Seismic Responses of RC Frames under Wavelet-Based Matched Accelerograms and Real Records

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SUMMARY:
Continuous wavelet transform has recently been used in matching response spectrum of real strong ground motions with design spectrum. As a new method for generation of spectrum compatible accelerograms, practical application of this approach needs more studies on seismic responses of structures under matched records. In present study, spectrum compatible accelerograms are generated by wavelet-based complete and partial matching procedures. Strong ground motion parameters of matched records are investigated first. Next, mean and variation of nonlinear seismic responses of two reinforced concrete (RC) special moment frames are investigated under the matched accelerograms and real records. Seeking maximum compatibility of mean response spectrum and design target, real records are selected by harmony search optimization algorithm. According to the results, when matching period interval involves fundamental nonlinear period of the structures, seismic responses have good agreement under matched and real records. It is also shown that the matching procedure is able to reduce variation of inter-story drifts in order to improve overall seismic response of structures.

Keywords: Wavelet Transform, Spectrum Matching, Harmony Search, Nonlinear Analysis

1. INTRODUCTION

Seismic analysis of linear structures can be carried out by equivalent static procedure or spectral analysis. These analysis procedures are simple and straightforward, but they are limited to regular and ordinary buildings. Meanwhile, seismic analysis of irregular or important structures must be carried out by linear or nonlinear time history analyses. Such analyses require some accelerograms as input seismic excitation as representative of expected strong ground motion in the site. As the legal seismic excitation in the well-known codes are introduced in terms of smooth design spectra given for each region and soil type, the required input records for time history analysis should be compatible with such standard spectra. These strong ground motion accelerograms can be chosen from artificial records generated by stochastic procedures, synthetic records generated by seismological models and/or modified or scaled real accelerograms.

In the stochastic approach, artificial records are generated by summation of sine waves with random phases. Main deficiency of this method is lack of constraints on records in the time domain leading to unrealistic accelerograms with excessive energy content and too many numbers of cycles [1]. Seismological models take into account the seismological source parameters, the path seismic waves travel through and local site effects. Although these models are developed based on wave propagation theories, they require thorough information on faulting mechanism, tectonic setting and geologic conditions of site rarely known in practical cases. In using real records, if the frequency content of the accelerograms does not experience significant changes in scaling or modification procedure, overall characteristics of the employed real accelerograms will remain stable. Adjusting approaches can be classified into amplitude scaling, time domain modification, frequency domain modification and time-frequency domain modification. Among the time-frequency domain methods, continuous wavelet transform (CWT) has been recently received attention in generation of spectrum compatible accelerograms [2]. Such an approach, hereinafter called wavelet-based spectrum matching, WBSM, is almost new in earthquake engineering, and uses wavelet transform as a novel mathematical tool. Hence, its practical application seems to require more studies on characteristics of wavelet-based matched records and on the seismic response of structures under generated records. In this way, Bahar and Taherpour [3] used WBSM to obtain complete and partial spectrum-matched acceleration records and used them to evaluate seismic responses of a special moment resisting RC frame under the matched records. They emphasized the importance of the effective frequency domain of the structure as matching interval.

In present study, our focus is on characteristics of records with complete- and partial-matched spectrum using WBSM method and on seismic responses of RC frames under the matched accelerograms and unmatched real records. In this way, first, 20 accelerograms, including near- and far-field records of low- and high-magnitude events, are matched on design spectrum in complete and partial WBSM procedures. Strong ground motion characteristics of matched records are discussed in detail. Next, harmony search, HS, optimization algorithm is specialized for selection of a 20-record set of real accelerograms seeking closest average response spectrum to the design target. Seismic performances of 4- and 12-story special moment resisting RC buildings are evaluated under matched and real records by nonlinear time history analysis. Mean and variation of seismic responses are discussed to explore application aspect of WBSM approach. Design spectrum of Iranian Standard No. 2800 [4] for soil type III and very high seismic risk region is used as target.

2. WAVELET-BASED SPECTRUM MATCHING AND OPTIMAL SELECTION OF REAL RECORDS

Main properties of a wavelet function are oscillatory nature and localized energy (say amplitudes) in time and frequency domain. Wavelet transform of $f(t)$ with the wavelet $\psi(t)$ can be defined as:

$$C(s,p)=\int_{-\infty}^{+\infty} f(t)\ \overline{\psi}_{s,p}(t)\ dt \ , \tag{2.1}$$

in which s denotes the shift parameter and represents frequency content of signal, and p called the shift parameter contains temporal data of transformation. $\psi_{s,p}(t)$ is obtained by translation and scaling of the mother wavelet $\psi(t)$ as follows:

$$\psi_{s,p}(t)=\frac{1}{\sqrt{|s|}}\psi\left(\frac{t-p}{s}\right) , \tag{2.2}$$

The bar symbol, $\bar{\ }$, above $\psi_{s,p}(t)$ in Eqn. 2.1 stands for complex conjugate. The function $f(t)$ can be reconstructed from its wavelet coefficients as:

$$f(t)=\frac{1}{K}\int_{0}^{+\infty} D(s,t)ds \tag{2.3}$$

where $D(s,t)$, called detail functions, are as follows:

$$D(s,t)=\int_{-\infty}^{+\infty} \frac{1}{s^2}C(s,p)\psi_{s,p}(t)dp \tag{2.4}$$

Before mapping the function $f(t)$ from the time-scale representation to the time domain representation, wavelet coefficients can be adjusted for a special target. This potential is used in WBSM for matching the response spectrum of the accelerogram on the design spectrum. Various mother wavelets have been introduced in literature [2] for this purpose. In the present research, the impulse response wavelet proposed by Suarez and Montejo [2] is used, defined as:

$$\psi(t) = e^{-\zeta \Omega |t|} \sin \Omega t \tag{2.5}$$

Being analogous to damping ratio and natural frequency of an SDOF oscillator, ζ and Ω control decay and temporal variation of the wavelet, respectively. The recommended values of $\zeta = 0.05$ and $\Omega = \pi$ in [2] are applied here. A discretized version of the wavelet transform can be applied in WBSM. In this case, scale parameter is discretized on a logarithmic grid as:

$$s_j = 2^{\frac{j}{v}} \tag{2.6}$$

that j takes integer values and v controls the density of the grid. The value of $v = 8$, recommended in [2], is applied in the present study. Limits of j can be determined by the desired period limits. The dominant frequency of detail function $D(s_j, t_i)$ is:

$$\omega_j = \frac{2\pi}{T_j} = \frac{\Omega}{s_j} = 2^{\frac{-j}{v}} \Omega \tag{2.7}$$

Having another look at Eqns. 2.3 and 2.4 reveals that by determining detail functions of an accelerogram, a signal will be decomposed to a series of time histories each having a known dominant frequency. In WBSM procedure, the response spectrum of accelerogram must be determined at period values T_j first. A value of 0.05 is chosen for the damping ratio ordinarily. Next, an adjusting measure must be introduced for modification of detail functions. The adjustment coefficients can be simply defined by the ratio of the spectral values in the target spectrum and those in response spectrum of the reconstructed accelerogram. If WBSM is carried out for pseudo-spectral acceleration values, adjusting coefficients are as follows:

$$\gamma_j = \frac{[PSA(T_j)]_{target}}{[PSA(T_j)]_{reconstructed}} \tag{2.8}$$

in which the $[PSA(T_j)]_{target}$ and $[PSA(T_j)]_{reconstructed}$ are spectral acceleration values at period T_j in the target spectrum and the response spectrum respectively. The detail functions are multiplied by adjusting coefficients, γ_j. Adjusted accelerogram is obtained using a discrete form of Eqn. 2.3. In complete matching WBSM, the response spectrum matches with the design spectrum in all periods, and adjusting coefficients are determined by Eqn. 2.8, but partial matching WBSM is done only for periods within a prescribed range, and so, adjusting coefficients for periods outside this range can be taken as unity to leave the frequency content of accelerogram undisturbed beyond the matching period interval.

Adjusting the detail function $D(s_j, t_i)$ alters the spectral values not only at dominant period of the detail function T_j, but also at the other periods specially those adjacent to the dominant period. Hence, the mentioned procedure for WBSM must be implemented iteratively until an acceptable level of matching between response and target spectra is achieved. For this purpose, after reconstruction of the adjusted accelerogram, its response spectrum is determined and the values of adjusting coefficients are updated. The detail functions will be adjusted and new adjusted accelerogram will be obtained. To quantify the spectrum-compatibility state, the matching error can be defined as the square root of mean of squared error values in discrete period points as:

$$Error(\%)=\sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(\frac{[PSA(T_j)]_{target}-[PSA(T_j)]_{reconstructed}}{[PSA(T_j)]_{target}}\right)^2}\times 100 \tag{2.9}$$

This procedure is continued until satisfying the matching criterion or reaching a predefined number of iterations. In this study, WBSM procedure is implemented for modification of 20 records in 4 matching period intervals. Initial accelerograms are selected from PEER NGA Database [5] from records of events with moment magnitude ranging from 5.5 to 7.5 and source-to-site distance (closest distance to fault rupture) ranging from 15 km to 100 km. Average shear wave velocity over 30-meter-depth top layer of soil for stations of these records lies in the range 175 m/sec to 375 m/sec (soil type III according to [4]). Table 2.1 shows some characteristics of the records.

Table 2.1. Characteristics of seed accelerograms in WBSM procedure

Rec. No.	Event	Date	Station	M_w	Distance (km)	V_{s30} (m/s)	Comp-onent
1	Whittier Narrows-01	1987/10/1	Santa Fe Springs - E.Joslin	6.0	18.5	309	318
2	Victoria, Mexico	1980/6/9	Chihuahua	6.3	19.0	275	102
3	Coalinga-01	1983/5/2	Cantua Creek School	6.4	24.0	271	360
4	N. Palm Springs	1986/7/8	San Jacinto - Soboba	6.1	23.3	371	000
5	Mammoth Lakes-01	1980/5/25	Long Valley Dam (Upr L Abut)	6.1	15.5	345	090
6	Friuli, Italy-01	1976/5/6	Conegliano	6.5	80.4	275	270
7	Dinar, Turkey	1995/10/1	Cardak	6.4	44.2	339	256
8	Coalinga-01	1983/5/2	Parkfield - Fault Zone 1	6.4	42.0	339	000
9	Morgan Hill	1984/4/24	Los Banos	6.2	63.2	271	180
10	Sierra Madre	1991/6/28	Tarzana - Cedar Hill A	5.6	48.2	257	000
11	Tabas, Iran	1978/9/16	Boshrooyeh	7.4	28.8	339	L1
12	Northridge-01	1994/1/17	LA - Centinela St	6.7	28.3	235	155
13	Kobe, Japan	1995/1/16	Kakogawa	6.9	22.5	312	090
14	San Fernando	1971/2/9	LA - Hollywood Stor FF	6.6	22.8	316	090
15	Landers	1992/6/28	Yermo Fire Station	7.3	23.6	354	270
16	Northridge-01	1994/1/17	LA - 116th St School	6.7	41.2	301	090
17	Landers	1992/6/28	Boron Fire Station	7.3	89.7	345	000
18	Cape Mendocino	1992/4/25	Eureka - Myrtle & West	7.0	42.0	339	090
19	Tabas, Iran	1978/9/16	Ferdows	7.4	91.1	275	T1
20	Imperial Valley-06	1979/10/15	Coachella Canal #4	6.5	50.1	345	135

Table 2.2. Matching Period Range Limits for All Intervals

Matching Interval	j_{min}	j_{max}	T_{min}(sec)	T_{max}(sec)
I_1	-51	11	0.0241	5.1874
I_2	-29	-13	0.1621	0.6484
I_3	-12	11	0.7071	5.1874
I_4-C_{04}	-33	-10	0.1128	0.8642
I_4-C_{12}	-23	-1	0.2572	1.9290

Wavelet coefficients and detail functions of selected records are determined in period range 0.0241 sec to 5.1874 sec. The range covers the band of effective periods for low-, mid- and high-rise structures in earthquake engineering applications. Matching interval I_1 covers the same period range used in decomposition of accelerograms. Interval I_2 represents the constant acceleration range of design spectrum which for soil type III, includes periods from 0.15 sec to 0.7 sec. Interval I_3 covers the last branch of design spectrum known as high-period range. Interval I_4 is the period range recommended in [4] for scaling of accelerograms and is defined as $0.2T_{structure} < T < 1.5T_{structure}$. $T_{structure}$ is the fundamental period of the structure based on provisions of [4], determined by analytic methods or experimental relations. Hence, endpoints of interval I_4 are dependent on fundamental period of the structure on which the matched records will be applied and differ from one structure to another. As in this study two RC frames are analysed under matched records, to distinguish interval I_4 for these frames, the code of interval is followed by the frame codes. C_{04} and C_{12} are the codes used for 4- and 12-story frames respectively. Table 2.2 shows the values of parameter j for definition of scale parameter and matching period range limits for matching intervals. Target spectrum for WBSM as shown in Fig. 2.1 is the design spectrum of Iranian Standard No. 2800 [4] for soil type III and very high seismic risk region (design base acceleration of 0.35g).

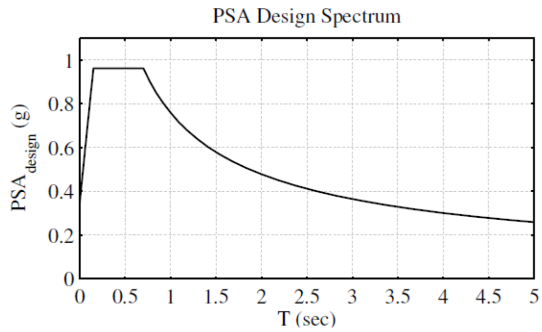

Figure 2.1. Design Spectrum of [4] for Soil Type III and Very High Seismic Risk

For comparison of seismic responses of RC frames under matched and real records, a procedure based on harmony search (HS) algorithm is implemented for selection of a 20-record set of real accelerograms seeking closest mean response spectrum to design one as detailed in [6]. In this study, a database of 196 records of 26 earthquakes with moment magnitude from 5.5 to 7.5, epicentral distance from 15 km to 100 km and site soil type III is collected from PEER NGA database [5] as seed accelerograms in HS algorithm. Fig. 2.2 shows the mean response spectrum of selected records and response spectrum of individual records of the set as well as design spectrum for the frames C04 and C12. Vertical green lines represent the scaling period limits for the frames.

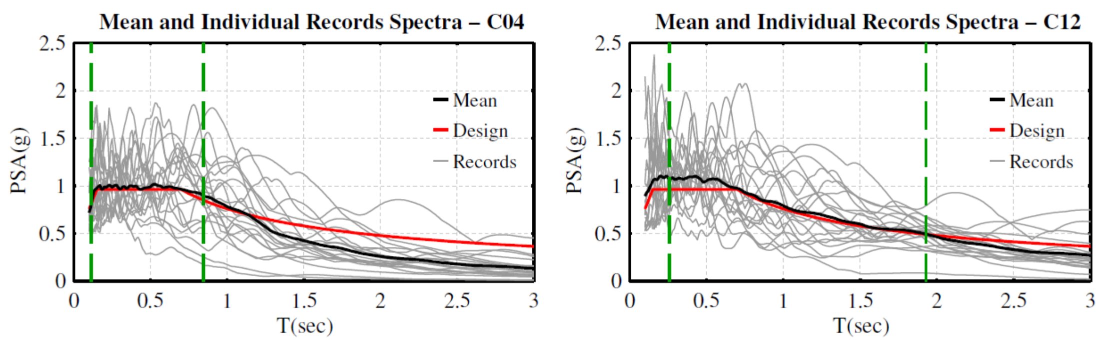

Figure 2.2. Mean Response Spectrum of Selected Records in HS Algorithm for 4 and 12 Story Frames

3. STRONG GROUND MOTION CHARACTERISTICS OF MATCHED ACCELEROGRAMS

Fig. 3.1 shows the PGA of records before and after matching in various intervals. PGA of original records are different in various records, and range from 0.06g in record 9 to 0.47g in record 12. After matching, minimum value of PGA is about 0.29g, and occurs in record 3 in matching interval I_2, and maximum value of PGA is about 0.61g, and occurs in record 4 in matching interval I_3. PGA values in other cases are generally within the range 0.35g to 0.45g. As can be seen, PGA values don't show sensitivity to matching period range and don't have a relevant relation with matching intervals.

Fig. 3.2 shows the peak ground velocity of accelerograms before and after matching process. In spite of PGA parameter, PGV has low sensitivity to high-frequency content of accelerogram, and represents the intensity of ground shaking in medium frequencies better than that PGA does. As realized from Fig. 3.2, PGV is highly correlated with low-frequency content of records so that matching of records in intervals I_1 and I_3 has increased the peak ground velocity of records significantly. Such an increase is seen for records matched in interval I_4-C_{12}, slightly lower than the increase for intervals I_1 and I_3.

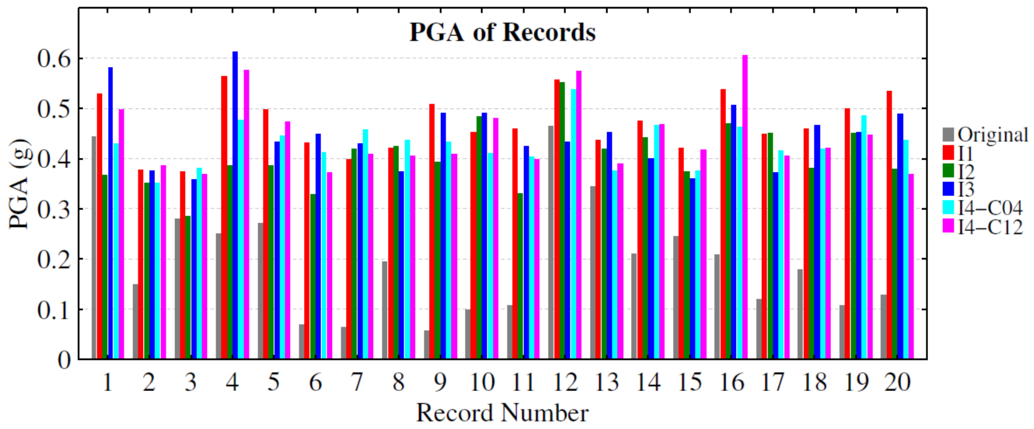

Figure 3.1. Peak Ground Acceleration of Records before and after Matching in Various Intervals

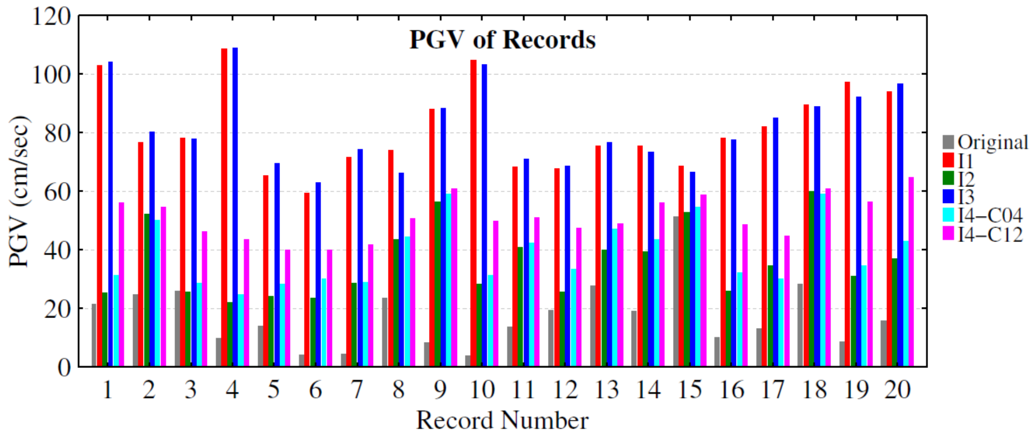

Figure 3.2. Peak Ground Velocity of Records before and after Matching in Various Intervals

Duration in addition to amplitude and frequency content is a meaningful predictor of performance in structures whose response is governed by damage that accumulates during earthquake. Here, significant duration, as defined by Trifunac and Brady [7], is evaluated in matched records as shown in Fig. 3.3. Generally, variation of duration through WBSM procedure is relatively low for intervals I_2 and I_4-C_{04} while matching in intervals I_1, I_3 and I_4_C_{12} have increased the duration of records significantly. For all of the records, maximum values of duration correspond to matching periods I_1 or I_3. In other words, as the matching interval tends toward high periods, matching procedure leads to increase of the record duration. This fact shows sensitivity of duration to low frequency components of the records. Additionally, for some records such as records 7 and 18 that had relatively intense low-frequency content before matching, WBSM procedure does not altered duration significantly. It can be concluded that implementation of WBSM procedure on records with weak low-frequency content may cause significant changes in duration. Hence, for structures whose performance is sensitive to duration of excitation, WBSM procedure should be used with caution. It is worth noting that the PGA despite other studied strong ground motion parameters of the matched records, which imply excessive energy content of matched records in intervals I_1, I_3 and I_4-C_{04}, have not high values in intervals including low frequencies. This fact rises from close correlation of PGA values with high-frequency components of the accelerograms.

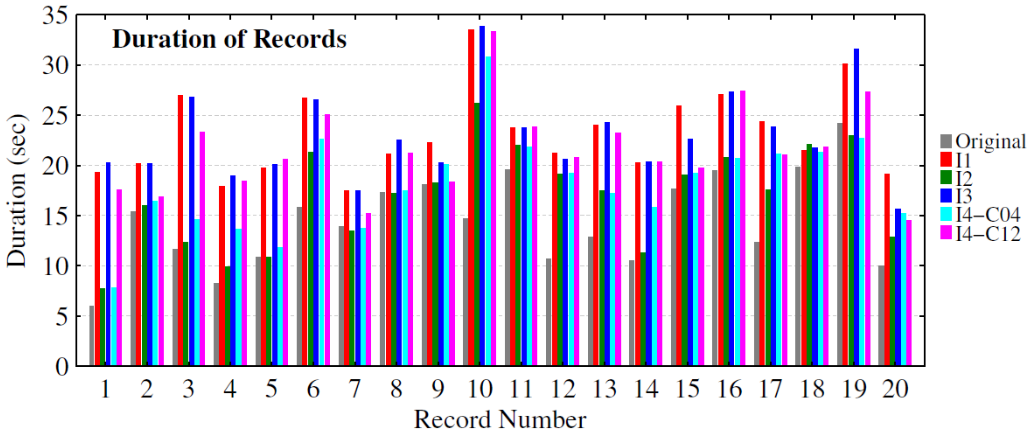

Figure 3.3. Duration of Records before and after Matching in Various Intervals

4. INELASTIC TIME HISTORY ANALYSIS OF RC FRAMES

Studied structural models include two 4- and 12-story special moment RC frames. Each frame has two 6-meter-width bays and story height of 3m in all cases. The frames are designed by direct displacement-based design method in [8]. Nonlinear analysis of frames is carried out by OpenSEES software [9]. Table 4.1 shows the properties of concrete and reinforcing steel used in structural models. Dead and live loads in all stories are 540 kg/m^2 and 200 kg/m^2 respectively. Gravity load is distributed assuming two-way slabs for story floors. "Nonlinear Beam Column" element having distributed plasticity along length is used in OpenSEES software for beams and columns. All beam-to-column connections are rigid, and P-Δ effects are considered in the analysis. Note that in the following charts, mean and mean ± one standard deviation of seismic responses under matched records are shown by notations "Mean WBSM" and "Mean WBSM±1σ" respectively. Similar notation is used for seismic responses under real records selected by HS.

Table 4.1. Properties of Concrete and Reinforcing Steel in Structural Models

Parameter	f'_c	E_c	ρ	f_y	f_{ys}	E_y
Value	35 MPa	27800 MPa	2.4 t/m^3	450 MPa	350 MPa	200000 MPa

Fig. 4.1 shows the inter-story drift ratios for frame C_{04}. Values of drift ratios are concordant in the matched records in intervals I_1 and I_3 with the corresponding values under real records. Reduction of standard deviation of drift ratios in these intervals shows that WBSM can generate records with similar effects on structures. In interval I_2 drift ratios under matched records are less than those under real records. This results from not explicitly including fundamental period of structure and shows the importance of this fact. In interval I_4 drift ratios under the matched records are less than corresponding values under real records. This interval include fundamental elastic period of structure, but as the structure experiences inelastic deformations, reduction of stiffness leads to increase of effective period of the structure. Since the interval I_4 does not include such inelastic periods, drift ratios under matched and real records don't coincide, consequently. Inspection of lateral forces at floor levels under matched and real records in Fig. 4.2 reveals the agreement of these responses under matched records in intervals I_1 and I_3 with the results of analysis under real records. As in the case of drift ratios, lateral forces under matched records in intervals I_2 and I_4 are less than those under real records. Generally, WBSM procedure can't reduce variation of lateral forces of stories effectively despite what this procedure does for drift ratios.

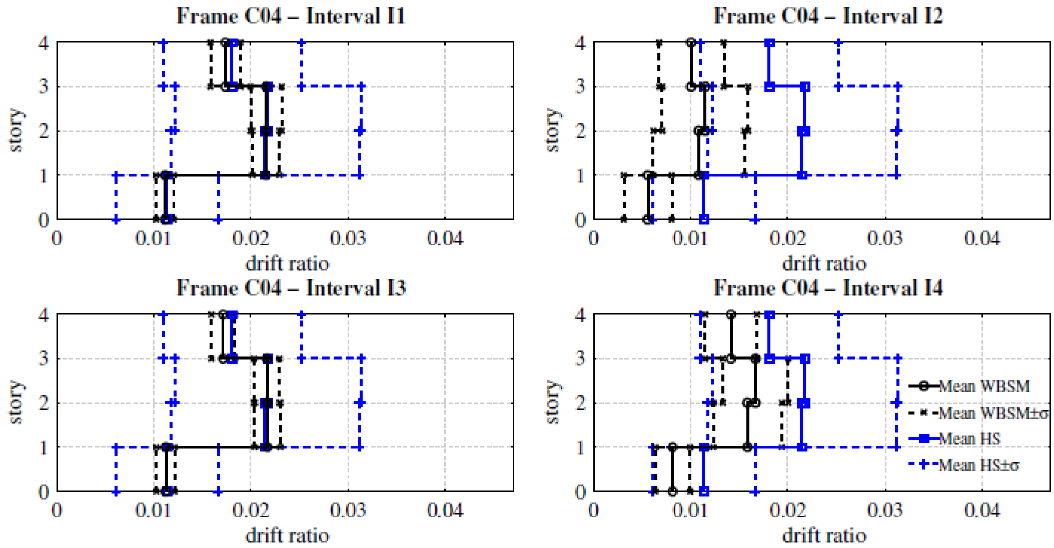

Figure 4.1. Inter-story Drift Ratios in 4 Story Frame under Matched and Real Records

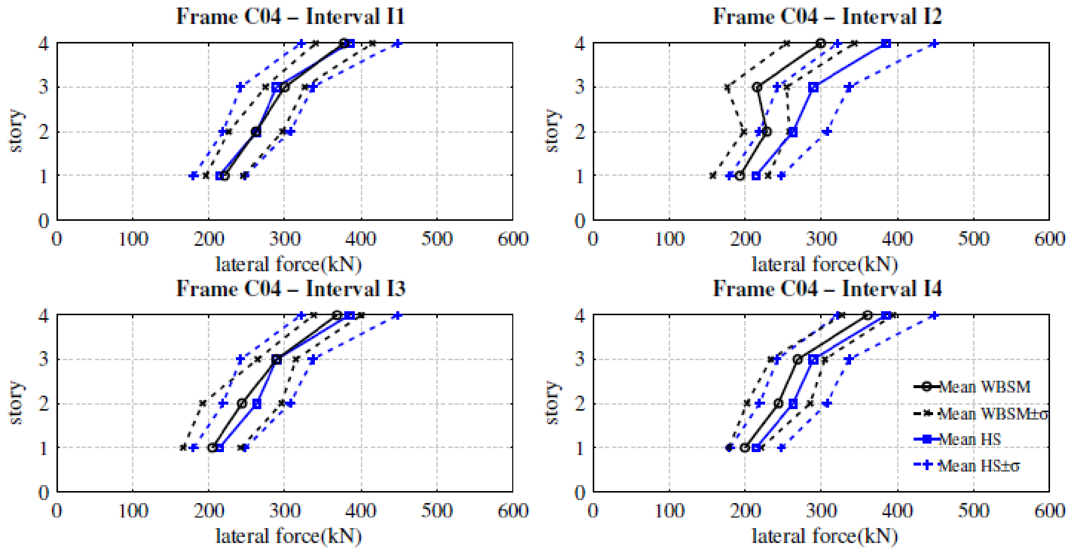

Figure 4.2. Lateral Forces of Floors in 4 Story Frame under Matched and Real Records

Drift ratios of frame C_{12} under the matched and real records are shown in Fig. 4.3. As can be seen, drift ratios under matched records in intervals I_0 and I_3 have good agreement with the corresponding values under real records. The standard deviation of drift ratios under matched records in these intervals is significantly less than those under real records. Hence, as in the case of frame C_{04}, WBSM procedure can decrease the variation of drift ratios with respect to real records. Drift ratios in matched records in interval I_2 are very low than those in real records. In interval I_4, drift ratios under matched records are close to corresponding values under real records in high stories (story 10, 11 and 12), but in lower stories, drifts ratios are underestimated under matched records with respect to those under real records. As in the case of frame C_{04}, these observations can be attributed to inclusion of fundamental period of structure in matching intervals I_1 and I_3. In assessment of lateral forces of stories under matched and real records in Fig. 4.4, WBSM has good performance in intervals I_1 and I_4 in viewpoint of closeness of mean responses under matched and real records. The lateral forces under matched records in interval I_3 are less than those under real records while drift ratios of stories in this interval was concordant with the corresponding values under real records. This results from not inclusion of periods of higher modes in the matching interval I_3 because higher modes contribute in lateral forces of stories more than they do in drift ratios. As in the case of frame C_{04}, the WBSM is not capable of reducing variation of lateral forces in matched records.

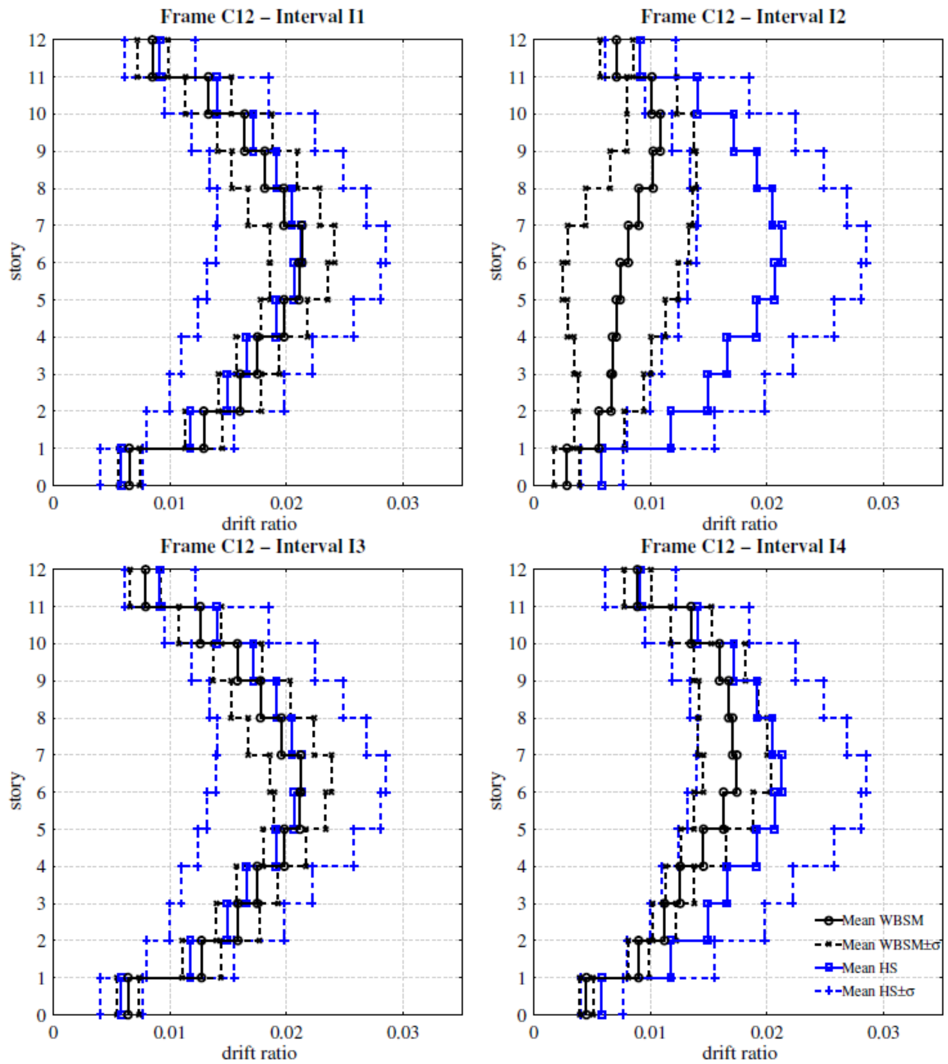

Figure 4.3. Inter-story Drift Ratios in 12 Story Frame under Matched and Real Records

5. CONCLUSIONS

In this study, continuous wavelet transform has been used in generation of spectrum-compatible accelerograms in complete and partial matching procedures. The strong ground motion characteristics of the matched records have been evaluated in detail. Then, a set of real accelerograms with mean response spectrum close to design one has been selected by harmony search. Inelastic responses of two special moment resisting RC frames have been evaluated under matched and real record. Spectral matching in intervals containing high periods have changed the duration of matched accelerograms significantly. Hence, matched records must be applied with caution in seismic analysis of structures sensitive to duration and energy content of shaking. Inter-story drift ratios under matched and real records have good agreement in matching intervals covering nonlinear fundamental period of the structures. Also, in these matching intervals, drift ratios under matched records have significantly less standard deviation than those under real records. Lateral forces of stories are consistent under matched and real records in matching interval I_1. But matching procedure can't reduce the standard deviation of these responses effectively. Generally, higher modes have more effect on lateral forces, and to have good agreement under matched and real records for lateral forces of stories, matching interval must include not only fundamental period of the structures but also effective periods of higher modes.

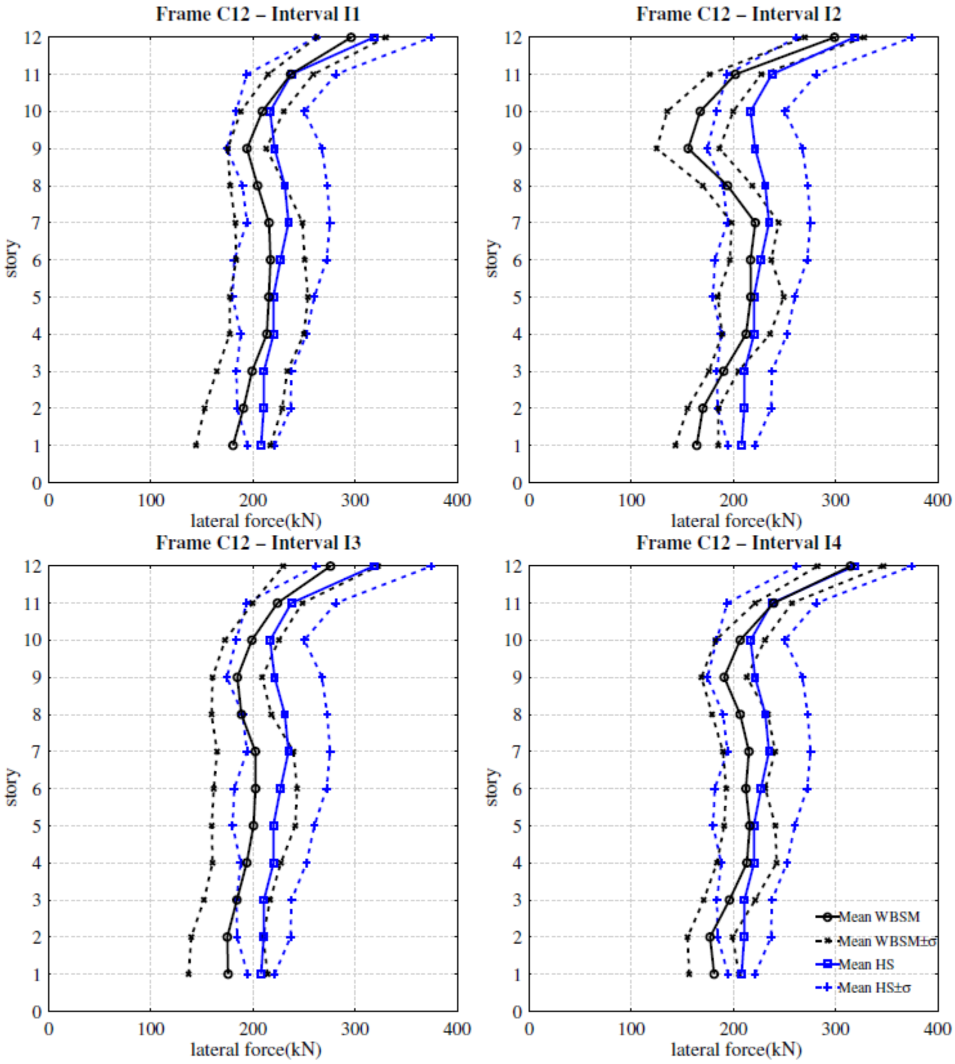

Figure 4.4. Lateral Forces of Floors in 12 Story Frame under Matched and Real Records

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