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Comparative study of seismic structural response to real and spectrum matched ground motions

H. Tajmir Riahi*, **H. Amouzegar and S. Ale Saheb Fosoul**

Department of Civil Engineering, University of Isfahan, Isfahan, Iran.

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Abstract. Developing the concept of performance based analysis and design has made nonlinear dynamic analysis an efficient method for quantification of the seismic response of structures. Generally, this analysis is done utilizing accelerograms, which are ground motions obtained from earthquakes. This research is focused on assessing the seismic structural response of a comprehensive set of reinforced concrete moment resisting frames under excitation of real accelerograms and ground motions that are spectrally matched to a target spectrum. The matching process is conducted in the time domain, and the ASCE 7-05 spectrum is used as the target spectrum. Comparisons are provided for a number of ground motion parameters and the effect of spectrum matching has been investigated. Additionally, the variation of structural response and the degree of compatibility and conservation of real and spectrally matched ground motions have been extensively discussed. It is shown that spectrum compatibilization effectively decreases the variation of structural response. However, the measure of observed bias thoroughly depends on the height of the structure. Finally, fragility curves of structural performance are provided and it is indicated that consideration of modeling uncertainties results in obtaining a fragility curve with reasonable resemblance to that obtained from real ground motions.

1. Introduction

Efficient performance based analysis and design require a rational selection of ground motion records, as well as accurate modeling of structural components. Fundamentally, the procedure of selecting, scaling and matching accelerograms plays a prominent role in dynamic analysis, and careful ground motion selection leads to a considerable reduction in the variance of structural response. There are different methods for obtaining proper accelerograms to be used in engineering designs. One of the most prevalent methods is artificial accelerogram, which is generated by white noises and also scaled natural ground motions. However, there is a substantial difference between artificial and natural records in terms of the number of cycles, frequency content and strong motion duration [1]. Besides, inelastic analysis requires suits of ground motions, with reasonable consistency with a predefined earthquake scenario. This scenario is based on many parameters, such as magnitude, source to site distance, shear wave velocity and site classification, which makes the procedure of record selection cumbersome.

One solution to this problem is appropriate scaling of records on a target spectrum (at least in the fundamental period or within a range of periods around the fundamental period of the structure). Because of inherent variability in the nature of the records,

*. *Corresponding author. Tel.: +98 311 7934522;*
Fax: +98 311 7932089
E-mail addresses: tajmir@eng.ui.ac.ir (H. Tajmir Riahi);
h_amouzegar@yahoo.com (H. Amouzegar);
saaber_a@yahoo.com (S. Ale Saheb Fosoul)

several dynamic analyses are required to obtain an accurate nonlinear seismic evaluation of structures. Exact spectrum matching is a method to decrease the number of dynamic analyses by reducing the differences of response and target spectra [2]. Response of single degree of freedom structures to these records must have a reasonable compatibility with an elastic design spectrum that reflects the seismic performance of the site of interest. Such consistency enables the structural response to be predicted more confidently through fewer analyses.

Seismic design codes usually recommend performing nonlinear dynamic analysis using three or seven records, and considering the maximum or average response of the structure, respectively. These numbers are usually suggested in order to guarantee the design purposes in the time history analysis. However, researchers frequently use a greater number of records, up to twenty or even forty, for exact prediction the median curve of Incremental Dynamic Analysis (IDA), as the most widespread method of nonlinear analysis [3]. Since the IDA requires successive scaling of each individual record, performing nonlinear dynamic analysis of complex structures with a numerous number of records seems to be too time-consuming, which makes this analysis nearly impractical. Many researchers have attempted to reduce the required number of records for IDA. Hancock et al. [2], Bazzurro and Luco [4] and Carballo and Cornell [5] showed that on the one hand, exact spectrum matching is one of the most effective approaches that can suitably decrease the number of input accelerograms of nonlinear dynamic analysis, and on the other hand, reduce the variability of the structural response.

Hancock et al. made a comparison of structural responses of reinforced concrete structures under spectrum matched accelerograms and suits of records selected according to different criteria. They concluded that bias is decreased by applying more constraints on the procedure of scaling and matching ground motion records [2]. Carballo and Cornell compared the structural response of SDOF and MDOF systems and derived that spectrum matched records make an unconservative bias on the estimation of median displacement based nonlinear structures. They concluded that this bias may be a consequence of neglecting the spectral accelerations other than the one at the fundamental period of the structure [5]. However, Buratti [6] showed that local variations of the spectral shape do not have any major effect on the observed bias.

Generally, most of the above-mentioned conclusions are derived from either SDOF systems or specific MDOF ones and there is no comprehensive study about the effects of spectrum matching on a broad range of frames. In this paper, effects of spectrum matching on ground motion parameters are studied first. Additionally, variation of engineering demand parameters at different hazard levels, and the degree of compatibility of real and spectrally matched ground motions have been extensively discussed, using a comprehensive set of reinforced concrete moment resisting frames. Also, the effects of spectral matching on the collapse assessment of these frames are investigated taking the advantage of fragility curves.

2. Different types of spectrum matching

Response spectrum matching is a process by which an earthquake record is altered, such that its response spectrum matches a desired target spectrum within a range of periods and a variety of damping values [7]. An additional advantage of this method is the possibility of making changes in the frequency content of ground motions in order to obtain new records for the regions that suffer from lack of ground motion records. Exact matching of a ground motion response spectrum on a target spectrum can be carried out by different methods, such as optimization algorithms (e.g. genetic algorithm) [8], adding/subtracting waves to/from the time histories in the frequency domain and using wavelet theory in the time domain. However, the most prevalent approaches in spectrum matching are the two undermentioned methods (i.e. Matching in the time and frequency domain). The following sections provide a brief introduction and history of each method.

2.1. Spectrum matching in frequency domain

Vanmarcke, Gasparini, Lee, Silva, Bolt, Gregor, Carballo and Cornell are pioneers of developing spectrum matching in the frequency domain [9-12]. This approach alleviates the domain of the Fourier spectrum without any alteration in its phases. It is essential to choose records with acceptable compatibility of response and the target spectrum in the interested domain of periods in order to maintain the nonstationary characteristics of the accelerograms. This rationale selection also leads to an augmentation in the rate of convergence of the matching process. This method has the advantage of generating records based on natural ground motions and minimizing the difference between their response and target spectra. It is also possible to scale records by a linear coefficient in many cases, which yields better consistency between response and target spectra. However, Naeim and Lew showed that the maximum building displacement under spectrum matched records in the frequency domain is approximated nearly twice that of those under records linearly scaled to exceed the target spectrum. They found that variation of the Fourier spectrum can cause differences in the displacement and velocity time histories. Consequently, this method overestimates the energy content, which leads to the mentioned bias in the maximum building displacement [13]. Besides, it is shown that matching in the frequency domain does not always yield a reasonable fit on the design spectrum, as the time domain and spectrum matched ground motions that have been made by this method show high visual differences from the initial time history [14].

2.2. Spectrum matching in time domain

Spectrum matching in the time domain is well introduced by Lilhanand, Tseng and Abrahamson [15,16]. Adding/subtracting wavelets with limited duration to/from the original accelerogram is the basis of the matching procedure in this method, which results in the proper consistency of the accelerogram response spectrum and target spectrum. The reverse impulse response time history of the single degree of freedom oscillator wavelet (briefly, reverse impulse response wavelet), in the time domain and the tapered sinusoid wavelet, are elementary wavelets for this method. The domain of the former wavelet suddenly decreases and approaches zero after peak response time is achieved, which leads to a limitation in the temporal extent of the modification made to the time history. The sinusoidal shape of the latter wavelet is period dependent and its timing is selected such that it is in shape with the maximum response of the acceleration time history [14]. These two mentioned wavelets are not suitable for simultaneous spectrum matching of ground motion records on a spectrum with diverse damping. Therefore, newer wavelets like the sinusoidal corrected wavelet and the corrected tapered cosine wavelet were introduced [1].

Spectrum matching in the frequency domain corresponds to adding/subtracting sinusoidal wavelets (with the Fourier phase of initial time history) in the time domain. Since the sinusoidal wavelet is added to the entire range of the time history, matching in the time domain gives better results, with respect to the frequency domain. Besides, the shape of the accelerogram remains constant in the time domain when the frequency domain does not maintain the natural appearance of record [14].

3. The spectrum matching procedure used in this study

It was mentioned in the previous section that spectrum matching in the time domain keeps the original shape of the ground motion record on the one hand and leads to better matching on the other. So, the focus of this study is on this method. Matching is performed by the RspMatch99 program, based on the modified algorithm of Lilhanand and Tseng [15] developed by Abrahamson [16] in order to enhance the convergence properties as well as nonstationarity of ground motions at low frequencies [17]. This procedure is carried out in two steps: first, utilizing a tapered cosine wavelet to match frequencies within 1 to 100 Hz, and second, using a reverse impulse response wavelet for matching frequencies in the range of 0.1 (long periods) to 100 Hz.

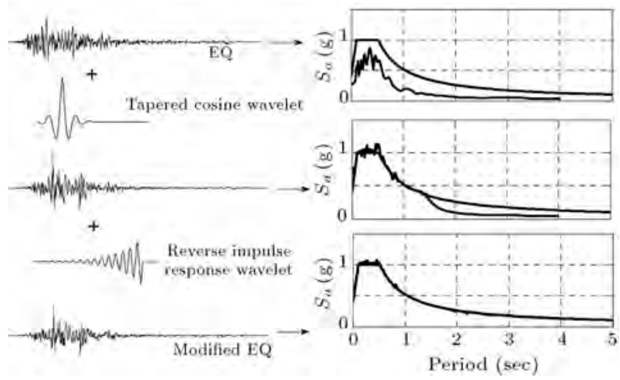

Figure 1. Steps of spectrum matching.

The design spectrum of ASCE7-05 for soil type C of the Los Angeles site is used as the target spectrum. Seismic ground motion maps of ASCE7-05 for the Los Angeles site offer spectral response acceleration (S_s) of 1.5 at a short period and 0.6 at a period of 1 sec (S_1). Figure 1 illustrates the applied procedure of spectrum matching in this study. As shown in this figure, adding a tapered cosine wavelet to the accelerogram decreases the differences of response and target spectra in mean periods, and adding a reverse impulse response wavelet minimizes these differences in all periods. Finally, a quadratic baseline correction has been conducted in order to modify the alteration of displacement and velocity time histories, due to the nature of added wavelets.

The ground motion database of this study consists of 39 horizontal pairs of far field earthquakes from Haselton's study (total 78 components), which include 22 pairs of far field FEMA695 ground motions [18]. There are some criteria for ensuring the proper selection of ground motion records, so that they represent strong motion that may cause structural collapse. These criteria are magnitudes greater than 6.5, the distance from source to site greater than 10 km (average of Joyner-Boore and Campbell distances) and peak ground acceleration and velocity greater than 0.2 g and 15 cm/sec, respectively. It should be noted that these earthquakes have occurred in soil types C and D. All these accelerograms are spectrally matched to the ASCE7-05 design spectrum. By taking a look at matched records, a suite of 20 accelerograms (Table 1) was selected, based on minimum alteration of their original shape, for utilizing in structural analysis. Figure 2 illustrates samples of proper and improper spectrum matching among all records. It is shown that performing proper matching keeps the original shape of the accelerogram and does not alter the domain of acceleration through the whole duration of the

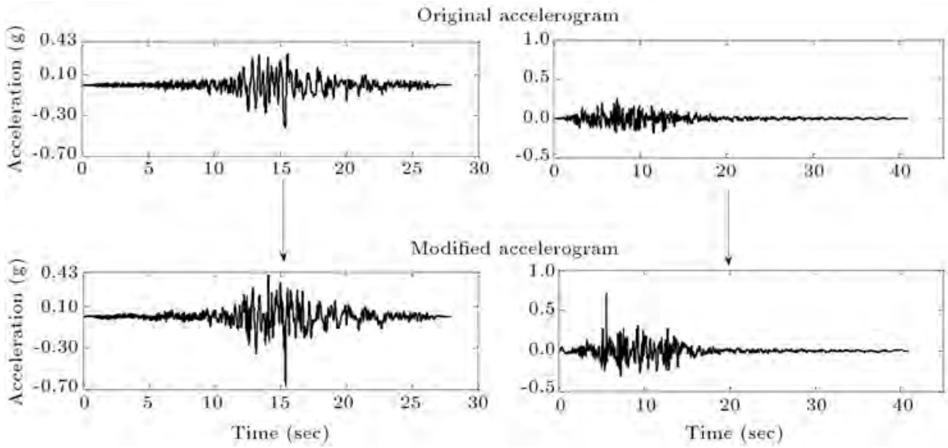

Figure 2. Samples of proper and improper spectrum matching.

Table 1. Specifications of the records used for spectral matching.

Number	PGA (g)	Magnitude	Year	Location	Station	Component
1	0.702	7.1	1999	Duzce, Turkey	Bolu	9°
2	0.686	7.1	1999	Duzce, Turkey	Bolu	90°
3	0.676	6.5	1979	Imperial Valley	Calexico Fire Station	225°
4	0.665	6.5	1979	Imperial Valley	SAHOP Casa Flores	270°
5	0.685	6.9	1995	Kobe, Japan	Nishi-Akashi	0°
6	0.659	6.9	1995	Kobe, Japan	Nishi-Akashi	90°
7	0.693	6.9	1995	Kobe, Japan	KJMA	0°
8	0.696	6.9	1995	Kobe, Japan	KJMA	90°
9	0.672	6.5	1987	Superstition Hills	El Centro Imp. Co. Cent	90°
10	0.674	6.9	1989	Loma Prieta	Gilroy Array #3	30°
11	0.699	7.4	1990	Manjil, Iran	ABBAR	90°
12	0.719	7	1992	Cape Mendocino	Rio Dell Overpass - FF	360°
13	0.688	7.6	1999	Chi-Chi, Taiwan	WGK	0°
14	0.671	6.5	1976	Friuli, Italy	Tolmezzo	0°
15	0.679	6.5	1976	Friuli, Italy	Tolmezzo	270°
16	0.674	6.7	1994	Northridge	LA - Saturn St	20°
17	0.659	7.3	1992	Landers	Coolwater	90°
18	0.69	6.7	1994	Northridge	Santa Monica City Hall	90°
19	0.668	6.7	1994	Northridge	Beverly Hills - 12520 Mulhol	35°
20	0.67	6.5	1979	Imperial Valley	El Centro Array #11	230°

earthquake. However, an improper matching maintain neither the shape nor the domain acceleration of the accelerogram.

4. Comparing ground motion parameters of original and matched records

In terms of structural response, Peak Ground Acceleration (PGA) represents the peak value of absolute acceleration obtained from the accelerogram of the component. Due to the relationship between horizontal acceleration and inertial forces, maximum dynamic force induced in a structure directly pertains to PGA. Peak Ground Velocity (PGV), is another descriptor of structural response, which is characterized as the maximum value of the first integration of the acceleration record, or, in other words, the velocity record. Because of the lower sensitivity of this parameter to higher frequency components of ground motions, it can predict the damage potential of the structure more accurately in the intermediate frequency range rather than the PGA [19].

The significant duration of an earthquake is defined as the time range of ground motion in which most of the strain energy is released and load reversals are occurred. In other words, an accelerogram with short duration cannot produce a sufficient number of load reversals and causes negligible structural damage, even if the amplitude of motion is high. On the contrary, a record with intermediate amplitude, but long duration, can cause substantial damage to the structure.

The mentioned parameters are directly related to frequency content and duration. Due to the importance of each of these parameters, it is worthwhile to introduce the parameters that contain more than one variable. One of these parameters is a_{rms} (root mean square of acceleration), which includes the effect of amplitude and frequency content of a strong motion record. v_{rms} (root mean square of velocity) and d_{rms} (root mean square of displacement) are also other parameters that have similar definitions, as follows:

$$a_{\text{rms}} = \sqrt{\frac{1}{T_d}\int_0^{T_d} \left[a(t)^2\right] dt},$$

$$v_{\text{rms}} = \sqrt{\frac{1}{T_d}\int_0^{T_d} \left[v(t)^2\right] dt},$$

$$d_{\text{rms}} = \sqrt{\frac{1}{T_d}\int_0^{T_d} \left[d(t)^2\right] dt}, \qquad (1)$$

where $a(t)$, $v(t)$, $d(t)$ are ground acceleration, velocity and displacement, and T_d is the duration of strong motion.

Acceleration and Velocity Spectrum Intensity (ASI and VSI, respectively) are defined as the integral of the pseudo-spectral acceleration and pseudo-spectral velocity of ground motion, each of which captures the effect of amplitude and frequency content in a single parameter.

$$\text{ASI} = \int_{0.1}^{0.5} S_a\left(\xi = 0.05, T\right) dT,$$

$$\text{VSI} = \int_{0.1}^{2.5} S_v\left(\xi = 0.05, T\right) dT, \qquad (2)$$

S_a, S_v and ξ are spectral acceleration, spectral velocity and damping, respectively.

Figure 3 illustrates ground motion parameters before and after spectrum matching. PGA, ASI and VSI values are fixed and stabilized after spectrum matching. Since the value of spectral acceleration at the lowest period is equal to PGA, all ground motions have a PGA equal to the value of the ASCE7-05 spectrum at a period of 0 ($T = 0$ sec) necessarily. So, the process of spectrum matching makes the PGA of all accelerograms unified and equal to the value of the ASCE7-05 spectrum. Basically, the values of ASI and VSI are spectrum dependent. Eq. (2) clearly indicates that these parameters are the integration of acceleration and velocity spectra. Again, the procedure of spectrum matching fits the response spectra of accelerograms on a target spectrum, which makes the surface under all of the response spectra equal to the surface under the target spectrum. Figure 3 shows the equality of the values of ASI and VSI for all ground motions. As this figure shows, values of significant duration remained unchanged, and values of the root mean square of acceleration have slight changes after matching, which indicates that the frequency content remained unchanged after matching. Besides, the values of the root mean square of velocity remain constant in all spectrum matched ground motions, which indicates that if a ground motion record needs to be matched on the ASCE7-05 spectrum, its values of the root mean square of velocity must equal 10 m/s.

Figure 4 illustrates acceleration spectra of original and spectrally matched records. The scatter nature of of original record spectra is apparent in the figure. After spectrum matching, this dispersion is significantly decreased and the spectra of matched records are approximately the same as the target spectrum.

5. Structural model database

The structural models used in this study are a vast range of reinforced concrete moment resisting frames consisting of thirty 2D frames. These frames are designed based on the ACI 318-05 code, and characteristics of the Ibarra model have been considered in its lumped plastic hinges. General properties used for the design of the frames, such as story height, bay width, loads, and seismic framing systems, are shown in Table 2. Also, Table 3 shows the general property of these frames, such as fundamental periods and mass participation ratios. An extensive description of each of them is provided in Haseltons study [3]. Frames with similar structural properties in Table 3 have different strength/stiffness distribution factors over height. All structural analyses are performed using the finite element program, OpenSees [20].

Evaluating the seismic performance and collapse potential of the structures requires hysteretic models, which capture the deterioration of structural components. The hysteretic model used in this study is the Ibarra model, which is provided for versatile modeling of cyclic behavior [21]. This model contains four basic modes of cyclic deterioration, referred to as: strength deterioration of the inelastic strain hardening branch, strength deterioration of the post-peak strain softening branch, accelerated reloading stiffness deterioration, and unloading stiffness deterioration. This model was implemented in the OpenSees open source program by Altoontash [22].

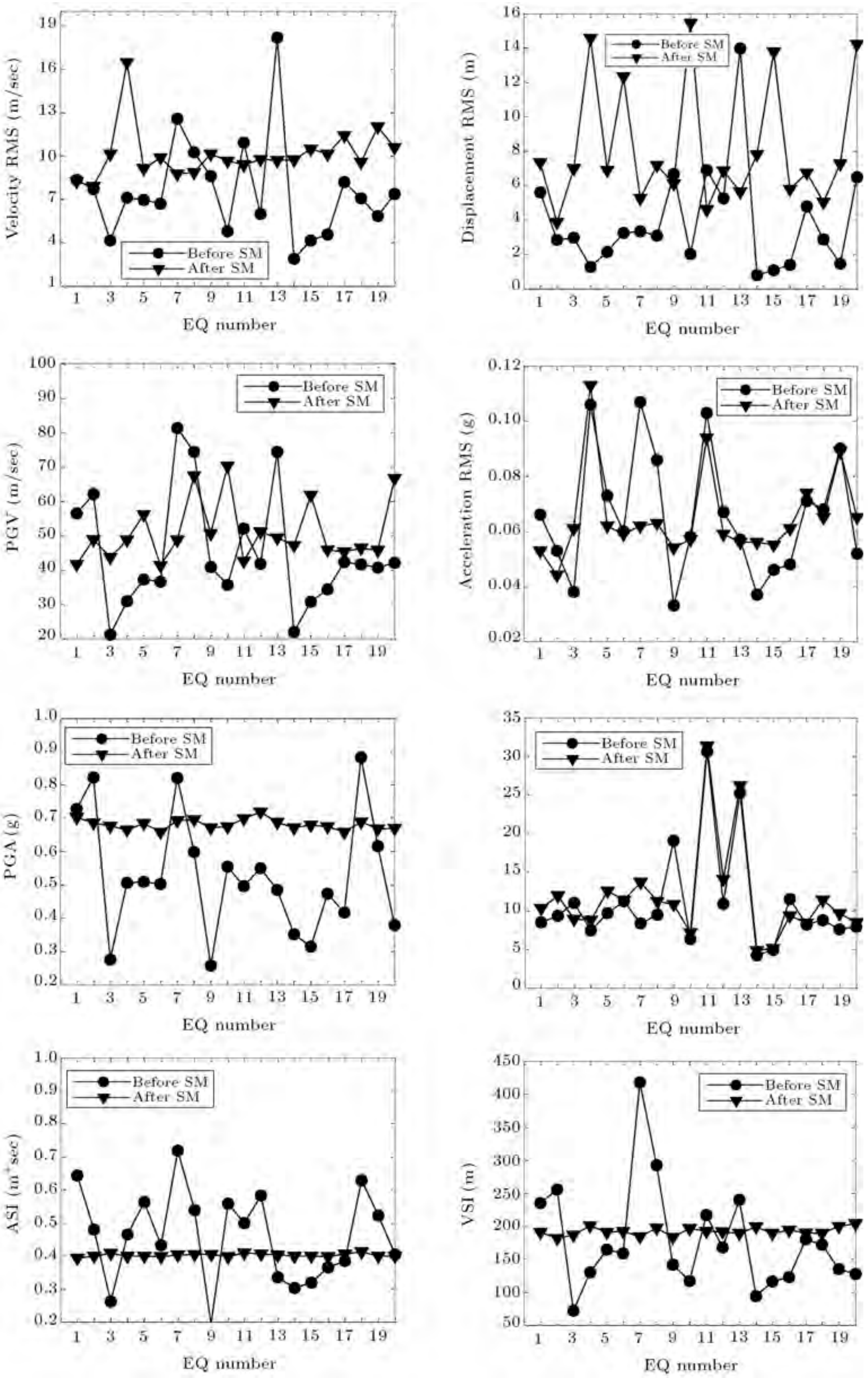

Figure 3. Ground motion parameters before and after spectrum matching.

6. Effect of spectrum matching on the variation of structural responses

Basically, researchers and practicing engineers are interested in assessing the effect of spectrum matching as an alteration in seismic input on the structural response. This section is focused on the results of performed nonlinear dynamic analyses of this study on a variety of reinforced concrete frames. Results of analyses indicate that spectrum matching reduces

Table 2. General properties used for design of the frames.

Design parameters	Design assumptions
Structural system:	
Reinforced concrete special moment frame (ACI 318-05)	
Seismic design level	IBC, design category D
Seismic framing system	Perimeter and space frames
Configuration:	
Building height	Stories: 1, 2, 4, 8, 12, 20
Bay width	20-30 feet
First story and upper story heights	15/13 feet
Element design:	
Concrete compressive strength	5-7 Ksi
Loading:	
Ratio of frame tributary areas for gravity and lateral loads ($A_{\text{grav}}/A_{\text{lat}}$)	0.1 (perimeter frame) - 1.0 (space frame)
Design floor dead load	175 Psf
Design floor live load	50 Psf
Assumed stiffness:	
Member stiffness assumed in design: Beams	0.5 EI_g
Member stiffness assumed in design: Columns	0.7 EI_g
Slab considerations	Slab not included in stiffness/strength design

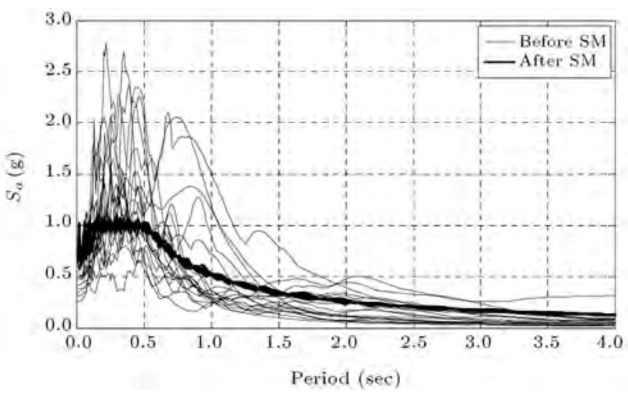

Figure 4. Acceleration spectra of original and spectrally matched records.

the variability of structural responses. For example, Figure 5 shows the maximum inter-story drift ratio of frame 1001 as a representative of analyzed frames, resulted from IDA, for all 20 records before and after spectrum matching. It is shown that the variability of responses has a significant reduction after spectrum matching, which verifies the obtained results of the study of Carballo and Cornell [5]. The intense approach of 16% and 84% fractiles toward the mean curve explicitly states this reduction, such that the difference of these two curves for a specific S_a (e.g. 1.5 g) diminished up to 70% after spectrum matching.

This significant decrease in the variability of responses indicates the major role of the shape of the response spectrum. This is especially true for higher mode effects in the vibration of tall buildings, or higher period effects in the vibration of significantly damaged buildings. Moreover, recent promotion of design codes have made buildings more ductile, which leads to extensive period elongation before collapse [3]. It is common in almost all the response spectra that an alteration of the period is accompanied by abrupt changes in spectral acceleration. However, spectrum matched accelerograms do not follow this rule, and any fluctuation in their spectral acceleration is thoroughly compatible with the shape of the target spectrum; it is even constant in some cases. This compatibilization of response and target spectra prevents the structure from experiencing a broad range of spectral accelerations and obliges it to follow the smooth trend of the target spectrum, as Figure 4 shows. This omission of fluctuations of spectral acceleration results in a reduction in the variability of structural response in the entire range of intensity measures, especially the inelastic range and collapse region. For example, Figure 6 shows a reduction in the variability of maximum inter-story drift in a whole range of IMs for frame 1021, excited by all 20 ground motion records, before and after spectrum matching.

In previous figures, it is shown that spectrum matching reduces the diversity of structural responses at high intensities. Now, it is still an important question as to how variability gets reduced in low intensity measures when the period of the structure is nearly constant. Figure 7 answers this question by

Table 3. General properties of the frames used in this study.

Frames	No. of stories	Framing system	First mode period (sec)	Second mode period (sec)	Mass participation Mode 1 (%)
2061	1	Space	0.42	-	-
2062			0.42	-	-
2063			0.42	-	-
2069		Perimeter	0.71	-	-
1001	2	Space	0.63	0.18	89.3
1001a			0.56	0.18	94.3
1002			0.63	0.18	89.3
2064		Perimeter	0.66	0.18	97.1
1003	4	Perimeter	1.12	0.33	89.5
1004			1.11	0.33	89.6
1008			0.94	0.30	91.5
1009		Space	1.16	0.35	90.6
1010			0.86	0.27	90.2
1011	8	Perimeter	1.71	0.54	87.4
1012		Space	1.80	0.60	87.8
1022			1.80	0.58	88.4
2065			1.57	0.51	88.2
2066			1.71	0.56	88.4
1023			1.57	0.51	88.2
1024			1.71	0.56	88.4
1013	12	Perimeter	2.01	0.68	86.3
1014		Space	2.14	0.72	87.4
1015			2.13	0.70	87.7
2067			1.92	0.63	87.6
2068			2.09	0.69	87.7
1017			1.92	0.63	87.6
1018			2.09	0.69	87.7
1019			2.00	0.67	87.4
1020	20	Perimeter	2.63	0.85	81.8
1021		Space	2.36	0.80	83.5

illustrating the inter-story drift ratio of frame 1021 at a spectral acceleration of 0.11 g. At this intensity level, the structure behaves almost linear; therefore, just the effects of higher modes are important on the structural response. As this figure shows, spectrum matching made the structural response of the story levels closer for different matched accelerograms. This is due to the fact that the response spectra of matched accelerograms are compatible at different periods, and hence, responses have little diversity. But structural responses are more scattered before spectrum matching because ground motions are scaled just at the fundamental period of the structure. Spectrum compatible accelerograms show the state of lower stories to be a little critical, while original ground motions make a worse situation for story 15, in addition to lower stories.

To compare the results more statistically, differences between maximum inter-story drift ratio obtained from spectrally matched records and original records are shown in Figure 8. Results for all frames are shown at two code seismic hazard levels; earthquakes with a 475-year return period (BSE1), and earthquakes with a 2475-year return period (BSE2). Frames are characterized by their fundamental periods. At these

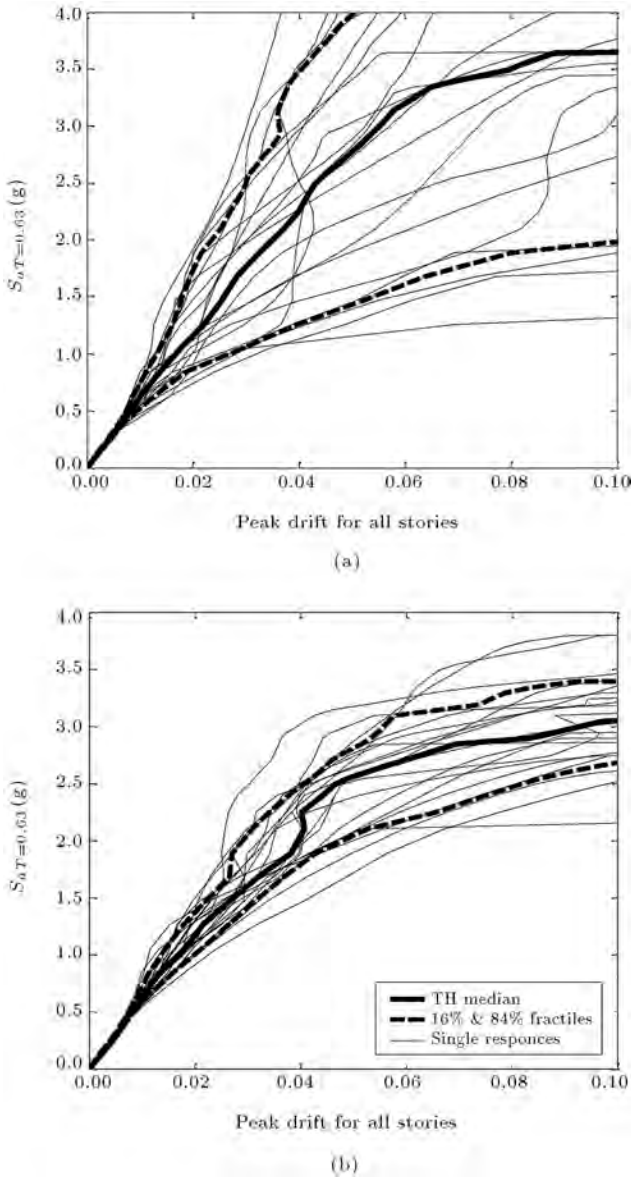

Figure 5. IDA curves of maximum inter-story drift ratio for frame 1001 resulted from records: (a) Before spectrum matching; and (b) after spectrum matching.

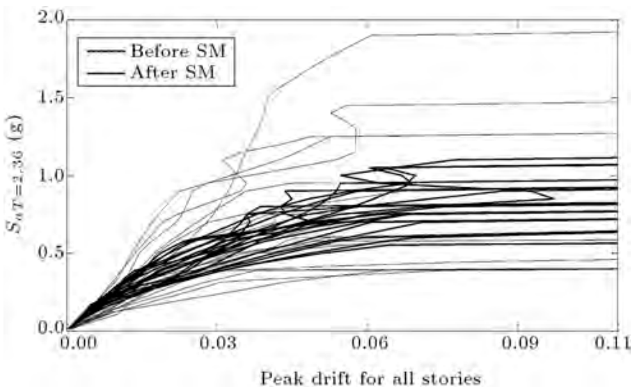

Figure 6. IDA curves of maximum inter-story drift ratio for frame 1021 resulted from records before and after spectrum matching.

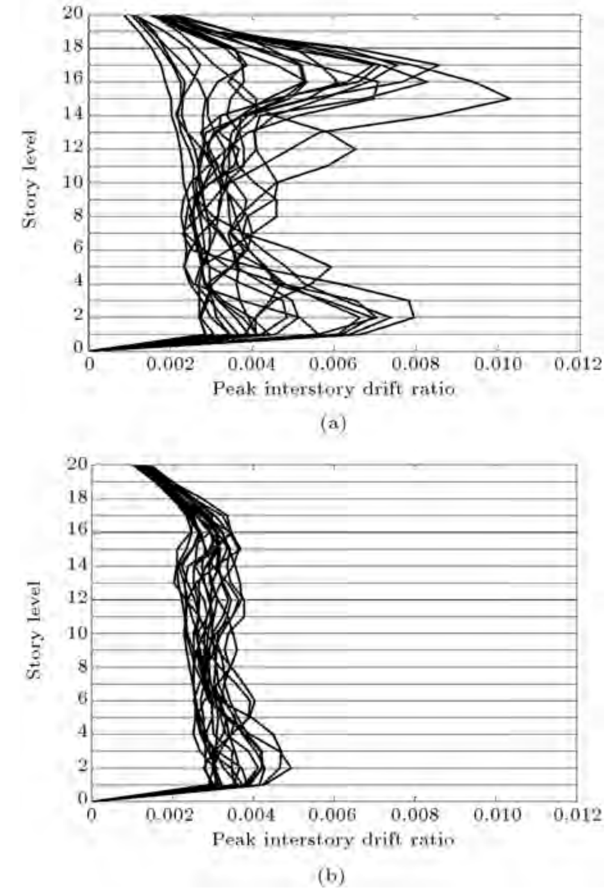

Figure 7. Maximum inter-story drift ratio at each story level for frame 1021 resulted from records: (a) Before spectrum matching; and (b) after spectrum matching at $S_a = 0.11$ g.

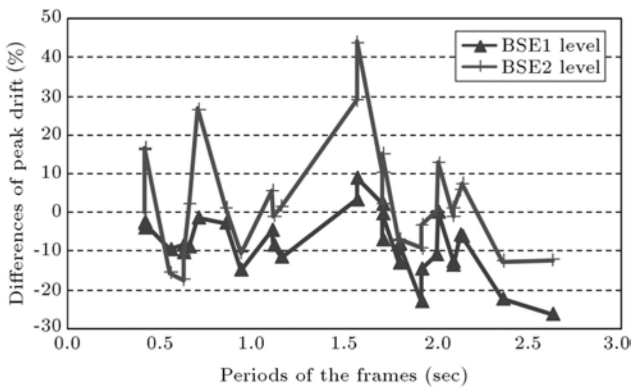

Figure 8. Differences of maximum inter-story drift ratio for all frames at BSE1 and BSE2 levels before and after spectrum matching.

levels of excitation, there is not a distinct trend in this figure and spectrally matched records overestimate and underestimate at different ranges of fundamental periods. In the BSE1 level, maximum inter-story drift ratios obtained for matched records are less than original records in most frames, however in the BSE2 level, there is a balanced distribution of larger and

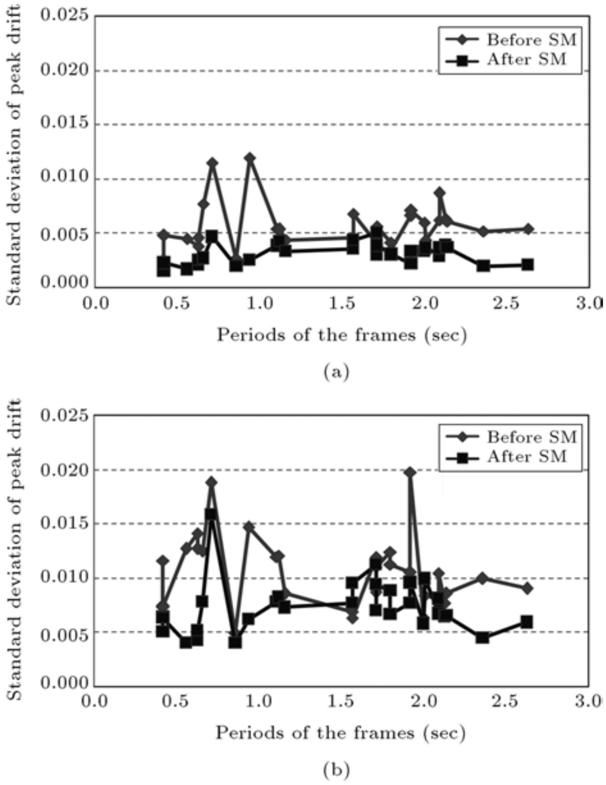

Figure 9. Standard deviation of maximum inter-story drift ratio for all frames before and after spectrum matching: (a) BSE1 level; and (b) BSE2 level.

fewer values. Generally, it can be judged that by increasing the seismic hazard level from BSE1 to BSE2, differences of maximum inter-story drift ratio increase in a positive trend.

Figure 9 compares the standard deviation of maximum inter-story drift ratio for all frames before and after spectrum matching. This comparison is done for BSE1 and BSE2 levels. In all frames, standard deviations of the results are reduced after spectrum matching. Also, increasing the seismic hazard level from BSE1 to BSE2 amplifies the variation of the results. Again, a general trend cannot be found for different frames and their fundamental periods.

7. Comparison of IDA curves

This section provides a comparison of structural response to IDA. Owing to the improvement of computer processors, the-state-of-the-art in structural analysis moved from elastic static analysis to non-linear dynamic analysis. Incremental dynamic analysis is a comprehensive set of single non-linear time history analyses, each of which is performed under incremental scaled ground motion records [23]. The output of such an analysis is a curve that represents the intensity measure versus engineering demand parameter that covers a broad range of intensity measures from elastic to non-linear and, finally, the collapse of the structure. The concept of this analysis is initially developed by Bertero and has been used by a variety of researchers, including Luco and Cornell, Bazzurro and Cornell, Yun and Foutch, Mehanny and Deierlein, Dubina et al., De Matties et al., Nassar and Krawinkler and Psycharis et al. [23].

This analysis has been conducted for all 30 reinforced concrete moment resisting frames, and the results are presented in Figure 10. Several researchers have noted that spectrum matched accelerograms demonstrate the unconservative bias of the median nonlinear response of the structure, owing to the fact that the response spectrum of original ground motions contains several peaks, which lead to a larger than median response in comparison with those spectrum matched [4,5]. However, the results of performed IDAs in this study show various trends of structural response. It is shown that median responses of all the frames have reasonable compatibility in the linear region before and after spectrum matching, except 20-story frames. Interestingly, the structural response of the nonlinear region is too diverse and does not comply with the mentioned studies. Spectrum matching makes a conservative bias in the structural response of 17 low-rise frames. Ten frames out of a total of 15 high-rise frames (8- and 12-story) showed a comparable compatibility of the median of structural response before and after spectrum matching. Three remaining frames, which are also high-rise, present an unconservative deviation of structural response after spectral matching. All in all, Figure 10 illustrates the increasing trend of the structural response of spectrum matched accelerograms.

8. Effect of spectrum matching on collapse performance of frames

Traditionally, the collapse potential of buildings was associated with parameters like roof or inter-story drift. Since the assessment of such parameters in the vicinity of the collapse point is very sensitive to many factors, such as type of elements used in the structural model and even the computer program employed for analysis, the collapse potential is defined based on spectral acceleration in which the structure becomes dynamically unstable. The Cumulative Distribution Function (CDF) of these spectral accelerations, with an assumption of log-normal distribution, forms the concept of the collapse fragility curve [24]. Despite there is no justification in the literature for the log-normal distribution function, it is known that the seismic response of nonlinear structures may fit a log-normal distribution [25]. Additionally, the distribution of collapse capacity demonstrates a long upper tail, which suggests that log-normal distribution may be a

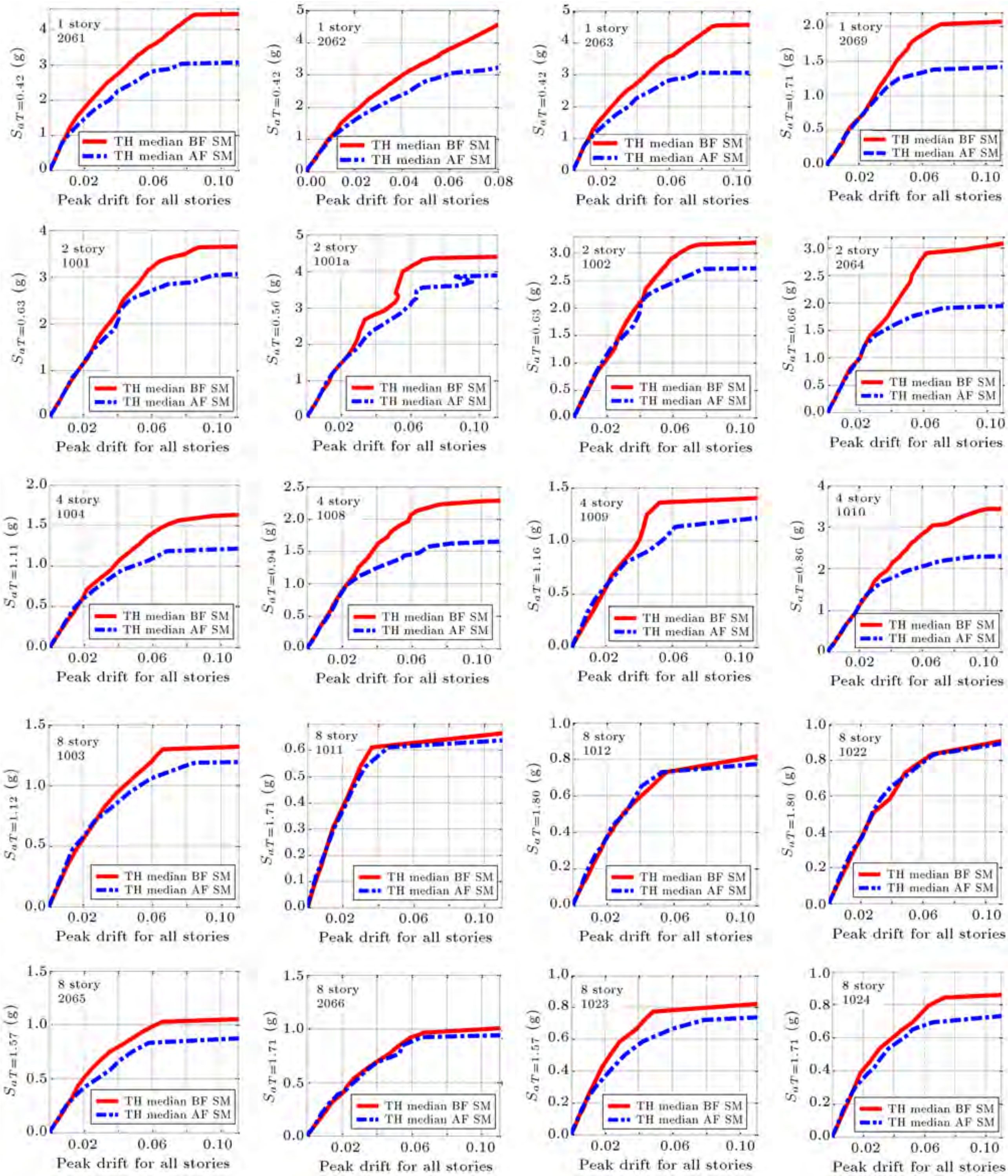

Figure 10. Median IDA curves of maximum inter-story drift ratio for frames resulted from records before and after spectrum matching.

good choice for drawing the cumulative distribution function. Furthermore, Ibarra has manipulated the Kolmogorov-Smirnov goodness-of-fit test, as well as the Log-Normal probability paper, in order to investigate how well this distribution model fits the obtained collapse capacity data [21]. He has tested a variety of systems with low, intermediate and high ductile characteristics, as well as flexible and stiff frames, and concluded that log-normal distribution is well fitted to the collapse capacity data. Therefore, this research does not examine any other distribution model and utilizes log-normal distribution.

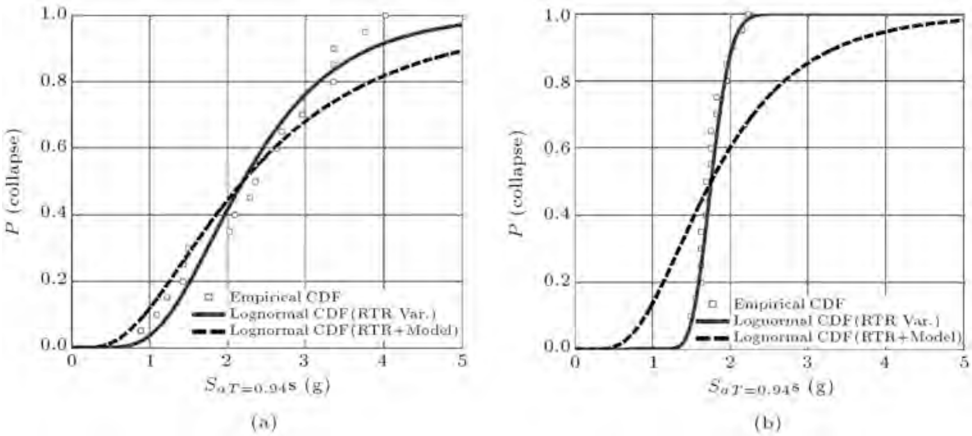

Figure 11. Fragility curve of frame 1008 for records: (a) Before spectrum matching; and (b) after spectrum matching

Modeling uncertainties are important parameters which are categorized as epistemic uncertainties (associated with lack of knowledge) and directly influence fragility curves. These parameters can be taken into account in drawing collapse fragility curves. Haselton has performed various nonlinear analyses on reinforced concrete structures in order to find the appropriate measure of modeling uncertainties [3]. This study has followed his research by utilizing the mean estimate method and increased the dispersion of the fragility curve by a value of 0.5.

It is mentioned that spectrum matching reduces the variation of structural response in a whole range of IMs. So, it is also expected to have a similar trend in collapse points. Figure 11 illustrates the fragility curve of frame 1008, with collapse IMs on the horizontal axis, corresponding to a peak inter-story drift ratio of 0.18 for original and spectrum matched records. Each figure contains two Cumulative Distribution Functions (CDF) with log-normal distribution. The solid line accounts for the probability of collapse, with mean and standard deviation of Record To Record (RTR) variability, and the dashed line is the log-normal CDF containing RTR and the additional variability of modeling uncertainties. The total uncertainty is calculated by Square-Root-of-the-Sum-of-Squares (SRSS) of RTR and modeling uncertainties.

As expected, spectrum matching caused a significant reduction in the variability of IM in which structural collapse occurs. Original records have a range of collapse points from 0.89 g to 4.03 g, when it ranges from 1.49 g to 2.23 g for spectrum matched records, such that the fragility curve tends toward a vertical line. Figure 11 shows that including modeling uncertainties has a negligible effect on the fragility curve because RTR variability substantially covers a spread range of dispersion in the original records. However, spectrum matching causes a significant difference between the two mentioned distributions on its extreme tails, as a consequence of the lower standard deviation of spectrum matched records. It should be pointed out that increasing the dispersion of the fragility curve by the value of 0.5 for spectrally matched ground motions results in the approaching of the curve towards a fragility curve obtained from real accelerograms. It demonstrates that considering modeling uncertainties for spectrum matched ground motions leads to obtaining similar results in comparison with real accelerograms.

Predictions of collapse probability at different IMs are different for original records and spectrally matched records. For example, frame 1008 totally collapsed on the IM of 2.23 g for matched records, when original records have 50% probability of collapse in similar IM. However, for lower IMs, this is vice versa, and the collapse probability of matched records is less than that obtained for original records.

To better investigate the collapse probability of the frames, fragility curves of six frames for original and spectrum matched records are compared in Figure 12. It is shown that the fragility curve of spectrally matched ground motions for frames with lower periods predict the collapse probability highly conservative. For example, the fragility curves of the frame with a period of 0.42 sec demonstrate a deviation of 40% in the mean prediction of collapse. As the period of structure increases, both fragility curves get closer, such that for a frame with a period of 1.71 sec, they are reasonably compatible with each other. This trend leads to unconservative prediction of collapse for tall buildings with high periods.

9. Conclusion

In this paper, the seismic structural response of a comprehensive set of reinforced concrete moment resisting frames was assessed using real accelerograms and spectrally matched ground motions. Also, changes of ground motion parameters, due to the spectrum matching, were investigated.

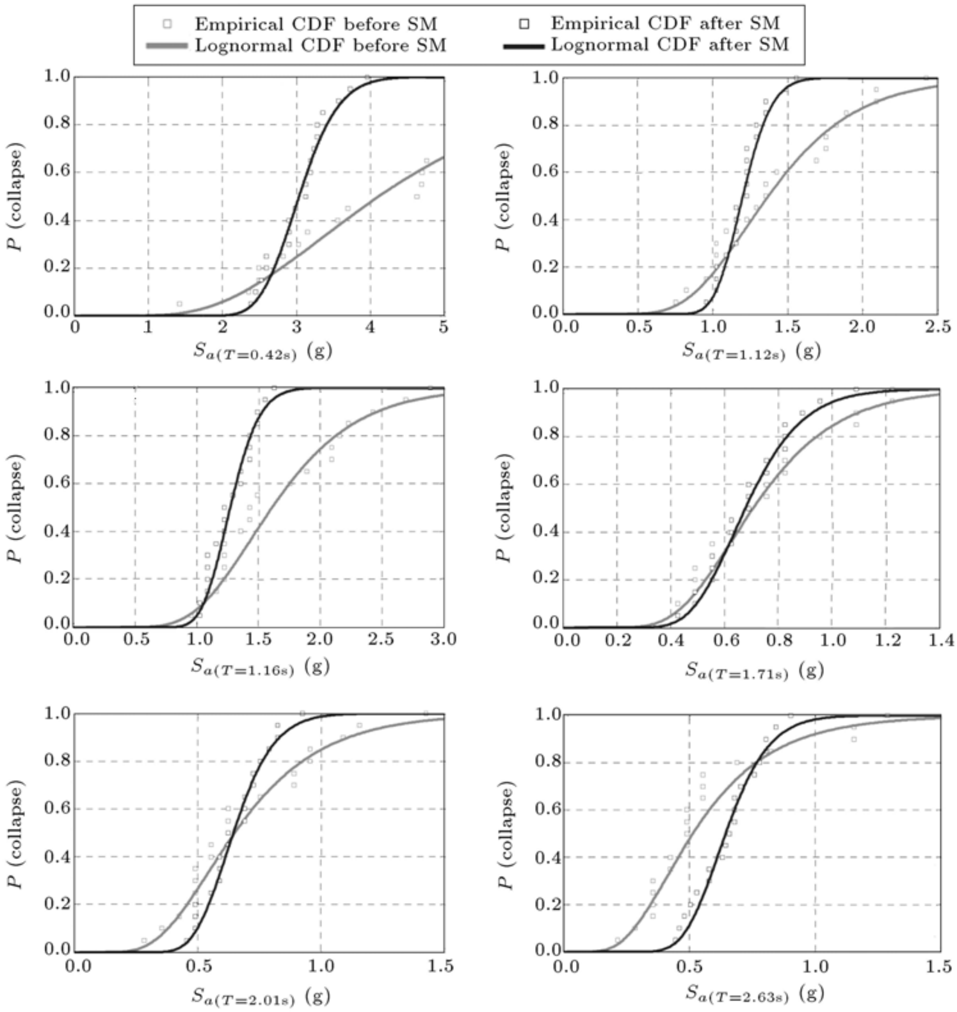

Figure 12. Comparison of fragility curves of six frames for original and spectrum matched records.

Comparison of ground motion parameters before and after spectrum matching showed that PGA, ASI, VSI and the root mean square of velocity values were changed to fixed values after spectrum matching. But, values of significant duration and the root mean square of acceleration almost remained unchanged after spectrum matching.

Spectrum compatibilization effectively decreased the variation of structural response in the entire range of intensity measures, which indicates the major role of the response spectrum shape in the performance of structures. However, the measure of observed bias thoroughly depends on the height of the structure.

The median response of most of the frames had reasonable compatibility in the linear region before and after spectrum matching. The majority of former research has shown an unconservative bias in the response of structures in the nonlinear range that are analyzed by spectrum matched ground motions. On the contrary, this paper indicates that this is not a general trend, and structural response is directly related to the height of the structure. Most low-rise structures have a conservative structural response. Increasing the height of the structure results in coincident responses for mid-rise and an unconservative bias for high-rise buildings.

Nonetheless, it was approved that spectrum matching generally leads to a considerable reduction in the variation of structural response in collapse prediction. Moreover, it was shown that spectrum matching makes significant changes in the shape of the fragility curve, such that it approaches a vertical line. However, interestingly, considering the effect of modeling uncertainties results in obtaining a comparable curve to that yielded from real accelerograms. It implies that it is possible to lessen the huge amount of calculations needed for IDA by the procedure of spectrum matching, and ultimately obtains a reasonable fragility curve by increasing the dispersion due to modeling uncertainties.

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Biographies

Hossein Tajmir Riahi is the Assistant Professor of Civil Engineering at University of Isfahan (UI), Isfahan, Iran. He received his PhD in Civil Engineering from Sharif University of Technology, Tehran, Iran, in 2009. He is a member of the Iranian Construction

Engineers Organization. His research interests include a broad area of topics in Structural and Earthquake Engineering with a special focus on the design and performance of seismic resistant structures and design of bridges and special structures. He regularly teaches Mechanics of Materials, Earthquake Resistant Design of Structures and Dynamics of Structures at UI. In recent years, his research interests mainly focus around the development of "Endurance Time Method" and Performance Based Design of Structures, the area in which he has published research articles in collaboration with Professor Estekanchi and Professor Vafai and his students.

Hamed Amouzegar was born in 1988. He is the graduate research assistant at the University of Massachusetts Dartmouth. He earned his BSc in Civil Engineering from Shahid Chamran University of Ahvaz, in 2011. He then attended University of Isfahan where he was awarded MSc in Structural Engineering in 2013. His research was based on the Seismic Analysis of Structures by evaluation of the "Endurance Time Method" on reinforced concrete structures. This method was compared to the nonlinear dynamic analysis method at different seismic levels. Currently, he is working on investigation of the stability of cold-formed, thin-walled structures by consideration of their imperfection geometries.

Saber Ale Saheb Fosoul was born in 1987. He earned a BSc degree in Civil Engineering from the University of Isfahan, in 2011, and currently, he is the student of MSc in Structural Engineering at University of Isfahan, Isfahan, Iran. His MSc thesis is entitled "Evaluation of effective hysteretic parameters in seismic performance of reinforced concrete moment resisting frames" that is focused on the sensitivity of seismic performance of reinforced concrete frames to the variations in seismic excitations and modeling uncertainties with innovations in the procedure of record selection. He is the member of the Iranian Concrete Institute. His research interests include Performance Based Earthquake Engineering, Seismic Reliability of Structures, Collapse Assessment of Structural Systems, Ground Motion Selection and Modification and Structural Health Monitoring. He is regarded as the co-translator of a book entitled "Random Vibration of Structures" into Persian.