method proposed by Hancock *et al*. [27], which works in time domain and is an improvement of method proposed by Abrahamson [28] by trying to reduce baseline drift in velocity and displacement of generated GMs.

GMs **Hal** uses Halldorsson and Papageorgiou [29] procedure. The method using response spectral database for earthquakes of different regimes including intraplate, interpolate and active tectonic regimes, calibrates the barrier model proposed by Papageorgiou and Aki [30]. It accounts for change in frequency content of ground motion for different regimes, magnitudes and distances. Considering disaggregation of hazard at assumed location of the building (longitudinal=-118.25 and latitude=34.05 PEER 2011/05) for MCE level ground motion, for T=5.2 sec mean magnitude and distance for spectral acceleration will be 7.2 and 23.9 km, respectively.

GMs **Clo** are generated using frequency domain spectral matching procedure as proposed by Clough and Penzien [31] on filtered white noise seeds.

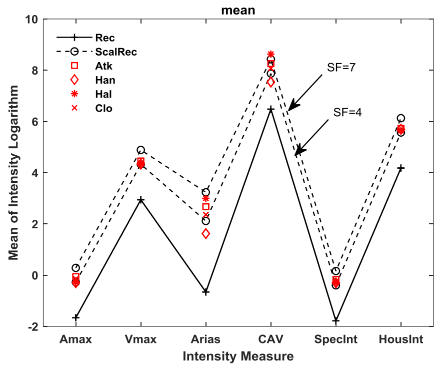
Different scaling methods could be classified as

- Selecting records based on distance, magnitude, and spectral acceleration at the fundamental period (Sa(T1)). Modification includes scaling spectral acceleration of each record to Sa(T1) of scenario GM. The method could provide an estimate of the mean and dispersion of EDPs.
- Selecting records with a spectrum similar to a target spectrum and implicitly accounting for distance and magnitude. Modification includes scaling spectral acceleration of the records to have a mean spectrum above the target spectrum in a range of periods. The method could only provide an estimate of the median value of EDPs.

ASCE 7-16 amplitude scaling and spectral matching methods could be categorized in the second group. In other words, the procedure adopted by ASCE 7-16 could only provide a good estimate of median of EDPs rather than their maximum values.

Different scale factors are suggested by different researchers to provide an unbiased estimate of EDPs. Kohrangi et al. [32] discussed the efficiency of different scalar and vector IMs for predicting different EDPs. To have an estimate of EDPs for different sets of GMs (recorded or simulated) considered in the study, the mean value and variance of different intensity measures are evaluated. The intensity measures considered here are

- Maximum acceleration
- Maximum velocity
- Arias intensity
- Cumulative absolute velocity (CAV)
- Spectral intensity
- Housner intensity



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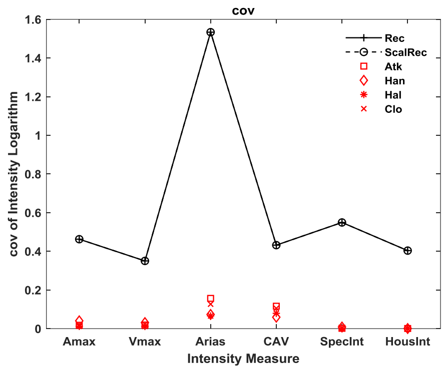


(b)

Fig. 3: Variation of intensity measures for different types ground motions, a) mean, b) cov.

All of the intensity measures are calculated using SeismoSpect [33]. Fig. 3 gives the mean and coefficient of variation (cov) of intensity measure logarithm. As could be seen, due to spectral matching simulated GMs possessing mean values well above mean of recorded (unscaled) GMs, by applying a scale factor of 4, it is anticipated that the mean value of EDPs for scaled recorded GMs (ScalRec) will be about the mean of EDPs for simulated GMs. For larger values of scale factor as required by the amplitude scaling procedure of ASCE 7-16, much larger values for mean of EDPs could be expected. This figure also gives cov of intensity measures. Cov for recorded GMs (scaled or unscaled) is much larger for all intensity measures considered in the study. Although recorded (Rec) and scaled (ScalRec) have the same cov, an increase in the mean value of intensity measures due to application of scale factor on recorded GMs (ScalRec) leads to a substantial increase in anticipated variation of intensity measures and consequently large variation in EDPs as will be discussed later.

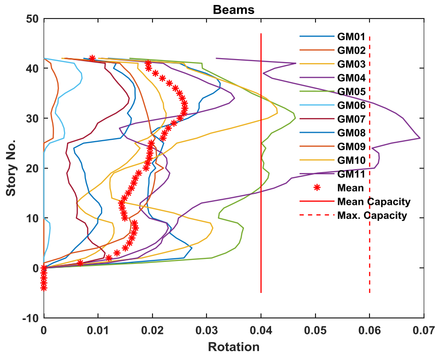
4. Results

Results of nonlinear response history analyses using different GM types are evaluated in global (drift) and local (plastic rotation) levels.

Fig. 4 gives the evolution of rotational demand for beams, columns, coupling beams, and walls for recorded GMs. The same pattern of behavior is also observed for simulated GMs and therefore herein, results are only presented for recorded GMs. As could be seen, the median and maximum rotational demand in coupling beams are the most critical EDPs that controls the design. For this reason, when discussing local EDPs in the following, discussion will be limited to rotational demand in the coupling beams.

Fig. 5 gives drift profile along structures height for Y direction which is the critical direction. As discussed in the previous section, drift limits of 0.04 and 0.06 are considered for mean and maximum drift demands respectively. All simulated GMs resulted in acceptable response in terms of mean and maximum drift demand, but the maximum drift of recorded GMs (**Rec**) well exceeds the maximum considered drift limit of 0.06. In fact, while from the perspective of LATBSDC, the structure is considered to be unacceptable, ASCE 7-16 categorizes it as an acceptable one. The ratio of maximum to mean drifts are 4.35, 1.45, 1.22, 1.30, and 1.37 for GM of sets 1 to 5. Large variation for **Rec** is anticipated and controls the design adequacy check. The extent of variation in the response (difference between maximum and mean values of the response parameter) changes for different spectrally matched GMs. The largest variation is observed for **Atk** and the smallest one is for **Clo**. The difference in the estimate of mean drift by different spectrally matched ground motions is not significant.

While ASCE 7-16 for recorded GMs allows up to 10% reduction in target spectrum, for spectrally matched GMs, it considers 10% increase in target spectrum, which results in about 22% increase in demand. Difference observed for these two types of GMs specially in the maximum values EDPs are much larger than that could be compensated by 22% increase in target spectrum. It is interesting that LATBSDC even does not require 10% increase in target spectrum for spectrally matched GMs.



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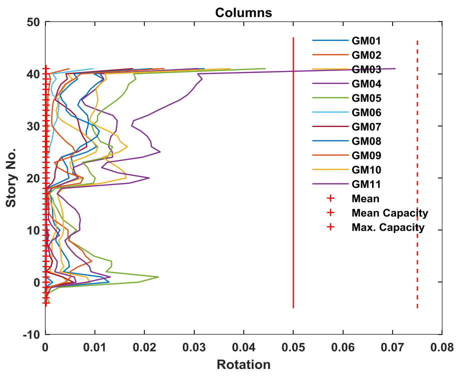

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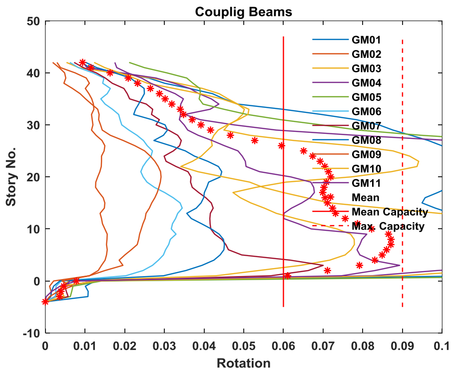

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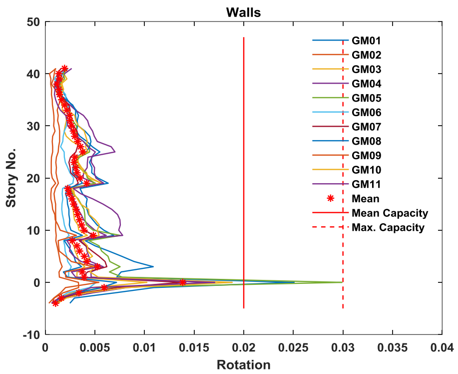

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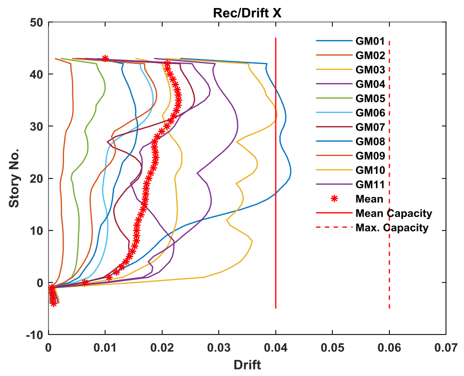
Fig. 4: Evolution of rotational demand in different stories for recorded GMs, a) beams, b) columns, c) coupling beams, d) walls.



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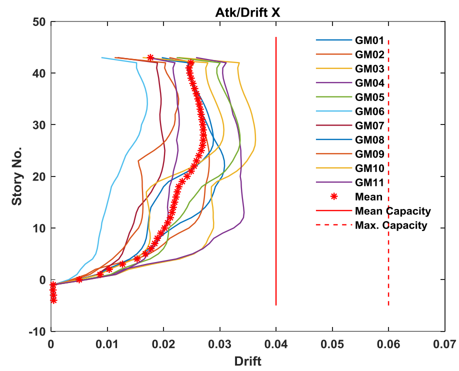

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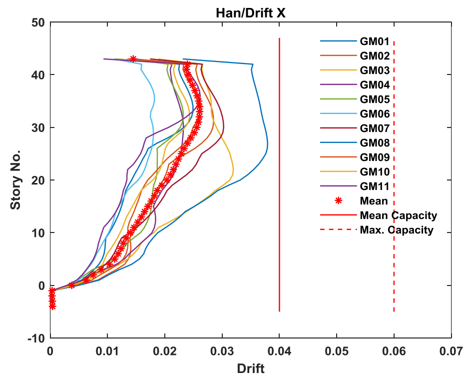

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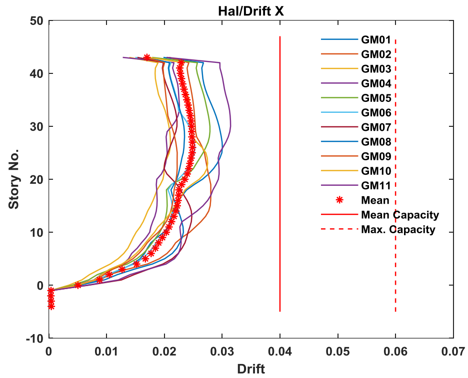

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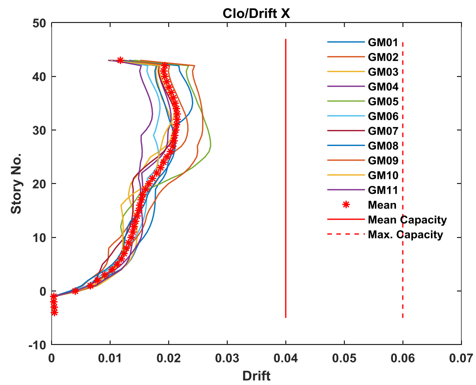
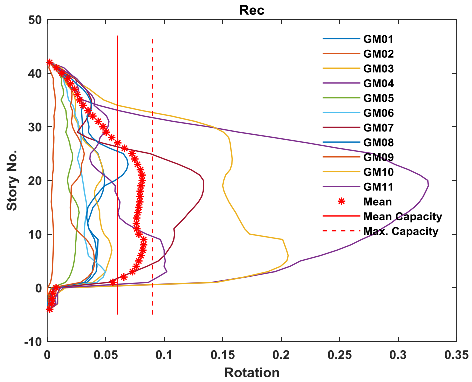


(e)

Fig. 5: Drift profile for different types of found motions, a) **Rec**, b) **Atk**, c) **Han**, d) **Hal**, e) **Clo**.

It could be argued that ASCE 7-16 requirements are written with the knowledge that there is a larger variation in response for recorded GMs, and consequently, no explicit limitation is imposed on the maximum observed drift. However, there is an explicit limit for local maximum deformations, where the code limited vaguely maximum local deformations to a valid range of deformation. Fig. 6 compares rotational demand in coupling beams for different GM types. Rotational demands in a large number of stories well exceed the permissible values for mean and maximum values for recorded GMs. For spectrally generated GMs mean value of the response parameters satisfies code's limitation, but the maximum of the response parameters exceed permissible ones for some of the spectrally matched GMs. The ratio of mean and maximum demand to capacity for Rec are 1.3 and 3.1; indicating that maximum response controls the design. For **Atk** GMs (the most critical spectrally matched GM) again maximum response controls the design.



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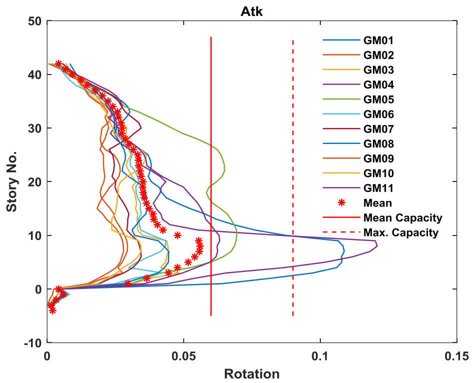

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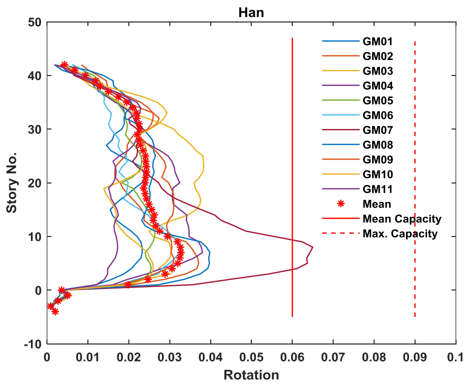

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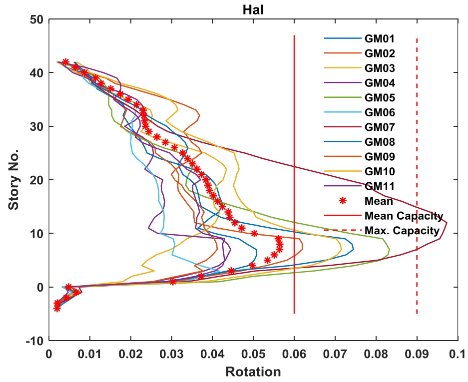

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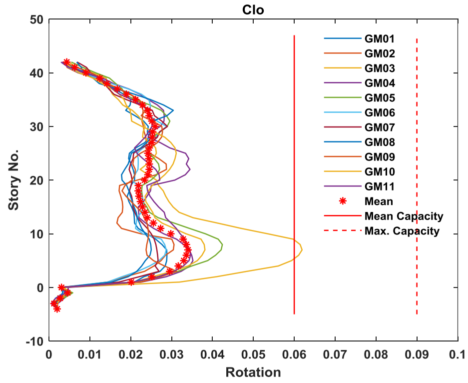

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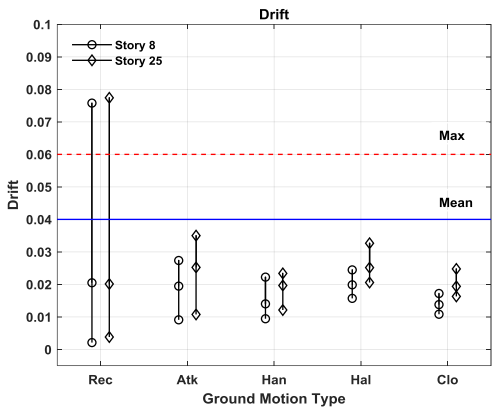
Fig. 6: Rotational demand for different GM types, , a) **Rec**, b) **Atk**, c) **Han**, d) **Hal**, e) **Clo**.

To have a better picture, Fig. 7 gives minimum, mean and maximum of stories 8 and 25 observed for drift in Y direction and rotational demand in coupling beams. These two stories are the location of significant nonlinear deformations. Concentrating on drift, it could be found that the design adequacy check is controlled by the maximum observed response rather than mean value. On the local level (rotational demand on coupling beam), although mean and maximum response values exceed permissible values, nonetheless design adequacy is primarily controlled by the maximum response.

As discussed in the preceding paragraph, the maximum value of EDPs are the main controlling parameter in the design adequacy check of ASCE 7-16. Returning to Fig. 3 it could be anticipated that variation in the EDPs could increase with increasing scale factors. In fact, the scaling procedure of ASCE 7-16 results in large scale factors that increase both mean and maximum values of EDPs. To show how minimum, mean and maximum values of EDPs evolve with increasing scale factor, evolution of scale factor and drift are plotted in Fig. 8. While some kind of saturation in local demand (rotational demand on coupling beams) occurs, there is uniformly increasing drift demand for increasing scale factors. This figure also gives a coefficient of variation of drift for orthogonal directions. There is a steady increase of cov for increasing scale factors. The coefficient of variation is comparable to those reported in PEER 2009/01 [34].



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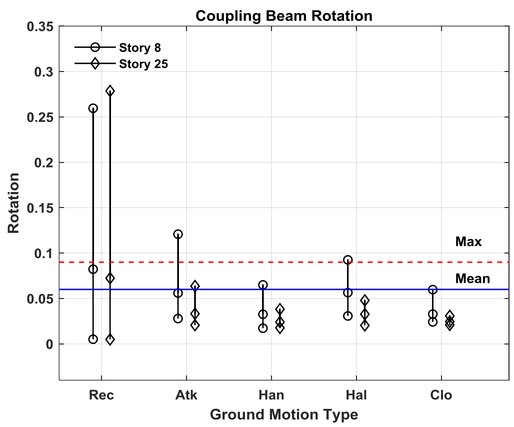
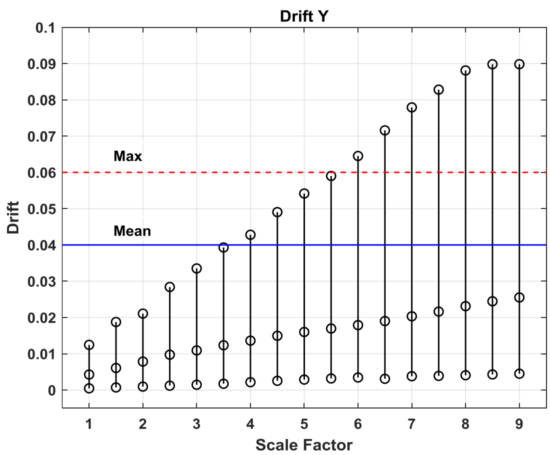


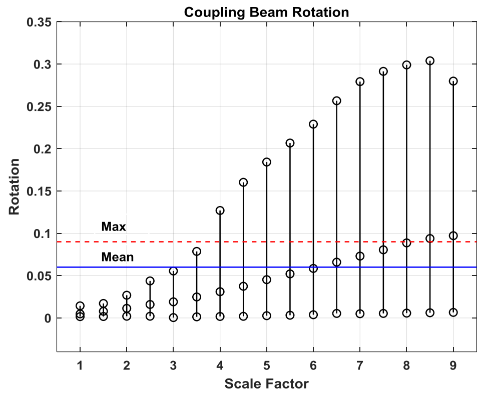
(b)

Fig. 7: Min, Max and Mean value of EDPs (drift and coupling beam rotational demand) in story 8 and 25 for different types of GMs, a) interstory drift, b) Coupling beam rotational demand.

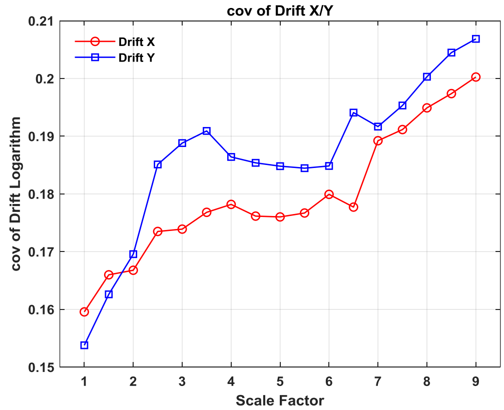
This figure shows a significant increase in variation and consequently maximum observed EDPs for increasing scale factors. Noting that current knowledge of element behavior prevents determination of the maximum capacity of element deformations with good accuracy, in fact, ASCE 7-16 procedure adopts a design strategy that is mainly based on maximum response.



(a)



(b)



(c)

Fig. 8: Evolution of drift mean and extreme values with scaling factor for EDPs in story 25, a) drift versus scale factor, b) rotational demand on coupling beam vs scale factor, c) cov of drift in orthogonal directions.

5. Conclusion

An investigation is made on applicability of nonlinear response history analysis procedure of ASCE 7-16 using recorded and spectrally matched ground motions on an example tall building. Different methods are adopted for generating spectrally matched ground motions. The study resulted in the following conclusions

- Amplitude scaling method of ASCE 7-16 results in unrealistically large-scale factors for tall buildings. Scale factors larger than 4, as obtained by using the ASCE 7-16 procedure, gives rise to unrealistically large demand in the structural elements.
- Estimation of different type of spectrally matched ground motions on the maximum values of EDPs could be significantly diverse. Considering probabilistic nature of the ground motions, this is an expected outcome.
- Large variation in the engineering demand parameters are observed for recorded ground motions, which controls design acceptability procedure of ASCE 7-16. While maximum local demand controls the design

adequacy check, ASCE 7-16 and LATBSDC remain silent on how to calculate the maximum deformation capacities. On the global level (drift) LATBSDC is more restrictive by limiting mean and maximum drift demand, where ASCE 7-16 does not introduce any explicit limitation for maximum drift.

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