Nonlinear Dynamic Behavior of RC Buildings against Accelerograms with partial Compatible Spectrum

Omid Bahar[1] and Abolfazl Taherpour[2]

[1]*Assist. Prof., Structural Dynamics Dept., International Institute of Earthq. Eng. and Seismology, IIEES, Iran*
[2] *M.Sc., International Institute of Earthq. Eng. and Seismology, IIEES, Iran*
omidbahar@iiees.ac.ir, ataherpour@gmail.com

ABSTRACT:

Recently, In order to obtain artificial accelerograms with compatible spectrum using wavelet an alternative way, named *two-band matching procedure*, is presented. This procedure is based on preserving the non-stationary characteristic of the original records in the modified accelerograms. It needs two earthquake records with different characteristics to match the short period and long period zones of the design spectrum, separately. Therefore, two accelerograms must be representative of a near fault and distant fault seismic events. The selected first one is Friuli with a closest distance to the rupture failure of 13 Km, and the selected second one is Tabas with a closest distance to the rupture failure of 94.4 Km. Then, four groups are arranged; (1) the fully-matched, (2) the 1st-semi-matched, (3) the 2nd-semi-matched, and (4) the partially-matched records. Finally, the dynamic inelastic time history analysis of a typical 16-story RC building designed by the Direct Displacement Based Design method (DDBD) against these groups is carried out. Different influence of the different matching procedure on the seismic behavior of the building is discussed, in detail.

KEY WORDS: Wavelet transform, partially matched spectrum, spectrum compatible records, the dynamic inelastic time history analysis, direct displacement based design, RC building

1. INTRODUCTION

Dynamic time history analysis needs some time history accelerograms. Except some specific areas of the world, there is very sparse real accelerograms with specific characteristics which may not coincide with a specific site condition. Among different proposed methods to generate artificial accelerogram Wavelet transform is one of a powerful method which can shape artificial accelerograms with response spectra match to a target spectrum. Since, this procedure is not unique we may generate a list of infinite artificial accelerograms, which has the same response spectra but different characteristics. On the other hand, when we want to select real accelerograms, which parameters or characteristics of them must be mentioned? Suarez, Montejo (2007) and Bahar, taherpour (2008) have introduced different procedures that lead to the generation of artificial records. Here, we focus on the matching procedure using Wavelet transform has been proposed by Suarez and Montejo in 2007. Since, some seismic codes such as the Iranian Code of Practice (2005), persist that the response spectrum of the scaled real accelerograms should not be less than the Code design spectrum in a specific frequency range. But, such records may be very strong. Therefore, the authors use the idea of matching procedure and expand it to a general form named '*partial matching procedure*'. This procedure is not new, it completely use the Suarez and Montejo procedure but in a specific range of frequencies.

Based on the matching range of periods using this procedure four groups are formed. The considered building is a 2-bay, 16-story RC two dimensional frame which is designed by the direct displacement based design method. Extensive dynamic inelastic time history analysis by using OpenSees software is carried out. The influence of the parameters, frequency contents, durations, and the total amount of input energies of the artificial accelerograms on the seismic behavior of the considered building are discussed in detail. Some notes are proposed for using this matching procedure in order to carrying out the time history analysis.

2. THE WAVELET TRANSFORM AND THE SPECTRUM-MATCHING PROCEDURE

The wavelet transform is a two-parameter transform: for a time signal *f(t)*, the two transformed domains are time "*b*" (also referred to as position) and scale "*a*", which is inversely proportional to a frequency. The continuous wavelet transform of a time signal *f(t)*, can be defined as follows

$$C(a,b) = \int_{-\infty}^{+\infty} f(t) y_{a,b}(t) dt, \qquad a,b \in R \tag{2.1}$$

where the $\boldsymbol{y}_{a,b}(t)$ is the mother wavelet $\boldsymbol{y}(t)$, that is scaled by a real constant $a > 0$, (the scale) and shifted by a real parameter *b* (the position) as follows

$$y_{a,b}(t) = \frac{1}{\sqrt{a}} y\left(\frac{t-b}{a}\right) \tag{2.2}$$

In all practical applications, the coefficients *C(a,b)* are modified somehow to achieve a given objective before they are transformed back to the original time domain. The signal *f(t)* can be retrieved with the so-called ‘‘reconstruction formula’’ as follows

$$f(t) = \frac{1}{K_y} \int_{a=0}^{\infty} \int_{b=-\infty}^{\infty} \frac{1}{a^2} C(a,b) y_{a,b}(t) dbda \tag{2.3}$$

The constant K_y depends on the mother wavelet but here is set equal to *1* because we are not interested in reconstruction of the original time function. The selection of the proper wavelet for a given application is crucial for the successful implementation of the wavelet transform. Suarez and Montejo (2005) have proposed a new wavelet, based on the impulse response function of an underdamped oscillator. The mother wavelet has the following form:

$$y(t) = e^{-z \Omega |t|} \sin \Omega t \tag{2.4}$$

where $\boldsymbol{z}$ and **W** are two parameters that govern the decrement and the time variation of the wavelet. The values of the parameters $\boldsymbol{z} = 0.05$ and **W** = $\boldsymbol{p}$ rad/sec found to be convenient for the modification of the recorded accelerograms (Suarez, Montejo, 2005).

The time function *f(t)*, we are interested in, is the ground acceleration $\ddot{x}_g(t)$ due to an earthquake. It is convenient to re-write Eqn. 2.3 as follows

$$\ddot{x}_g(t) = \int_{a=0}^{\infty} \left(\int_{b=-\infty}^{\infty} \frac{1}{a^2} C(a,b) y_{a,b}(t)\, db \right) da = \int_{0}^{\infty} D(a,t)\, da \tag{2.5}$$

Where $D(a, t)$ is the ‘‘detail functions’’ that will be defined later. It is mentioned that the function $\ddot{x}_g(t)$ in Eqn. 2.5, is the accelerogram of the modified earthquake motion. In practice, a set of n discrete scale values "a_j" are used. Based on Suarez, Montejo (2005) the values used for the discrete wavelet transform are define as follows

$$a_j = 2^{j/8} \tag{2.6}$$

The values of j are related to the matching domain of periods (frequencies). It changes from *-50* to *12* for the fully-matched records. For the semi-matched records, it changes from *-50* to *-8* for the 1st-range, and from *-8* to *-12* for the 2nd-range. Finally, for the partially-matched records it changes from *-18* to *6*. In practical applications the ground acceleration signal $\ddot{x}_g(t)$ is always sampled at equal time intervals Δt. We will assume that the accelerogram is sampled at N discrete time t_k. Since "b" is a time scale as well, it will also be discretized as a set of N values. The discrete coefficients of the wavelet transform given by Eqn. 2.1 will be calculated using the approximate expression

$$C(a_j, b_i) \approx \frac{\Delta t}{\sqrt{a_j}} \sum_{k=1}^{N} f(t_k)\, \psi\left(\frac{t_k - b_i}{a_j}\right); \qquad j = 1,\ldots, n, \quad i = 1,\ldots, N \tag{2.7}$$

In terms of the discrete scales, the detail functions of Eqn. 2.5 are then defined as follows

$$D(a_j, t_k) \approx \frac{\Delta b}{a_j^{5/2}} \sum_{i=1}^{N} C(a_j, b_i)\, \psi\left(\frac{t_k - b_i}{a_j}\right); \qquad j = 1,\ldots, n, \quad k = 1,\ldots, N \tag{2.8}$$

The predominant frequency ω_j and period Tj of each detail function are

$$\omega_j = \frac{\Omega}{a_j}; \qquad T_j = \frac{2\pi}{\Omega} a_j \tag{2.9}$$

First, the discrete scale values a_j are selected in such a way that the periods Tj defined in Eqn. 2.9 reasonably span the range of periods of the target seismic response spectrum. Then, the details functions were obtained from the wavelet decomposition of a particular earthquake record. The ground response spectrum of original accelerogram is first calculated at the values of the periods Tj defined by the discrete values of a_j in Eqn. 2.6. Then the ratios γ_j between the values of the target and the calculated spectra are computed

$$\gamma_j = \frac{[S_a(T_j)]_{\text{target}}}{[S_a(T_j)]_{\text{reconstructed}}} \tag{2.10}$$

The detail functions $D(a_j, t_k)$, are multiplied by these ratios and a new accelerogram is calculated using Eqn. 2.5. The response spectrum of this updated accelerogram is calculated, a set of new ratios γ_j are computed and the previous detail functions are corrected. The process continues until all the ratios γ_j become sufficiently close to *1* or a pre-established maximum number of iteration is reached. For more detail, an interested reader may refer to Suarez, Montejo (2005).

3. REAL ACCELEROGRAMS FOR MATCHING PROCEDURE

Researchers have affirmed that in practical applications, selection of the records for linear/nonlinear time history analysis should be done with caution, such that they must be representative of different acceptable events in a specific site. But, which parameters are more important? During past decades, many specific or time varying parameters have been introduced to represent the inherent specification of the real accelerograms. In this paper, among these variant parameters, we focus on the frequency content and the total energy in detail, and some other parameters, in general. To examine effect of partial and semi-matching procedure, the records of two earthquakes with epicenters close and faraway from the site were selected. The first record corresponds to the Friuli earthquake (Italy 1976) measured at Forgario Cornino station with a closest distance to the rupture failure of 13 km and a USGS Site Classification B. The second accelerogram belongs to the Tabas earthquake (Iran 1978) registered at Ferdows station with a closest distance to the rupture failure of 94.4 km and a geometric or CWB Site Classification A. These two accelerograms have different characteristics; soil classification, closest distance, PGA, PGV, PGD, duration and total amount of energy, but their frequency contents are very similar. This is the problem that it will be treated later because it seems to be the most important and dominant feature that should be mentioned when selecting real accelerograms for matching procedure.

4. ARTIFICIAL ACCELEROGRAMS FOR TIME HISTORY ANALYSIS

The target spectrum is the design response spectrum of the building, the spectrum of the Iranian Code of Practice, Standard-2800 (2005), for seismic zone 1 and soil type III, a USGS site classification C. We have many different choices to do matching procedure; *(1)* the fully-match domain, *(2)* the semi-match (includes the 1st and the 2nd-semi-match) domain, and *(3)* the partially-match domain. The matching domains are the domains of the periods in which, the response spectra of the artificial accelerograms should be matched to the target spectrum, *i.e.* '*0.01~4.0sec*', '*0.01~0.5sec / 0.5~4.0se*c', and finally '*0.44~3.2sec*'. The period domain of the partially-matched records is based on the definition of the Standard-2800 (2005); about 0.2~1.5 times the fundamental periods of the considered building. So, for each real accelerogram we have generated four artificial accelerograms. After checking the end value of the velocity time history of the artificial accelerograms, baseline correction is carried out for records that need correction (Suarez, Montejo 2007, Bahar, Taherpour 2007, 2008). Main characteristics of the all artificial records are tabulated in Table 1.

Table 1 Main characteristics of the artificial accelerograms

Seismic Parameter (Record No.)	Friuli Record				Tabas Record			
	Full M. (1)	1st-Semi (3)	Partial (7)	2nd-Semi (9)	Full M. (2)	2nd-Semi (4)	Partial (8)	1st-Semi (10)
PGA(%g)	0.51	0.44	0.40	0.35	0.46	0.28	0.28	0.38
PGV(cm/s)	90.9	28.0	78.6	83.7	86.3	82.1	72.1	23.7
PGD(cm)	93.3	13.66	23.5	89.2	83.7	61.7	88.5	8.1
Duration(s)	11.8	9.0	11.0	12.7	23.7	27.9	27.6	23.2
Energy/Mass (kN)	62'456	5'175	45'125	54'860	79'800	78'357	60'143	5'945
AI (cm/s)	325.6	211.4	258.6	212.3	662.1	339.6	414.3	497.4

5. DYNAMIC INELASTIC TIME HISTORY ANALYSIS

The considered building is a typical 2-bay, 16-story RC building. Length of each bay and height of each story are *6m* and *3m*, respectively. This building was designed by the direct displacement based method developed by priestly (Bahar, Kaffashian 2006). This method is a strong and stable design method that is formed by the realistic inelastic dynamic behavior of RC buildings during earthquakes. In this method, the RC frame is designed based on a specific target displacement obtained from a design spectrum, which is here the spectrum of the standard-2800 (2005) for soil-type III. The maximum ground acceleration is set to *0.35g*. The first six periods (frequencies) of the building are *2.21sec (0.45Hz), 0.779sec (1.25Hz), 0.461sec (2.17Hz), 0.308sec (3.25Hz), 0.226sec (4.42Hz), and 0.171sec (5.85Hz)*, respectively. Comparing between periods of the building and the dominant period domain of the artificial accelerograms shows that the fully-matched records affect all the periods of the building. The 1st-semi-matched records affect the third and higher modes. The 2nd-semi-matched records affect first and second modes of the building. Finally, the partially-matched records affect the first three modes of the building.

The dynamic inelastic time history analysis for all artificial accelerograms using the OpenSees software (2006) is carried out. Nonlinear Beam-Column element assuming fiber section model is used. The inelastic behavior of beams and columns with confined and unconfined effect of concrete sections using USC_RC software (2001) and P-D effect are assumed (Taherpour, 2007).

5.1 The full- and partially-matched artificial accelerograms

These artificial accelerograms include the Friuli fully (1) and partially (7) matched records, and the Tabas fully (2) and partially (8) matched records. Detailed analysis shows that the spectrum-matching procedure using wavelet such as other similar methods amplifies a limited range of the frequency content of the real accelerograms. This changes the primary characteristics and frequency content of the records, Table 1. For instance, the Fourier amplitudes of these four artificial records are drawn in Figure 1. It can be seen that their frequency contents are very similar. The only differences between the Friuli and Tabas artificial records are in the latent length of their records, *22sec* and *40sec*, which can alter the amount of the total input energy of the records.

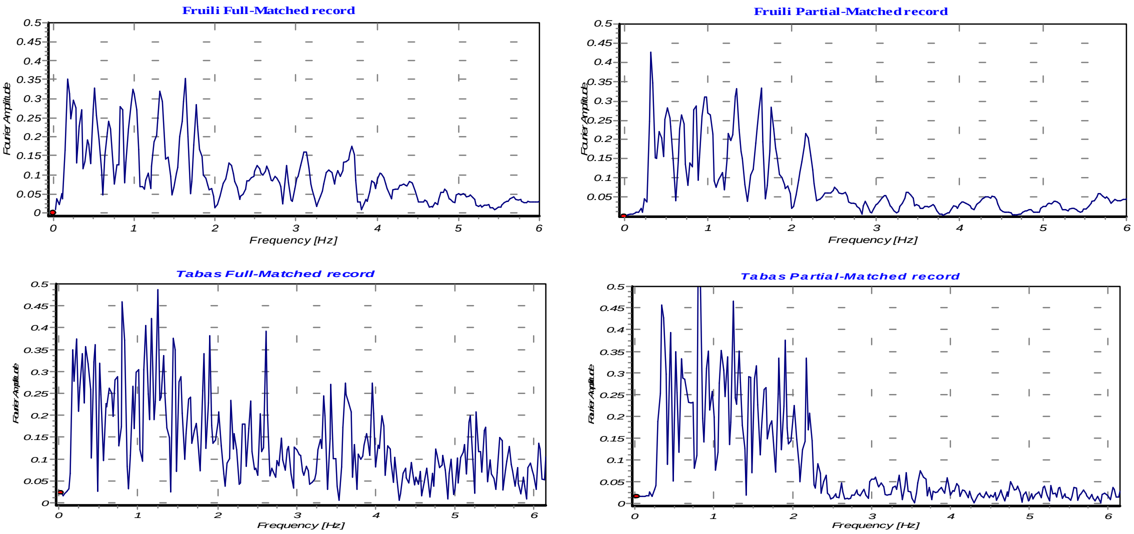

Figure 1 The Fourier amplitude of the Friuli and the Tabas artificial accelerograms

Figure 2 shows the displacements and the drift ratios of the floors for the fully and partially-matched records. All of these records affect the basic modes of the building. The maximum responses are belongs to the records (2), (1), (8) and (7), respectively. By once more viewing the Table 1, it can be seen that the parameters such as PGA, PGV, PGD, duration and also Arias intensity of the records do not explain the effectiveness of the records. For instance, the energy fluxes of these four records are also drawn in Figure 3. It is evident that the amount of the energy flux of the fully-matched records is very larger than the partially-matched records, while there is no effective difference between the responses of the building during occurrences of these two groups of accelerograms.

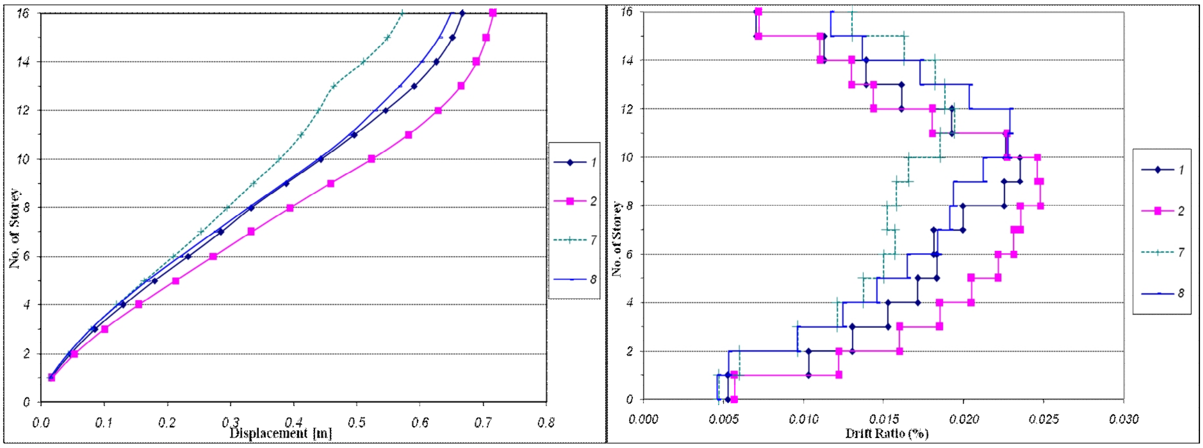

Figure 2 The displacements and the drift ratios of the floors, the Friuli full (1) and partially (7) matched records, the Tabas full (2) and partially (8) matched records

Since the basic modes of the building are excited, we may only notice to the total input energy per mass of the records. It can explain the differences between the responses of the building; *79800kN*, *62456kN*, *60143kN*, *45125kN* that are of the artificial records numbered (2), (1), (8) and (7). Based on their total amount of input energies, the similar responses of the records numbered (1) and (8) are also very interesting. Therefore, it seems that the effective parameters of the records to be noticed for a time history analysis are the well known parameters; frequency content and the total input energy of the artificial accelerogram.

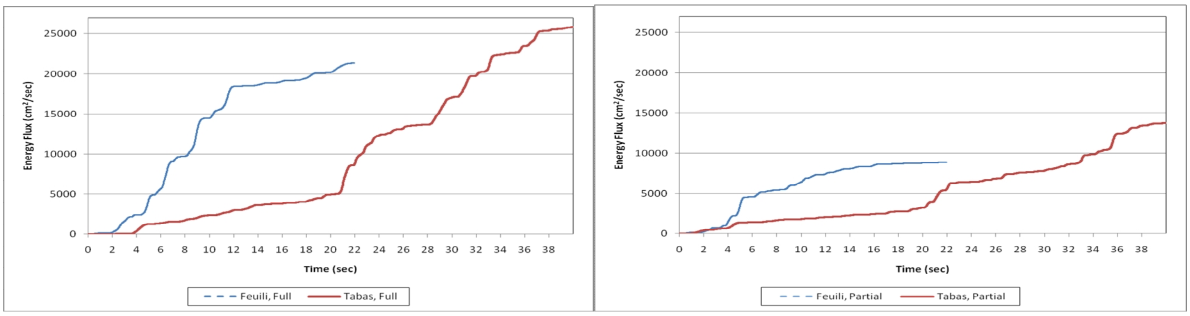

Figure 3 Energy flux of the records; the Friuli full (1) and partially (7) matched records, the Tabas full (2) and partially (8) matched records

5.2 The 1st and the 2nd-semi-matched artificial accelerograms

These artificial accelerograms include the Friuli 1st (3) and the 2nd (9) semi-matched records, and the Tabas 1st (10) and the 2nd (4) semi-matched records. The 1st-semi-matched records amplify the third and higher modes of the building, while the 2nd-semi-matched records affect the two first modes of the building. The resulted responses are shown in Figure 4. The records numbered (3) and (10) cannot strongly excited buildings because the basic frequencies of the building are out of their frequency content; modes 1 and 2. On the other hand, the record numbered (4) with the total input energy per mass larger than the record numbered (9), *78358kN* versus *54860kN*, has slightly more effect on the responses of the building.

5.3 The partial and the 2nd-semi-matched artificial accelerograms

These artificial accelerograms include the Friuli partial (7) and the 2nd-semi (9) matched records, and the Tabas partial (8) and the 2nd-semi (4) matched records. The records numbered (7) and (8) amplify the first three modes of the building, while the records numbered (9) and (4) amplify the first two modes of the building. The displacements and the drift ratios of the floors are shown in Figure 5.

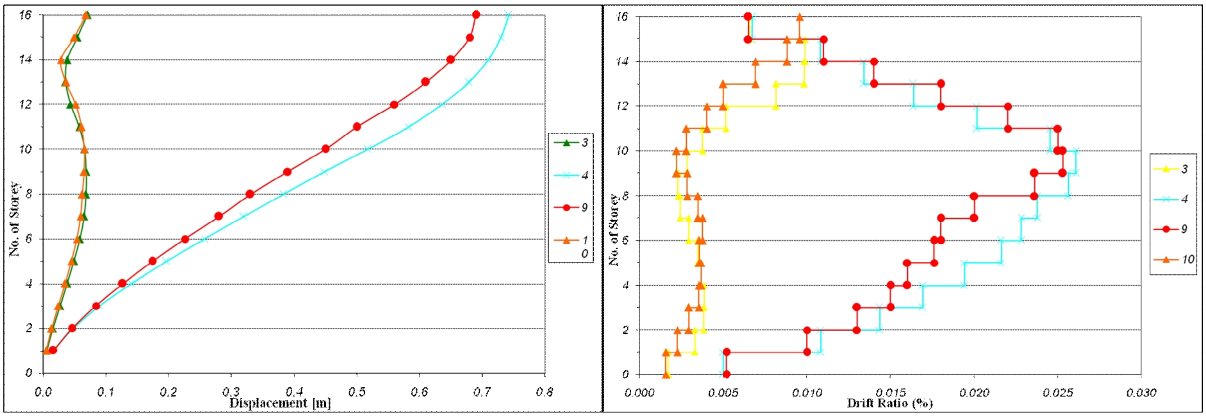

Figure 4 The displacements and the drift ratios of the floors, the Friuli 1st (3) and the 2nd (9) semi-matched records, and the Tabas 1st (10) and the 2nd (4) semi-matched records

It seems that the responses against records numbered (7) and (8), because their frequency content, are more reliable than the records (4) and (9). So, by eliminating more effective modes of the building from the frequency content of the artificial records we may obtain unrealistic larger responses. Therefore, matching procedure should be carefully used besides deep knowledge of the low frequencies, which is effective on the building seismic behavior.

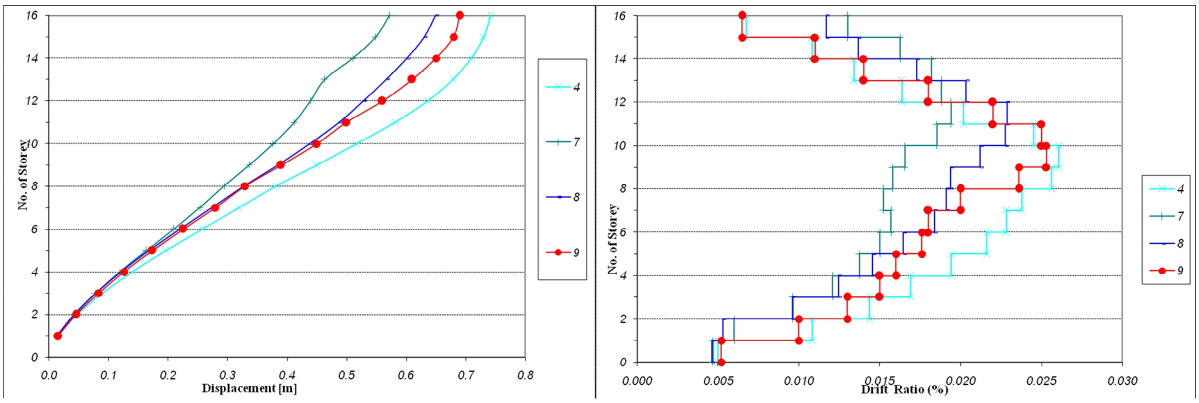

Figure 5 The displacements and the drift ratios of the floors, the Friuli partially (7) and the 2nd (9) semi-matched records, and the Tabas partially (8) and the 2nd (4) semi-matched records

6. CONCLUSIONS

Dynamic time history analysis needs some time history accelerograms. Except some specific areas of the world, there is very sparse real accelerograms with specific characteristics which may not coincide with a specific site condition. Wavelet transform is a powerful method which can shape artificial accelerograms with response spectra match to a target spectrum. In this paper, the authors expand the matching domain to a ‘partially-match domain’. But, this matching procedure changes the primary characteristics and also frequency content of the records. Detailed analysis shows that using these matching procedures should be carefully used such that the frequency content of the artificial records cover all the effective frequencies of the building to be considered. Also, analysis shows that the primary characteristics of the real accelerograms are not so important. But, using real accelerograms with closer response spectra in the dominant frequency content range of the considered building with respect to the target spectrum are strongly proposed. And also, designers must be always careful about duration of the records. It has a direct and effective influence on the total amount of the input energy that buildings should be experienced.

REFERENCES

Bahar, O. and Kaffashian, M. (2006). A new spectrum based artificial acceleration records. Journal of Science and Technology of Sharif (accepted-in Persian).

Bahar, O. and Taher-pour, A. (2007). Evaluation of nonlinear dynamic behavior of a 16-Story frame building during earthquake records generated by wavelet transform. Journal of Science and Technology of Sharif (accepted-in Persian).

Bahar, O. and Taher-pour, A. (2008). Selection of Artificial Spectrum Compatible Accelerograms for nonlinear Dynamic Analysis of RC Buildings. The 14th World Conference on Earthquake Engineering October 12-17, 2008, Beijing, China.

Suarez, L.E. and Montejo, L.A. (2005). Generation of artificial earthquakes via the wavelet transform. *Int. Journal of Solid and Structures* **42**, 5905-5919.

Suarez, L.E. and Montejo, L.A. (2007). Applications of the Wavelet transform in the generation and analysis of spectrum-compatible records. *Structural Engineering and Mechanics* **27:2**.

Taherpour, A. (2007). Generation of artificial accelerograms using wavelet transform and its effect on inelastic behavior of RC buildings. MSc Thesis in Earthq. Eng., International Institute of Earthquake Engineering and Seismology.

(2001). USC_RC: Analysis of reinforced concrete members. Civil eng. dept., University of Southern California [USC], available from URL: http://www.usc.edu/dept/civil_eng/structural_lab/asad/

(2005). Iranian Code of Practice for seismic resistant design of buildings, Standard No. 2800-05, the 3rd edition.

(2006). OpenSees, ver. 1.7.2. Pacific Earthquake Engineering Research Center [PEER]. University of California, Berkeley, available from URL :http://opensees.berkeley.edu/