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A STUDY OF ENDURANCE TIME METHOD IN THE ANALYSIS OF ELASTIC MOMENT FRAMES UNDER THREE-DIRECTIONAL SEISMIC LOADING

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ABSTRACT

Endurance Time (ET) method is a time history based analysis procedure that applies special intensifying acceleration functions for estimating the seismic performance of structures at different excitation levels in each single analysis. One of the extensions of the ET method is in the seismic assessment of buildings considering multi-component excitation. In this paper, a procedure for three-directional seismic analysis of buildings is proposed and application of this method to several steel moment frames is investigated. Several Steel Moment Frames were designed according to INBC Code. These Frames were analyzed under ET acceleration functions in horizontal and vertical directions simultaneously and results were compared to Response History Analysis. It is observed that ET method can predict the results from multi-component analysis, including vertical excitation, with reasonable accuracy. Scattering and accuracy of the results are also investigated.

Keywords: Endurance time method; intensifying acceleration functions; multi-directional excitation; vertical excitation

1. INTRODUCTION

With the development of new computational tools, the potential for realistic modeling of complex structures is increased and in this situation, increasing demand for improved and more accurate methods for seismic assessment of structures is reasonable logical expectation. In response to increasing demand for application of complex methods, some new methods were developed which estimate structural behavior realistically due to not only taking dynamic characteristics of structure into account but also considering earthquake excitation as it takes place.

Earthquake-induced ground motions have three translational components. There are some codified provisions that require consideration of the effects of symultaneous ground motions components in the seismic analysis of sensitive and special structures [1]. Although Three-dimensional analysis under actual records can be considered as the most accurate method for

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seismic analysis, it has two major drawbacks. Firstly, for a particular site specification, the number of available recorded accelerograms might not be sufficient and the selection of consistent accelerograms complicates the issues. Secondly, analysis of structures under these earthquakes is time consuming and interpretation of results for complex structures is quite difficult. Therefore, it is advantageous to use simplified methods that can estimate structural behavior under multi-directional excitation with satisfactory approximation and with less computational effort.

The Endurance Time method is a procedure that can be used in both the linear and nonlinear seismic analysis of structures [2]. Its simplicity is one of the priorities of ET method over response history analysis under actual ground motions. In the ET method, the response of a structure can be monitored against time which is correlated to the intensity of excitation.

In this paper, the extension of the application of the ET method to linear seismic analysis of structures under three-directional excitation is investigated. ET method is evaluated by comparing its results with results of time history analysis under actual records, considering two horizontal and one vertical component of excitation.

The first part of this paper is devoted to a brief review of code regulations and some investigations on the three-dimensional analysis of buildings. Then, various structures, which are designed according to the INBC code, are analyzed by ET analysis under proposed algorithm. Finally, by comparing results of ET method with three-directional analysis under three components of ground motions, the capability and limitations of ET method in three-directional analysis of steel moment frames is evaluated and a procedure for proper scaling of ET functions for multi-component analysis is proposed. The treatment of the subject in this paper is limited to the linear analysis, however, the main objective is to lay the foundation required in order to expand the method into nonlinear analysis where the main advantages of the method can be realized.

2. REVIEW OF CODE PROVISIONS AND RESEARCH ON THREE-DIMENSIONAL ANALYSIS

Major seismic codes propose essentially the same suggestions for applying earthquake ground motions for the purpose of three-dimensional time history analysis; however, they provide various methods for scaling and application of components of records [3]. In this research, the INBC code is chosen to be applied to time history analysis of models [4]. Based on this seismic code, time history analysis shall be performed under seven couple of accelerograms, representative of horizontal components of each ground motion. These two components shall be applied simultaneously along principal directions of structure and the average of responses should be considered for design of members. When vertical component of earthquake needs to be considered, an equivalent static load, which is a coefficient of dead load should be applied. Research show that equivalent vertical load estimates the response of structure unrealistically. So, taking the vertical component of earthquake directly into account seems to be necessary [5].

Considerable amount of research has been conducted on the subject of three-dimensional analysis. Many investigations have been performed to find specifications of components of an earthquake [6] and the structural response under multiple components of the selected ground motion [7].

3. ENDURANCE TIME METHOD

In this paper, it is intended to extend the ET method into three-directional excitation form. In order to explain the concepts, it is assumed that relative seismic behavior of two buildings needs to be assessed. These frames are fixed on a shaking table and subjected to a set of specially designed intensifying excitations, (Figure 1, 2). To simulate three-directional excitations, three intensifynig accelerograms, called “ET acceleration functions” (ETAF), are imposed simultaneously in perpendicular directions, two in horizontal and one in vertical. These ETAF are generated in such a way that their response spectra increase by the time, hence response of structure under this kind of accelerogram gradually increases with time. A typical ETAF is depicted in Figure 2.

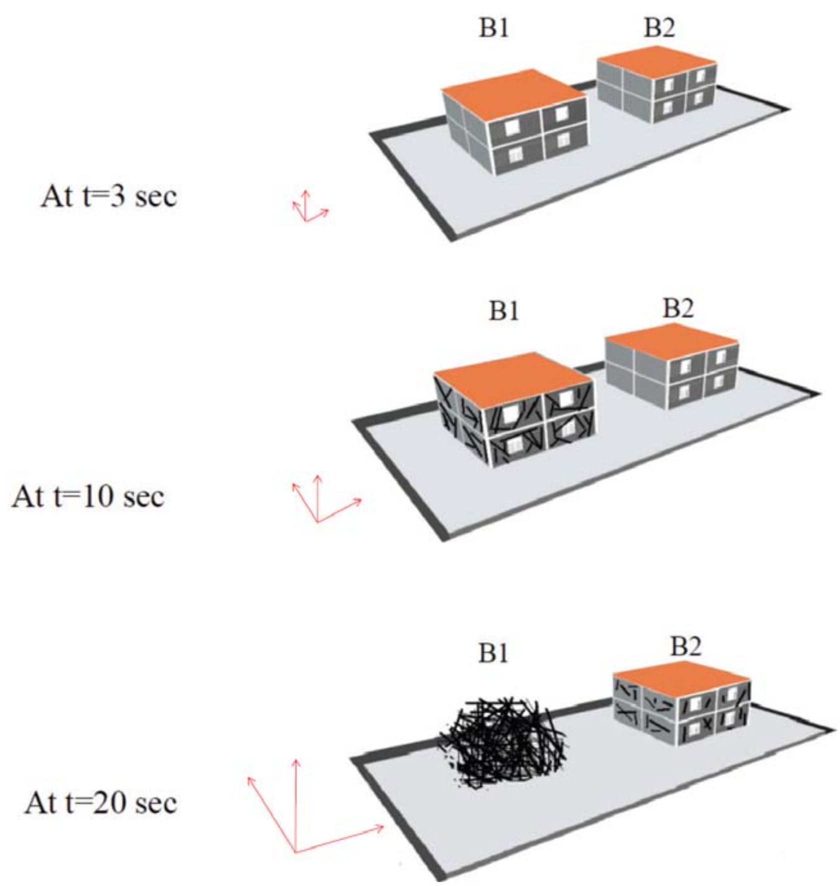


Figure 1. Three-dimensional ET hypothetical experiment.

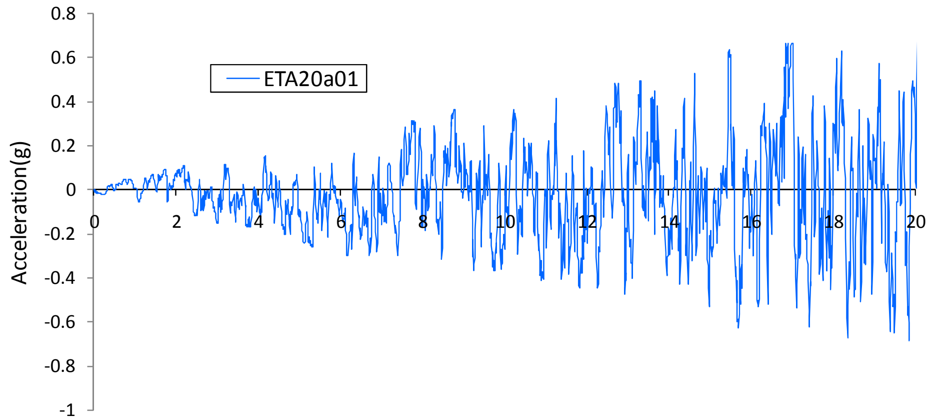
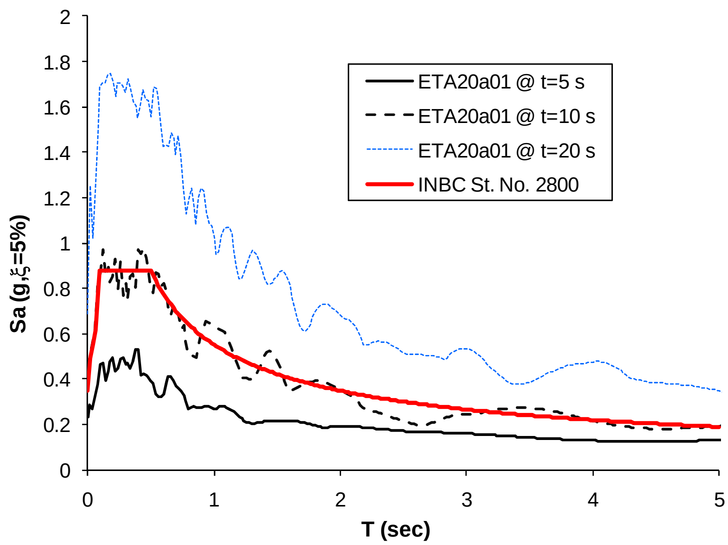


Figure 2. A typical ET acceleration function.

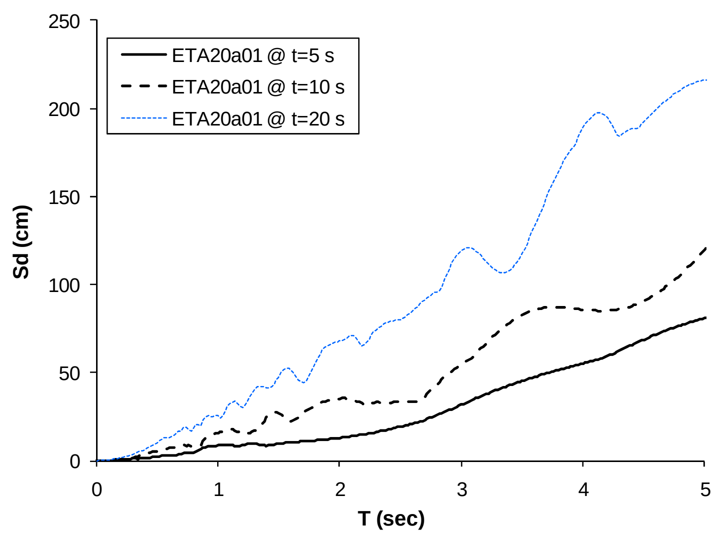
As it can be seen in this figure, at the beginning of excitation (t=3 sec), both buildings are undamaged, but as the time passes (t=10 sec), cracks are appeared in nonstructural elements in building B1, while B2 is still uncracked. In this circumstance, it can be concluded that at particular intensity which takes place at t=10 s, B1 is no longer functional, but B2 still reserves its operation. As the time further passes and as a result, intensity of excitation increases, more damage will occur in buildings until at t=20 sec, B1 is completely collapsed and several cracks appear in B2. The experiment can be continued until both buildings fail. In ET method, seismic resistance of structures are judged based on the intensity of the excitation that they can endure based on the desired failure criteria. So, in the above case, B2 is considered to be more resilient to dynamic excitation. By using a properly designed excitation function, this endurance can be correlated to the intensity level of ground motions that the intended structure can be expected to endure [2].

By the definition of Endurance Time, for three-directional analysis of a structure by ET method, the structure is analyzed under intensifying ET acceleration functions applied in principal directions of structure simultaneously and response of the building is monitored versus time. Then Endurance Time is determined according to desired damage criteria and their acceptance limit. Finally, by comparing Endurance Time of the frame with target time, seismic resistance of the structure could be evaluated. In this respect, some important definitions should be clarified for accurate and appropriate use of ET method. The details on characteristics of ETAF are studied by [8].

The most important component of ET method is ET acceleration functions. Intensifying characteristic of these acceleration functions is important. As depicted in Figure 3, response spectra of an acceleration function named ETA20a01 (Figure 2), which is consistent with design spectrum in INBC code for soil condition type 2, is scaling up with time.



(a)



(b)

Figure 3. Response spectrum of a typical ETAF at different times, (a) Acceleration spectrum, (b) Displacement spectrum

It is obvious that response of ETAF at t=10s is twice of its response spectrum at t=5 s at various periods of vibration. This specification can be achieved by setting some constraint in generation of ETAF. In this regards, using a simple linear scale factor, Sa (and Sd) can be set to reach the required target level at any desired time. By this approach, we define the target response of ET acceleration functions as in Eq. (1) and Eq. (2):

$$S_{aT}(T,t)=\frac{t}{t_{Target}}S_{aC}(T) \tag{1}$$

$$S_{uT}(T,t)=\frac{t}{t_{Target}}S_{aC}(T)\times\frac{T^2}{4\pi^2} \tag{2}$$

The problem of generating accelerograms with such characteristics was approached by formulating it as an unconstrained optimization problem in the time domain as follows:

$$\text{Minimize}\,F(a_g)=\int_0^{T_{max}}\int_0^{t_{max}}\{[S_a(T,t)-S_{aT}(T,t)]^2+\alpha[S_u(T,t)-S_{uT}(T,t)]^2\}dt\,dT \tag{3}$$

Where a_g is the ET accelerogram being sought and α is an optimization weighting parameter set to 1.0 in this study [2].

Besides ET acceleration functions, definition of suitable target time has critical role in evaluation of structure by ET method. Target time is the time that response of standard building is expected to satisfy performance requirements. For example, assume that a one story standard frame is designed to reach allowable drift of 0.005 under design spectrum. In this state, if the ETAF are calibrated in such a way that response spectra of ETAF at time t=10 s match the design spectrum, the drift ratio in this frame at t=10 s, so called "target time", reaches its allowable limit.

Now, if two other frames were subjected two those ETAF which are calibrated according to standard design spectrum at t=10 s, the drifts can be monitored against time (Figure 4).

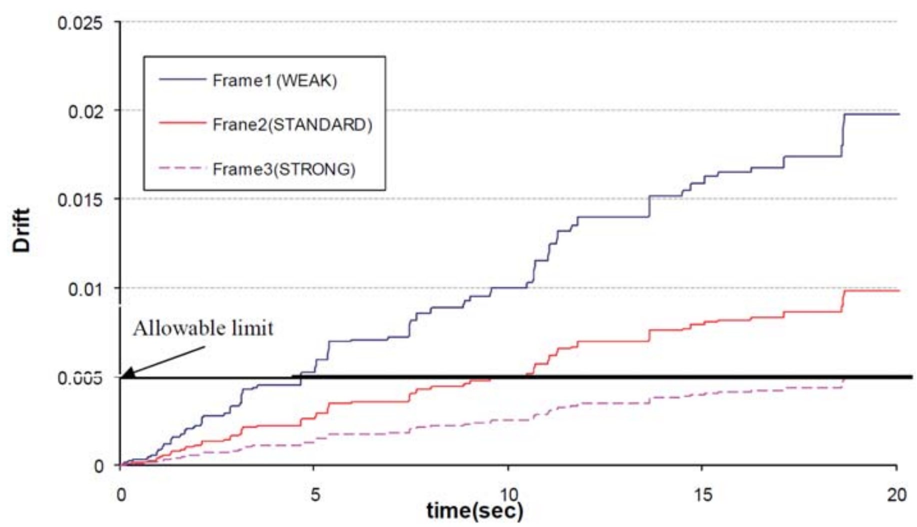


Figure 4. Identification of weak, standard and strong frames with concept of target time

In Figure 4, drift in F1 (weak frame) reach its limit at t=5 s and as this time is less than target time, this frame doesn't pass acceptance criteria and is not acceptable, while ET in F3 (strong frame) is much more than target time, therefore this frame is expected to endure under earthquakes with intensities higher than required and might not be economical.

For various applications, several sets of ETAFs were produced to match different response spectra. The set of ETAF which is used in this study is consistent with the average response spectrum of 1st component of seven ground motions selected from FEMA 440 soil condition C records.These three ETAFs are named as , ETA20f01, ETA20f02 and ETA20f03, respectively.

ET method was proposed in 2004, since then many applications of ET method in linear and non-linear analysis of different types of structures were studied. Studies showed that ET method can be used in linear and nonlinear seismic analysis of 2D steel frames [9- 11]. Also it is used for estimation of nonlinear response and damage index in structures [12]. Also studies show that this method can potentially be used for seismic analysis and design of non-building structures, such as concrete gravity dams [13].

4. PROPOSED ALGORITHM FOR THREE-DIRECTIONAL ET ANALYSIS

An algorithm for seismic analysis of structures under multi-component excitations is proposed in Figure 5. First, having design spectrum for the site, a set of compatible ETAFs should be selected. There are several sets of ETAFs which are compatible with INBC code for various soil conditions.

Then, ETAFs should be scaled. The scaling procedure is similar to that for ground motions and seismic codes can be used, the only difference is that the scaling of ETAF should be applied at target time (i.e. t=10 s in current study). Each pair of ETAF shall be scaled such that for specified period between 0.2T and 1.5T, the average of the SRSS Spectra of the 5 percent-damped response spectra, does not fall below 1.3 times the corresponding ordinate of the design response spectrum.

The common assumption for ratio of vertical acceleration to horizontal acceleration is 2/3. This factor is consistent with the average ratio of vertical to horizontal accelerations for selected earthquakes. Thus, for considering vertical acceleration in ET analysis, a factor of 2/3 is multiplied with determined scale factor for horizontal components.

Next, like response history procedure, the structure is analyzed under three scaled ETAF in principal directions of the building. After that, Endurance Time of the structure, based on specified damage index, is computed. At the final step, by comparing Endurance Time with target time, the behavior of structure can be assessed, e.g. if Endurance Time is less than t=10 s, the structure is under-designedand if ET is greater than t=10 s, the structure is stronger than required.

Another interpretation of results is that structural response at target time is compared with its allowable value. For weak and strong frames, ET response at t=10 s is greater and less than allowable value, respectively. It should be noted that only a single target time has been considered in this research for the matter of simplicity and the fact that the models are being analyzed elastically. However, in practice, several target times related to different hazard levels can be considered simultaneously. Obviously, potential advantages of ET method are in reduction of the computational demand in nonlinear multi level seismic assessment of structures. Thus, in this research, it is intended to lay a part of the foundation required for the development of ET method into a procedure for full three dimensional nonlinear seismic assessments.

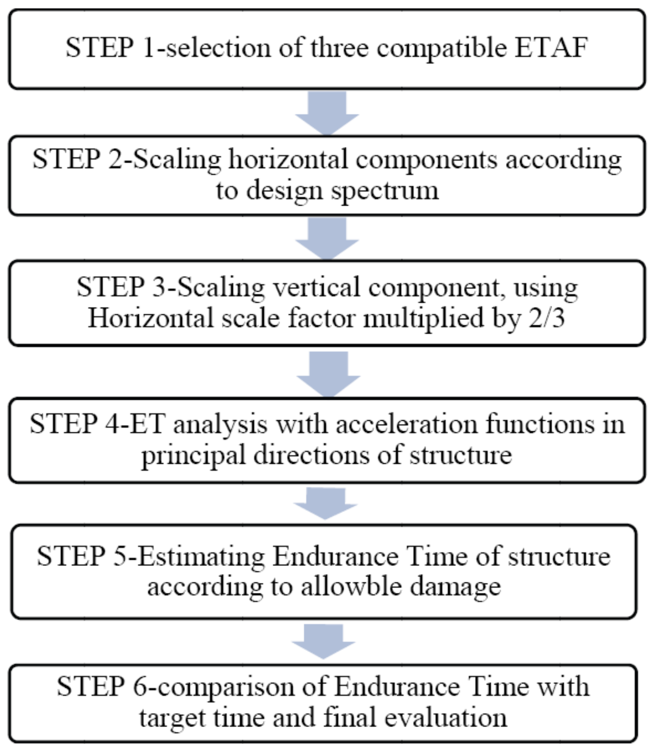


Figure 5. Proposed flowchart for three-directional analysis of structures by ET method

5. STRUCTURAL MODELS

The investigated models were generated in such a way that effects of modal shapes, periods of vibration and torsion are considered in analysis.In this way, six steel moment resistant frames with 3, 5 and 15 stories in two states of regular and irregular were studied. For all frames, the story height and apans are 3.2 m and 6m, respectively.

The models are named, based on lateral resistant system, the number of stories, spans in both directions and irregularities. In this matter, F represents the Frame, 3D refers to a three-dimensional model, MM is representative of the moment resistant frame in both X and Y directions, S, X, Y state for the number of stories, spans in X direction and spans in Y direction, respectively and IR means irregularities, and a frame without IR refers to regular and symmetric buildings. Figure 6 illustrates the models used for bi-directional analysis.

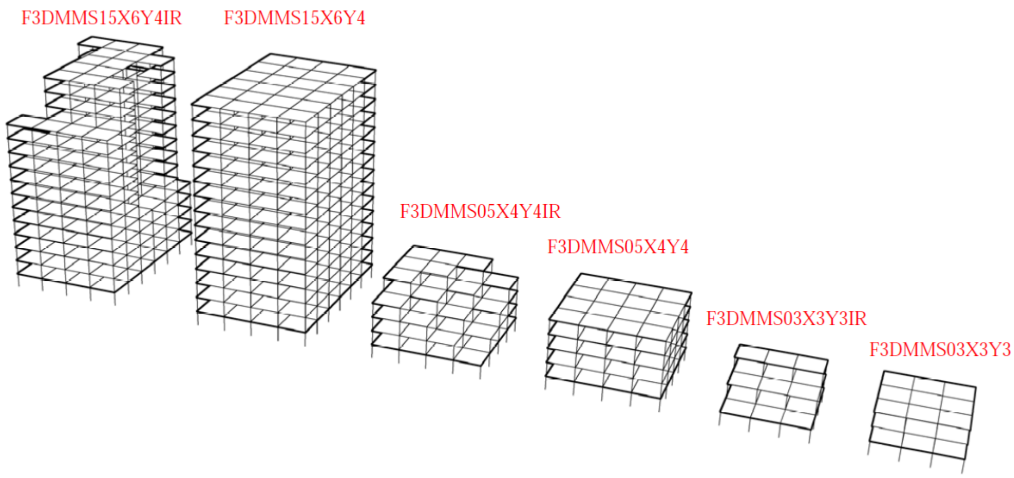


Figure 6. Investigated models

Table 1: Investigated frames, properties and design assumptions

Name	No. Stories	No. Span X	No.Span Y	Seismic Coefficient	Base Shear (KN)
F3DMMS3X3Y3	3	3	3	0.125	1221.5
F3DMMS3X3Y3IR	3	3	3	0.125	749.24
F3DMMS5X4Y4	5	4	4	0.106	2880.8
F3DMMS5X4Y4IR	5	4	4	0.106	2184.3
F3DMMS15X6Y4	15	6	4	0.074	13844
F3DMMS15X6Y4IR	15	6	4	0.074	11630

Table 2: Investigated frames, dynamic properties of 3 first modes of vibration

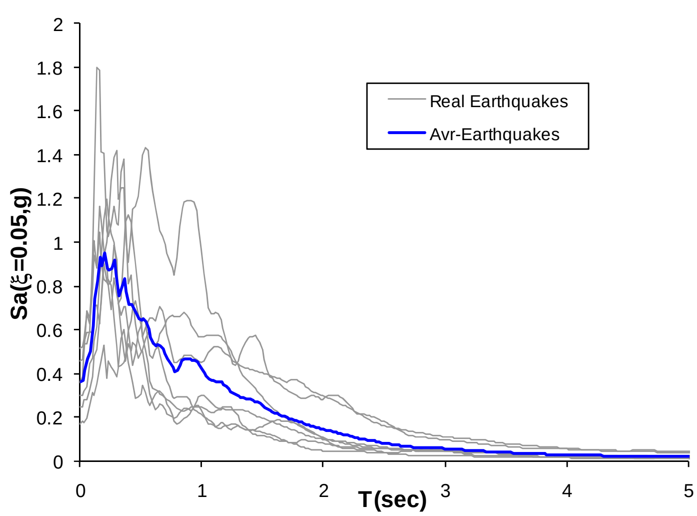
Name	Mode of Vibration	Period of vibration	Modal Mass Participation Ratio	
			1st Principal Direction	2nd Principal Direction
F3DMMS3X3Y3	1st translational	0.702	0.81	0
	2nd translational	0.702	0	0.81
	Torsional	0.664	0	0
F3DMMS3X3Y3IR	1st translational	0.723	0	0.577
	2nd translational	0.667	0.733	0
	Torsional	0.508	0	0.169
F3DMMS5X4Y4	1st translational	1.088	0.757	0
	2nd translational	1.088	0	0.757
	Torsional	0.977	0	0
F3DMMS5X4Y4IR	1st translational	0.942	0	0.525
	2nd translational	0.871	0.707	0
	Torsional	0.691	0	0.194
F3DMMS15X6Y4	1st translational	2.365	0	0.711
	2nd translational	2.355	0.715	0
	Torsional	2.24	0	0
F3DMMS15X6Y4IR	1st translational	2.068	0	0.55
	2nd translational	2.013	0.68	0
	Torsional	1.829	0.02	0.11

6. SELECTION OF GROUND MOTIONS AND ET ACCELERATION FUNCTIONS

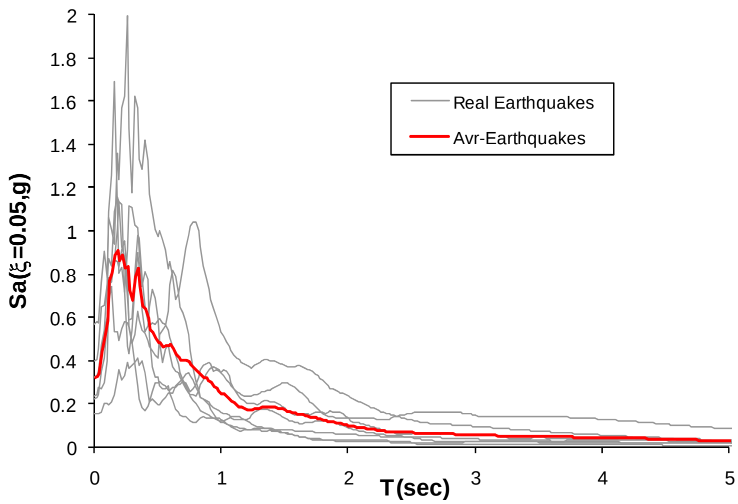
In this paper, the time history analysis is performed, using two horizontal and the vertical components of seven ground motions to verify results from ET method. These accelerograms are chosen from 20 records that FEMA 440 provides for soil condition C [14]. These records and their components are illustrated In Table 3. The average response spectra of these earthquakes, which are scaled according to code requirements, are illustrated in Figure 7.

Table 3: Properties of real accelerograms and their components

Earthquake	Station Name	Station Number	Abbreviation	Component (deg)	PGA (cm/s^2)
Landers	Yermo, Fire Station	12149	DSP000	0	167.80
			DSP090	90	151.05
			DSP-UP	UP	163.80
Loma Prieta	Saratoga, Aloha Ave.	58065	STG000	0	494.50
			STG090	90	317.90
			STG-UP	UP	381.80
Loma Prieta	Gilroy, Gavilon College Phys Sch Bldg	47006	GIL067	67	349.10
			GIL337	337	318.80
			GIL-UP	UP	187.20
Loma Prieta	Santa Cruz, University of California	58135	LOB000	0	433.10
			LOB090	90	387.00
			LOB-UP	UP	360.20
Loma Prieta	Anderson Dam, Downstream	1652	AND270	270	239.40
			AND360	360	235.10
			AND-UP	UP	148.60
Morgan Hill	Gilroy #6, San Ysidro Microwave Site	57383	G06090	90	280.40
			G06000	0	217.87
			G06-UP	UP	397.20
Northridge	Castaic, Old Ridge Route	24278	ORR360	360	504.20
			ORR090	90	557.30
			ORR-UP	UP	213.00



(a)



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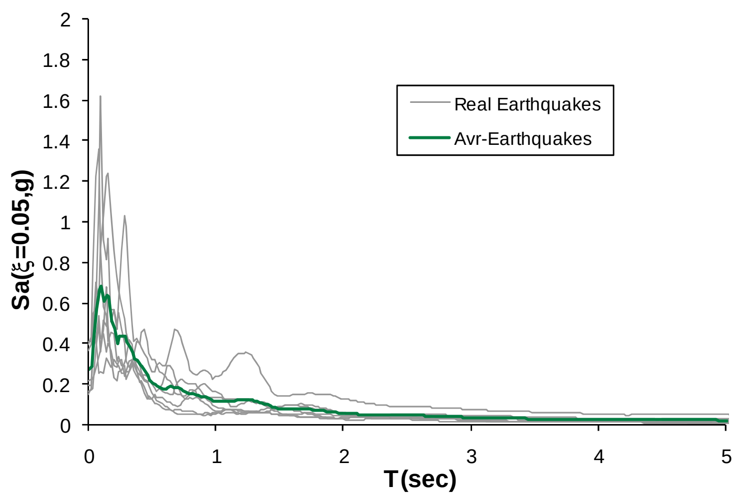


(c)

Figure 7. Response spectra of three components of selected earthquakes. (a) First horizontal component, (b) Second horizontal component, (c) Vertical component

One important issue in Figure 8 is that averages of both horizontal components of earthquakes are nearly the same, in spite of the remarkable difference between the response spectra of horizontal components of each earthquake (Figure 7). Although the spectrum of each component is not exactly the same at periods between 0.5 and 2 secs, however, because in ET analysis the aim is estimating the envelope response of structure due to ground motions components in principal directions, the ETAFs in horizontal directions are in the same level of intensity and their response spectra equal to average of response spectra from the first component of selected ground motions.

The average response spectrum of the major components of these records is assumed as design spectrum and is used for response spectrum and ET analysis. Therefore ETAF should be generated to be compatible with this spectrum at target time, i.e. t=10 s. As mentioned before, there are several series of ETAF which are produced for various purposes. Among these acceleration functions, f series of ETAF (ETA20f01, ETA20f02 and ETA20f03) is consistent with assumed design spectrum and have appropriate specifications to be used in this study. The response spectra of these acceleration functions are calculated at t=5 s and t=10 s and compared with design spectrum in Figure 8.

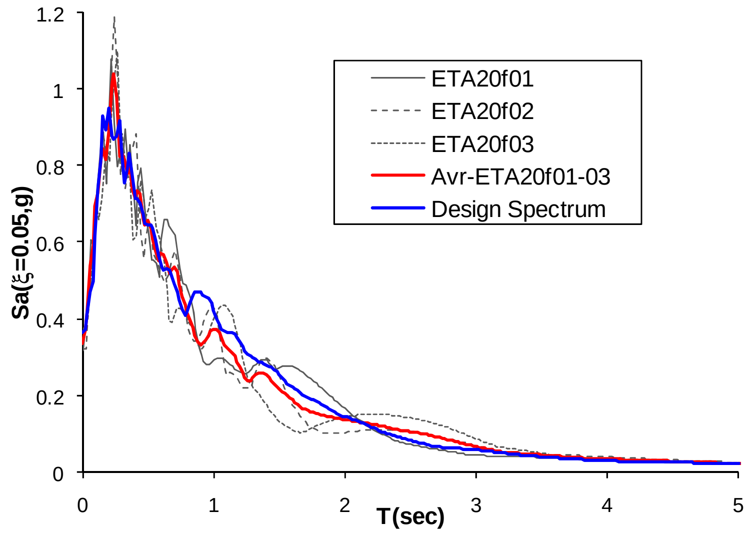


Figure 8. A comparison between response spectrum of ETAF at t=5 s. and design spectrum

It is obvious that the optimization process has been quite successful in converging to the target values. It is noticed that almost the same level of conformity has been achieved at all times from 0 to 20 s by the definition of the target function. As evident from Figure 8, some random deviations from the target response should be expected considering the random nature of input accelerograms. In order to improve the accuracy of the analysis results, it is recommended to use the average of the results from at least three accelerograms. Also it should be noted that from Figure 8 the design spectrum is comparable with ETAF at t=5 s, while target time is set to t=10 s, therefore a scale factor of 0.5 is required for ETAF to reach design spectrum at target time.

7. THREE-DIRECTIONAL ANALYSIS

7.1 Scaling procedure

Different approaches have been proposed for scaling of earthquake records, such as the square root of the sum of the squares (SRSS), arithmetic and geometric mean and the maximum spectral response. Among scaling methods, SRSS was selected because of a better fitness with the target spectrum.

Due to the fact that ETAFs are somewhat similar to real accelerograms, the mentioned methods are used to obtain the scale factor for ETAF. It should be noted that, not only did the results from all scaling approaches lead to the same value for ETAF; this scaling factor did not change significantly from one frame to another; while these scale factors were considerably different in actual accelerograms. The major reason for such consistency of scaling methods in ETAF is that they are consistent with the design response spectrum.

7.2 Effect of vertical acceleration

For elastic analysis, vertical acceleration doesn't influence the horizontal displacements. Therefore for the sake of vertical effect, internal force, such as maximum moment in beams and axial force in columns are investigated for 3-story irregular building in Figure 9. In studied models, the mass of elements is assumed as lumped mass and are considered for 100% of Dead load plus 20% of Live load at the ends and middle of beams.

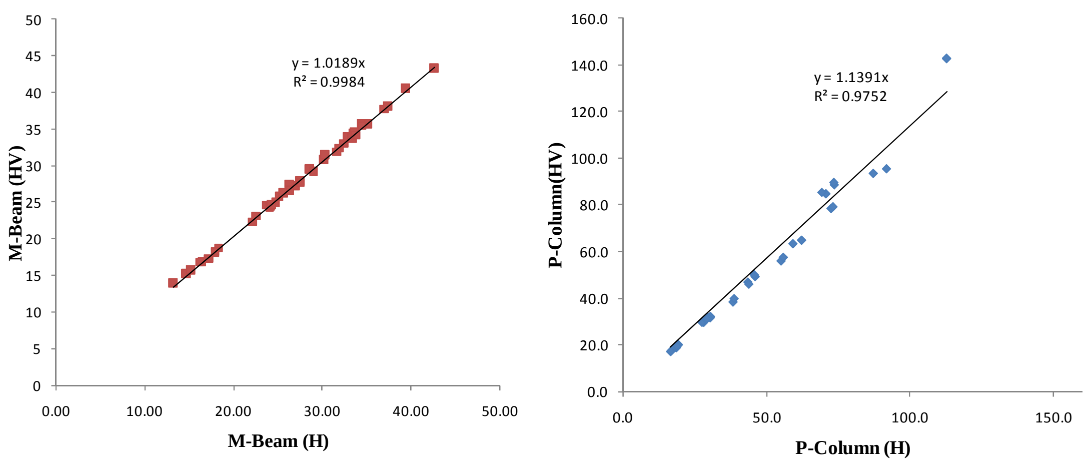


Figure 9. Effect of vertical acceleration on internal force in structural elements, F3DMMS3X3Y3IRX, a) Moment in beams, b) Axial force in columns

As it can be seen in these figures, the effect of vertical acceleration is more pronounced in columns axial forces. It is obvious that axial force in columns considerably increase when vertical excitation is considered for analysis, also it is seen that columns have different sensitivity to vertical acceleration. However, moments in beams and columns remain almost unchanged for the investigated frames.

The axial force in two columns with different sensitivity to vertical acceleration is derived by ET analysis with and without considering vertical acceleration in the analysis (Figure 10).

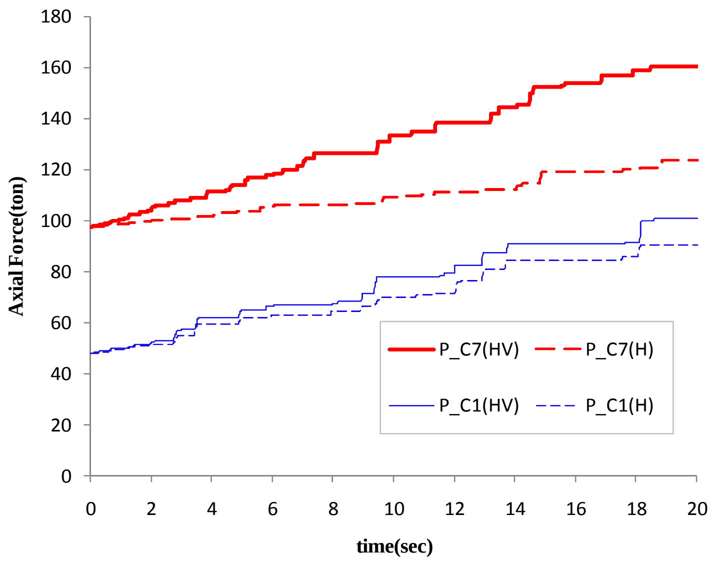


Figure 10. Axial force in columns under Horizontal vs. Horizontal+vertical components. F3DMMS3X3Y3IRX

In Figure 10, for column C7, the ET curve, considering vertical excitation is remarkably higher than the ET curve without vertical acceleration, while for C1 the effect of vertical acceleration is negligible. In this situation, time history analysis using actual records and ET method, taking vertical acceleration directly into account are important and should be applied simultaneously in the analysis with horizontal components.

7.3 Multi-component analysis by ET method

When considering response history analysis, most of the regulations set forth in design codes for general three-dimensional time history analysis, are also applicable for ET analysis. However, some special characteristics of ET acceleration functions require particular consideration. Although ET acceleration functions are statistically independent, all ET acceleration functions are produced in the same manner and use the same assumptions; thus, statistically, the intensity and response spectrum at each time are, theoretically, the same for all ETAF in a set of ETAF. Therefore, definition of major or minor component in the ET method is not relevant. Because all ETAF in each set are alike, to reduce discrepancies, sets of ET acceleration functions are obtained by replacing ET acceleration functions alternatively with each other; i.e. the first set of ET excitations, named"ETA20f-1,2,3" include ETA20f01 in X, ETA30f02 in Y and ETA20f03 multiplied by a factor of 2/3 in vertical direction, the second set, named " ETA20f-2,3,1" is a combination of ETA20f02 in X, ETA20f03 in Y and ETA20f01 with a factor of 2/3 in vertical direction and the third set, " ETA20f-3,1,2" is made up of ETA20f03 and ETA20f01 in X and Y and ETA20f02 with a factor of 2/3 in vertical direction, respectively. These sets are applied to the structure alternatively and results are averaged for final evaluation.

Using ET method, the 3D models were analyzed and results compared with those from time history analysis under previously mentioned real accelerograms in a situation where components of records are applied in principal directions of structures. For instance, Maximum displacements of the irregular 15 story building, obtained from these methods are compared in Figure 11.

Infact in ET analysis, time is a representative of intensity. It is obvious that results from the ET method are continuously increasing by the time, while responses of real accelerograms appear as points as well as static and response spectrum methods. These values are compared with the ET method at target time, i.e. t=10 s in this study (Figure 11).

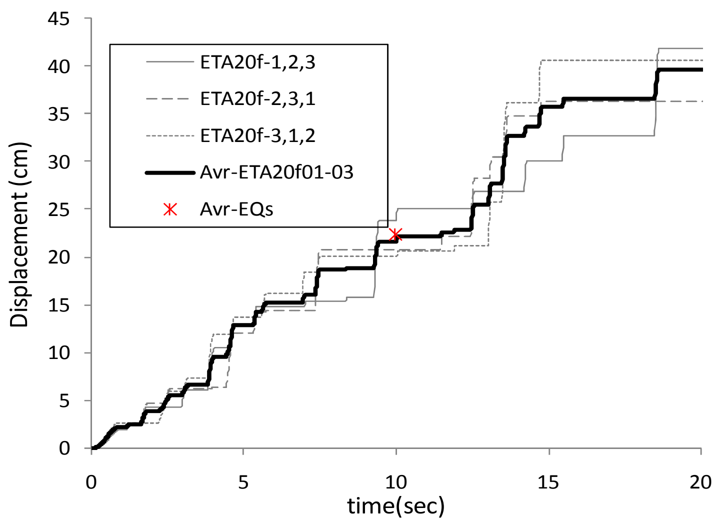


Figure 11.Maximum displacements at top of F3DMMS15X6Y4IR under 3 components of earthquakes and ETAF

As it can be seen, the displacement at top of building is almost the same for ET method and response history analysis. In this model, as shown, the average response to ground motions is very close to response of ETAFs at target time. In Table 4, the relationships between results of ETAFs and ground motions are discussed.

In Figure 12, for irregular 15-story building, displacements and drifts of stories in ET method at t=10 s is compared with time history analysis under ground motions considering all translational components. It is apparent that ET method and time history analysis similarly estimate the displacement response of frame. In this study, averaging the results from 3 sets of ETAF has been applied in order to reduce the random scattering of the results. The number of analyses to be averaged depends on the nature of the problem and in some cases, a single analysis may provide good approximation.

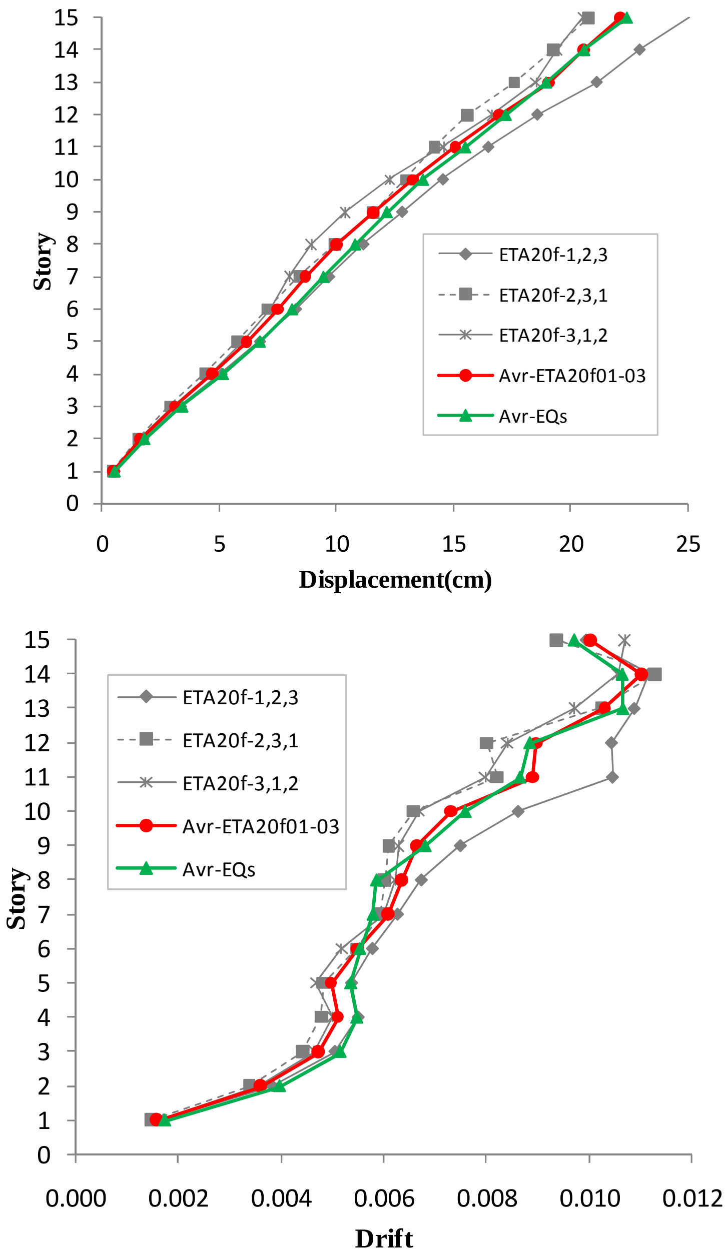
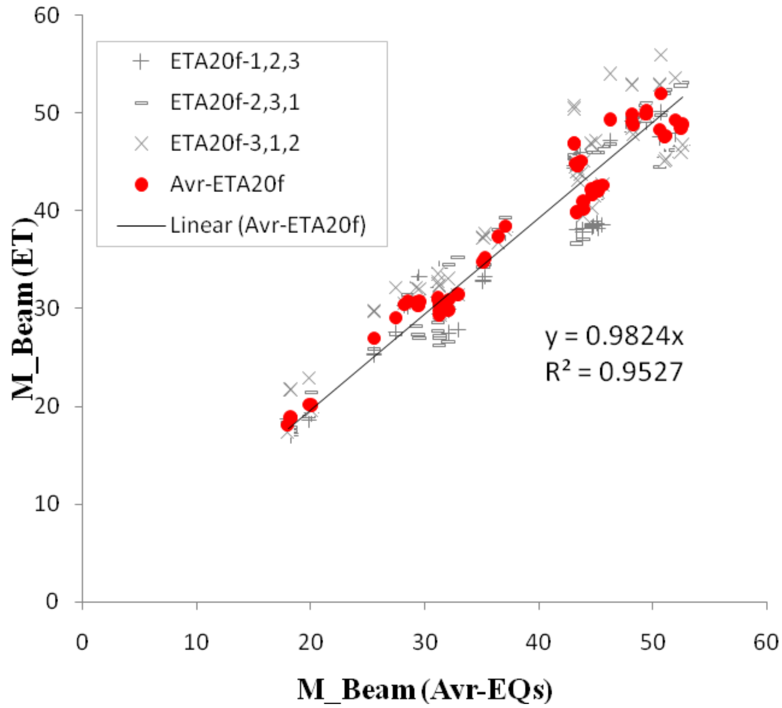


Figure 12. Maximum displacements and drifts of stories. F3DMMS15X6Y4IR

In addition to displacements and drifts, internal forces in all members, including beams and columns, were investigated. The maximum moment in beams and axial force in all columns of the regular 5 story frame are depicted in Figure 13 for each series of ETAF versus time history analysis.



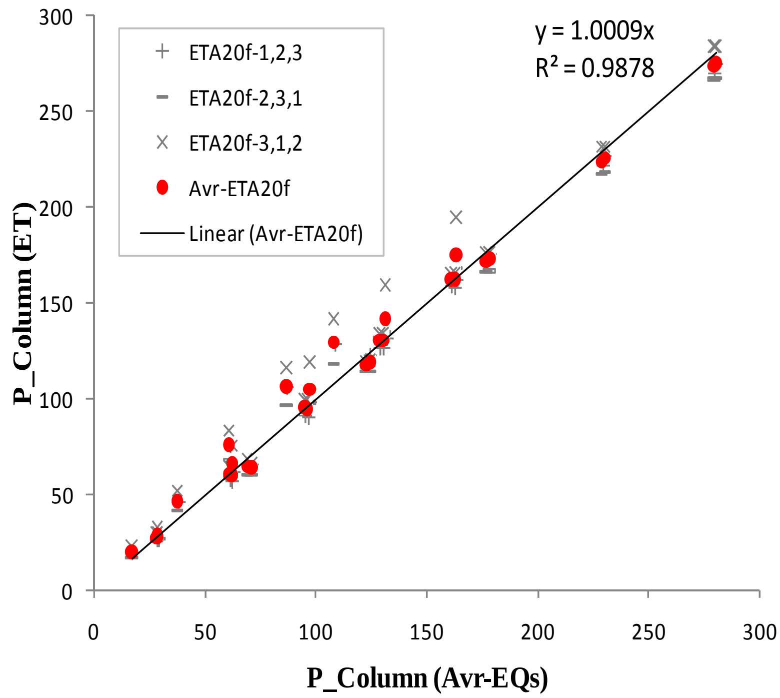


Figure 13. Comparison of time history analysis with ET method, considering vertical excitation effects, F3DMMS05X4Y4

There are some differences between results of ETAF and ground motions, these differences occur mostly due to the incompatibility of response spectra of ET acceleration functions and design spectrum. This problem is caused by the roughness of the target spectrum and optimization problems in generating ET acceleration functions.

To reduce these discrepancies, compatibility between ETAF response spectrum and design spectrum should somehow be improved; this goal can be achieved by producing more optimized ET acceleration functions or using more than three acceleration functions in ET analysis. Due to the fact that this incompatibility can be reduced because of the negligibility of this difference, current set of ET acceleration functions are regarded as acceptable.

The correction factor is defined as the relation between results from ground motions and ET analysis at target time (t=10 s).

As mentioned before, by using one set of ETAF, the discrepancies of results may be significant and not accurate enough for final design purpose. But using average of three sets of ETAF, results are appropriately correlated with results from time history analysis and are quite reliable. In addition to irregular 15 story frame, the correction factor (CF) and correlation coefficient (ρ) of results between the ETAF and ground motions is derived for studied frames which are presented in Table 4.

Table 4: Scale factor and correlation coefficient of structural responses under ETAF and real earthquake

Models	ETAF Combination	Displ		Mb		Pc		Mc	
		CF	ρ	CF	ρ	CF	ρ	CF	ρ
	ETA20f-1,2,3	0.980	0.973	0.953	0.960	0.935	0.998	1.026	0.993
	ETA20f-2,3,1	0.965	0.969	0.967	0.933	0.971	0.998	0.836	0.992
	ETA20f-3,1,2	1.119	0.993	1.058	0.983	0.983	0.992	1.104	0.994
F3DMMS03X3Y3	Avr-ETA20f01-03	1.021	0.997	0.993	0.999	0.963	0.999	0.989	0.998
	ETA20f-1,2,3	0.920	0.984	0.956	0.975	0.955	0.996	0.902	0.808
	ETA20f-2,3,1	1.075	0.995	1.034	0.937	0.990	0.997	0.996	0.857
	ETA20f-3,1,2	0.856	0.976	0.999	0.914	0.992	0.987	0.966	0.955
F3DMMS03X3Y3IRX	Avr-ETA20f01-03	0.950	0.992	0.997	0.991	0.979	0.998	0.954	0.935
	ETA20f-1,2,3	0.945	0.991	0.954	0.952	0.987	0.995	0.818	0.972
	ETA20f-2,3,1	0.961	0.975	0.977	0.957	0.972	0.996	1.057	0.989
	ETA20f-3,1,2	1.055	0.968	1.016	0.947	1.044	0.988	0.937	0.979
F3DMMS05X4Y4	Avr-ETA20f01-03	0.963	0.992	0.982	0.978	1.001	0.995	0.937	0.985
	ETA20f-1,2,3	1.045	0.932	0.954	0.952	0.987	0.995	0.992	0.934
	ETA20f-2,3,1	0.890	0.962	0.977	0.957	0.972	0.996	0.735	0.984
	ETA20f-3,1,2	0.826	0.940	1.016	0.947	1.044	0.988	0.991	0.982
F3DMMS05X4Y4IRXY	Avr-ETA20f01-03	0.920	0.987	0.982	0.978	1.001	0.995	0.906	0.976
	ETA20f-1,2,3	0.975	0.947	0.917	0.972	1.110	0.994	0.827	0.997
	ETA20f-2,3,1	0.840	0.973	0.868	0.968	1.029	0.993	0.787	0.989
	ETA20f-3,1,2	0.844	0.956	0.862	0.961	0.978	0.999	0.891	0.997
F3DMMS15X6Y4	Avr-ETA20f01-03	0.886	0.972	0.882	0.988	1.039	0.997	0.835	0.998
	ETA20f-1,2,3	1.042	0.992	0.967	0.965	0.919	0.984	1.070	0.994
	ETA20f-2,3,1	0.952	0.993	0.930	0.965	0.909	0.981	0.874	0.989
	ETA20f-3,1,2	0.974	0.993	0.901	0.977	0.937	0.990	0.880	0.987
F3DMMS15X6Y4IRXY	Avr-ETA20f01-03	0.989	0.998	0.933	0.993	0.922	0.988	0.942	0.996

As can be seen in Table 4, the mean value of correlation coefficient between each set of ETAF and real accelerograms for various responses of studied frames is near 0.95 for studied indexes and the Standard Deviation is 0.05. This means that all members conform to almost a constant correction factor and with application of this factor, the average response of ground motions can be more accurately estimated by the ET method. However to improve the accuracy, average of three pairs of ETAF is used. The next point in this table is that discussed CFs for all frames are about 1, (with maximum 19% tolerance), meaning that results from the ET method at target time is the same as results from the average of ground motions.

According to results obtained by this research it is found that ET method is a reliable method which is capable of being used for three-dimensional analysis of buildings under three-directional excitations in linear analysis. The results are closely comparable with those obtained by time history analysis. This method is advantageous, because not only it doesn't have limitations of Codes provisions for considering vertical acceleration, but also it is straightforward for application and interpretation of results. Based on these observations, the investigation of ET method in nonlinear three-dimensional analysis is strongly recommended.

8. CONCLUSIONS

In this paper, a multi-component version of the ET method including the vertical component is proposed and compared to time history analysis of three dimensional elastic moment frames using ground motions. Several three dimensional steel frames with 3,5 and 15 stories were designed and analyzed with mentioned approaches under three-directional excitations and results were compared.

It is observed that by considering the analysis results from response history method as the reference, ET method can predict behavior of structures with appropriate approximation. The average of correction Factor in analysis results by ET and standard time-history of the studied frames is about 0.95 with SD equal to 0.05. Also the correlation of coefficients for nearly all studied frames are close to unity. Average of results from ground motions that is being used for design of structure can be estimated by ET method with acceptable approximation. The correlations of results approve the validity of proposed procedure for linear analysis considering multi-component excitation including the vertical component.

These results lay a foundation for the extension of the proposed procedure to nonlinear region where to full advantages of the proposed procedure can be realized.

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