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Estimating the response of concrete moment frames subjected to individual ground motions using endurance time excitation functions fitted to average acceleration response spectra

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Abstract. Endurance Time (ET) method is an efficient time history-based analysis procedure that applies special acceleration functions for estimating the seismic performance of structures at different excitation levels in every single analysis. For some structures with complex models, such as dams, it is impractical to conduct multiple seismic analyses due to the high computational cost. In such cases, for obtaining accurate structural responses, it is recommended that researchers pay conscious attention to choose compatible Endurance Time Excitation Functions (ETEFs) regarding the basic properties of their structures, such as the soil type of the site, the selected design spectrum, and the type of the analysis. However, in this study, it is observed that using various ETEFs to analyze a concrete moment frame subjected to a single earthquake ground motion will cause us to obtain unreliable responses. In other words, different ETEF series have significantly different accuracies (26% error) in predicting the responses of the mentioned structure which is subjected to individual earthquake ground motions. This problem is mainly caused by the turbulent nature of a single ground motion spectrum, which is in contrast to the smooth shape of the ETEF spectrum. One solution to avoid this problem could be to produce a specific ETEF.

1. Introduction

Time history analysis can generate different results for a specific structure subjected to different ground motions. This difference occurs because no two seismic ground motions have the same records. To observe the behavior of the structure under the action of an earthquake, a large number of seismic records must be selected and utilized. However, the Endurance Time (ET) method can provide a proper setting for this observation by a single ET analysis. In other words, a single ET analysis is equivalent to analyzing earthquakes of all intensities [1].

Several series of Endurance Time Excitation Functions (ETEFs) have been generated so that they could match the target acceleration spectrum (code design spectrum or spectrum produced by the ground motions) whereas the duration consistency has not been directly considered [2]. Although several tables containing the basic attributes of each ETEF series are provided in the references, unfortunately, for most of the research, researchers select the most recently

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produced series or a random one, ignoring these tables and the attributes of their projects. In this study, it is proved that various series of ETEFs have significantly different accuracies in predicting the responses of structures subjected to the earthquake ground motions.

There are several types of structures on which it is impractical to perform multiple time history analyses because of the tremendous computational cost or other limitations. A great example is dam structures. In analyzing such cases, specific ET records should be chosen or produced that are compatible with the basic properties of the project. In such large models, a large number of errors are unacceptable, and using the appropriate ETEF series to analyze the system again will waste a lot of time and effort. Shaking table tests, especially full-scale tests, also have conditions that make it impractical to perform multiple analyses.

The structure studied is an eight-story concrete moment resisting frame (three floors underground) located in Tehran. The geometrical information of the structure is shown in Figure 1.

The analysis and design procedures of the structure are in agreement with the Iranian National Building Code standard 2800 and ASCE7-10. It is assumed that the shear wave velocity of the site where the structure is located is 425 m/s. In other words, in agreement with Refs. [3,4], the C-type soil and type II are selected, respectively. The total weight and lateral stiffness of the structure were equal to 7,416.71 ton_f and 212.42 ton_f/cm respectively, and the fundamental vibration period of the structure was equal to 1.18 seconds. The mass participation ratio of the dominant mode of vibration (first mode) was equal to 57.7%. The damping ratio of the system is assumed to be 0.05. The structure is classified as risk category II or medium importance according to Refs. [3] and [4], respectively, and the design base shear is equal to 976 ton_f [4].

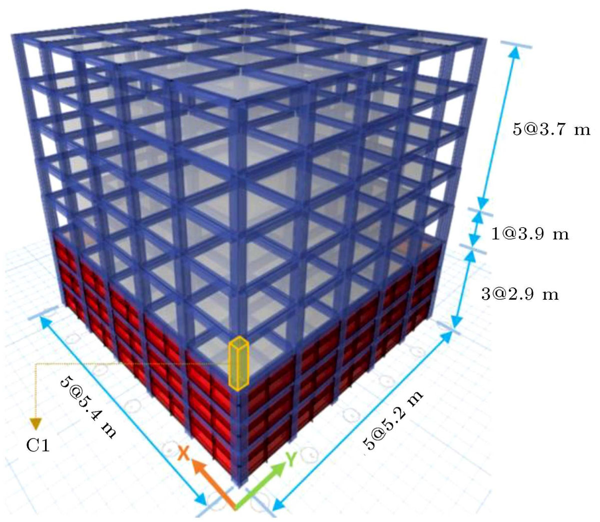

Figure 1. General view of the studied structure.

In this study, to compare the responses of different series of ETEF and earthquakes, the following parameters are randomly selected. The studied structure subjected to the mentioned records is analyzed, and the response time histories of these parameters are determined. The so-called "control parameters" are as follows:

1. Base shear in X direction;
2. Roof displacement in X direction;
3. Axial force of column C1 at story 1 (C1 is marked in Figure 1).

In the present study, an engineering software suitable for the analysis and design of multi-story buildings has been utilized for analyzing the structure [5]. The three-dimensional model of the structure under study is analyzed in a single direction (X direction) without considering the effects of torsion. The type of analysis is nonlinear modal analysis assuming that the material used has perfect elastic-plastic behavior.

2. Reference ground motions set

The first horizontal component of the 22 far-field records, proposed by FEMA P-695, has been utilized in this study, and the two components recorded in other directions are ignored. These ground motions are applicable to structures located on soil type C [6]. Table 1 shows the description of the selected ground motions used in this study, and Figure 2 shows their unscaled response acceleration spectra. It should be noted that all records are obtained from the Pacific Earthquake Engineering Research Center (PEER) ground motion database. For the sake of simplification, the selected ground motions are applied to the studied structure merely in its X direction. Due to the concentricity of

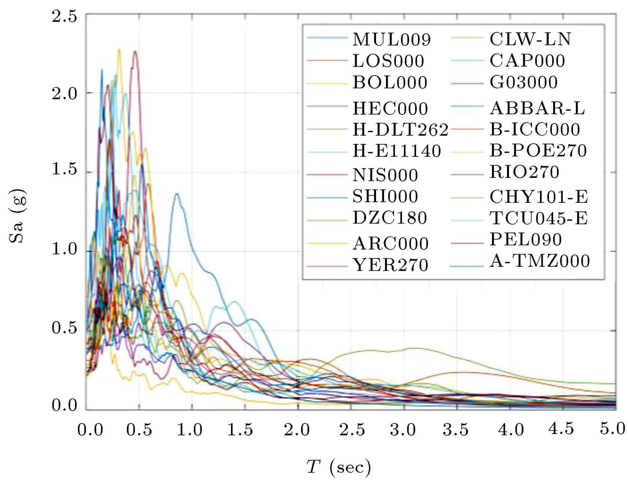

Figure 2. Unscaled response acceleration spectra of the selected ground motions.

Table 1. Description of the selected ground motions [6,7] .

ID no.	Recorded seq. no.	Lowest freq. (Hz)	File name	PGA_{max} (g)	PGV_{max} (cm/s)
1	953	0.25	NORTHR/MUL009	0.52	63
2	960	0.13	NORTHR/LOS000	0.48	45
3	1602	0.06	DUZCE/BOL000	0.82	62
4	1787	0.04	HECTOR/HEC000	0.34	42
5	169	0.06	IMPVALL/H-DLT262	0.35	33
6	174	0.25	IMPVALL/H-E11140	0.38	42
7	1111	0.13	KOBE/NIS000	0.51	37
8	1116	0.13	KOBE/SHI000	0.24	38
9	1158	0.24	KOCAELI/DZC180	0.36	59
10	1148	0.09	KOCAELI/ARC000	0.22	40
11	900	0.07	LANDERS/YER270	0.24	52
12	848	0.13	LANDERS/CLW-LN	0.42	42
13	752	0.13	LOMAP/CAP000	0.53	35
14	767	0.13	LOMAP/G03000	0.56	45
15	1633	0.13	MANJIL/ABBAR–L	0.51	54
16	721	0.13	SUPERST/B-ICC000	0.36	46
17	725	0.25	SUPERST/B-POE270	0.45	36
18	829	0.07	CAPEMEND/RIO270	0.55	44
19	1244	0.05	CHICHI/CHY101-E	0.44	115
20	1485	0.05	CHICHI/TCU045-E	0.51	39
21	68	0.25	SFERN/PEL090	0.21	19
22	125	0.13	FRIULI/A-TMZ000	0.35	31

centers of mass and stiffness of the studied structure, the effects of torsion are neglected.

To perform the dynamic analysis, the ground motions should be scaled. The scaling approach of the 16th chapter of ASCE7-10 is utilized in this study. The design spectrum of ASCE7 should be initially determined. Ref. [8] has provided the required parameters for Tehran city. Figure 3 shows the design response spectrum of the studied structure.

ASCE7 introduced the procedure of scaling seismic ground motions, which will be briefly explained below. The selected earthquake ground motions shall be scaled such that in the period range from $0.2T$ to $1.5T$, where T is the fundamental period of the structure, the values of the earthquake acceleration spectra do not fall below the corresponding ordinate of the design response spectrum [3,9]. The flowchart indicated in Figure 4 provides a general view of the scaling procedure. Figures 5 and 6 provide a general view of the scaling procedure of this study.

As can be seen in Figure 6, the unscaled acceleration spectrum of the earthquakes needs to be multiplied by 1.64 to stand above the design spectrum in the determined period range. Therefore, all ground motions should be multiplied by 1.64 before being defined in the engineering software to meet the requirements of the selected design codes.

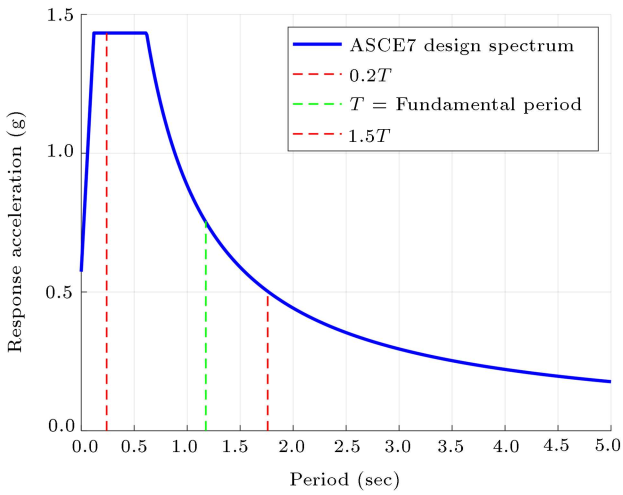

Figure 3. ASCE7 design spectrum for the studied structure [3,8].

3. Selected series of ETEFs

The ETEFs are designed in such a way that their intensity increases over time. The excitation starts from the minimum intensity and gradually increases over time until the structure collapses. Utilizing these functions provides a proper setting for observing the structural responses through the entire range of

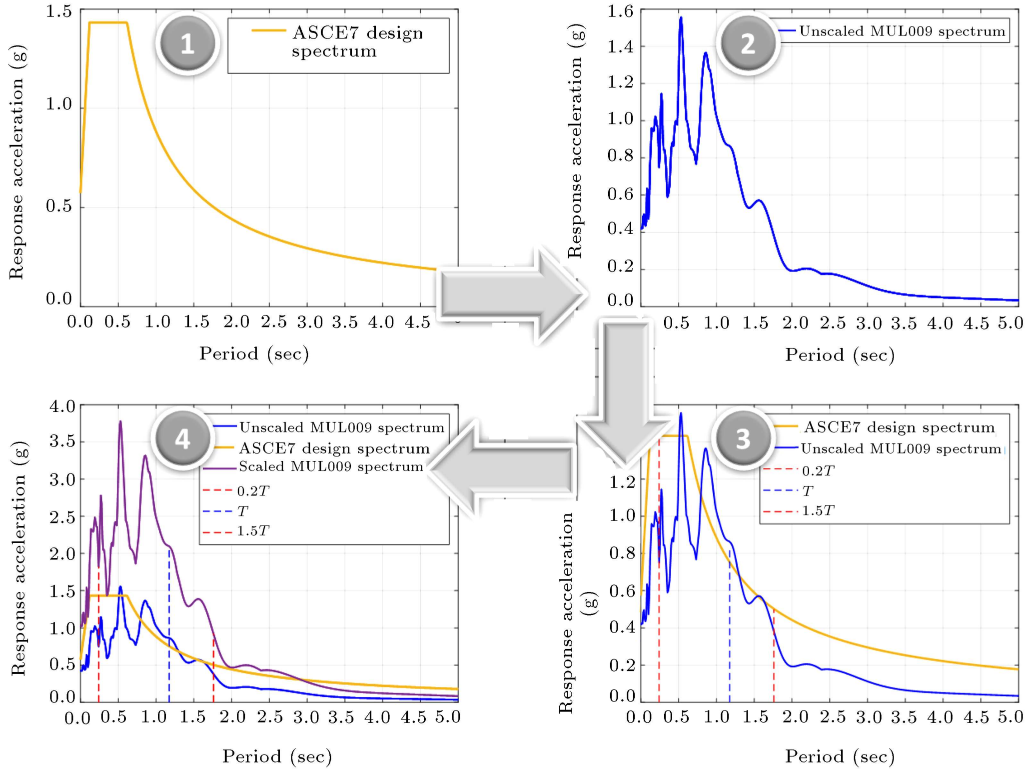

Figure 4. Flowchart indicting the procedure of scaling a single earthquake record.

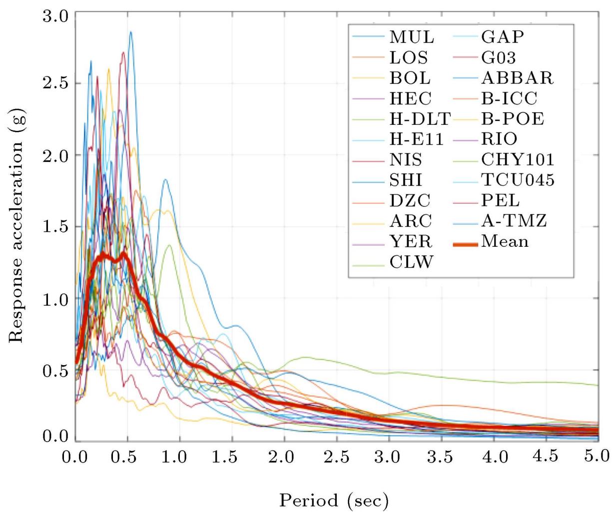

Figure 5. Unscaled spectra of the selected ground motions and their average.

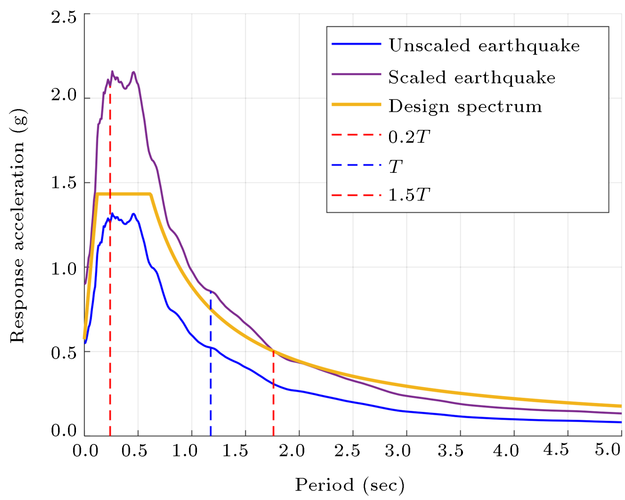

Figure 6. Overview of the procedure of scaling the average of the selected earthquake records.

intensities. Therefore, this method reduces the number of required time-history analyses. ETEFs are produced using numerical optimization methods in such a way that their acceleration response spectrum until any specific time is proportional to the intended design acceleration spectrum [10,11]. In this study, four series of ETEFs suitable for structures located on C-type soil structures are randomly selected. When the structure is subjected to 3 single records for each series, the time histories of the control parameters are determined [12]. The names of the selected ETEF series and their brief description are presented in Table 2.

4. Target times of ETEF series

The comparison of the structural responses obtained from the analysis of structure subjected to earthquake and ET records is performed within a time window from zero to the target time [13]. The target time

Table 2. Brief description of the selected Endurance Time Excitation Function (ETEF) series [12].

ETEF series	ETA40g	ETA40h	ETA20in	ETA20jn
Design spectrum	ASCE7 for Los Angeles (Ss = 1.5; S1 = 0.6; Fa = 1.0; Fv = 1.3; TL = 8)	Average spectra of 7 records for soil C FEMA 440 selected by Dr. Tajmir	Average of 20 records (multiple directions) used in FEMA 440 for soil type C	ASCE7 for Tehran seismic characteristics for soil type C
Number of points	4096	4096	2048	2048
Sampling frequency	100 Hz	100 Hz	100 Hz	100 Hz

is when the intensity of the excitation created by the ETEF is equal to the average intensity of the earthquakes. The intensity criterion is usually the intensity of the acceleration spectrum in the range $0.2T$ to $1.5T$ [14]. Within this period range, the average intensity of the ETEF spectra should be pursued until it reaches that of the earthquake ground motions at a particular time, which is the target time. This time will be the target time [15,16]. In simple terms, the necessary condition for comparing ETEF with ground motion is to determine the target time for each ETEF.

The procedure for determining the target time of ETA40g series records when the structure is under the action of the MUL009 earthquake is shown in Figure 7. As shown in Figure 7, after determining the fundamental period of the studied structure, the spectra of the MUL009 earthquake and ETA40g records in several time windows starting at zero and ending at the target time were derived. It was determined that if the ETA40g records target time was equal to 17.47 seconds, the area below their graph of acceleration spectrum would have the least discrepancy in comparison to that of the MUL009 record in a period range starting at $0.2T$ and ending at $1.5T$.

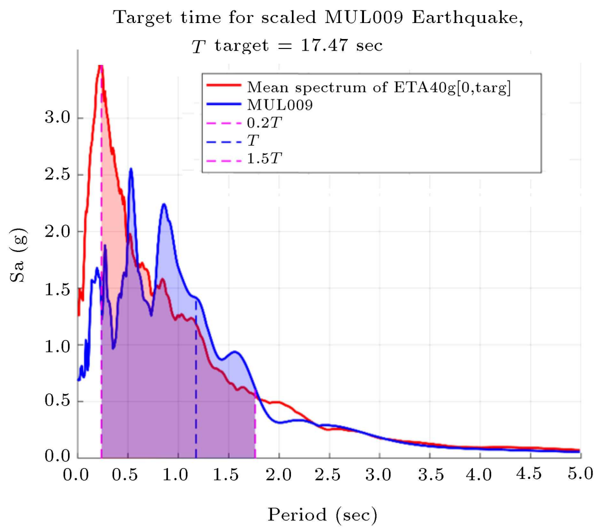

Figure 7. Matching the target time of ETA40g record for MUL009 scaled earthquake record.

5. Structural responses and performing the comparison

Table 3 contains the maximum responses of the control parameters of the structure subjected to the scaled ground motions. These results have been obtained from nonlinear time history analysis and will be compared to their corresponding values from ET analysis. For a general comparison, Table 4 is provided which contains the maximum values of the selected control parameters of the structure subjected to ETEFs and ground motions. Its last column contains the average error percentages of each ETEF series, which is used to estimate the responses of the structure subjected to each selected scaled earthquake record. It should be noted that the data in ETEF rows are the average of the three individual records in each series of ETEFs. For a much better illustration of the data provided in the aforementioned table, Figure 8 is provided.

It can also be concluded from Table 4 that ETEFs have high statistical dispersion in estimating the response of the structure under each seismic condition. For instance, ETEFs can estimate the responses in the CAP000 earthquake with an average error percentage of 14, but in the case of the H-DLT262 earthquake, this parameter is equal to 42%.

It is worth mentioning that every series of ETEFs consists of three single records; for instance, the ETA20inx series contains "ETA20inx01", "ETA20inx02", and "ETA20inx03" records that vary in their excitation functions. Since ET references contend that using merely one or two of these records, results in wrong responses, for obtaining more precise and accurate results, all of them must be imposed to the structure and the maximum of absolute of their response time histories (not the mean or median of them), shall be utilized [17]. However, recently researchers have become more and more interested in the production and utilization of a single ETEF with the help of special mathematical procedures (such as spectral matching methods) [18].

Based on Figure 8, it is apparent that in a few cases, ETEFs have noticeable errors in estimating the results of a few earthquake cases such as the MUL009 earthquake, but on the other hand, there are some

Table 3. Maximum amounts of the chosen parameters (case: earthquakes).

No.	Earthquakes	Base shear X (ton_f)	Roof disp. X (cm)	Column C1 force (ton_f)
1	MUL009	5450	65	27.9
2	LOS000	3470	21.1	13.9
3	BOL000	6400	35	23.6
4	HEC000	2730	35.3	16.5
5	H-DLT262	1990	14.9	7.7
6	H-E11140	2920	16.8	10
7	NIS000	4170	20.8	18
8	SHI000	2460	32.3	16.3
9	DZC180	2730	27	19.2
10	ARC000	1440	8.6	5.1
11	YER270	3080	38.2	17.9
12	CLW-LN	2720	16.3	8.4
13	CAP000	4470	45.1	22.9
14	G03000	5470	15.7	13.9
15	ABBAR–L	4850	13.5	10.8
16	B-ICC000	3420	37.4	18
17	B-POE270	4900	25.4	16.2
18	RIO270	3400	36.5	19.6
19	CHY101-E	2780	25.9	13.1
20	TCU045-E	4120	16.6	14.6
21	PEL090	2360	20	10.7
22	A-TMZ000	2890	14.6	9.9

$$\mu(\%) = \frac{Value\ of\ control\ parameter_{Earthquake} - Value\ of\ control\ parameter_{ET}}{Value_{Earthquake}} \times 100. \quad (1)$$

Box I

cases like the ARC000 earthquake that ETEFs have estimated precise structural responses. It is expected that the comparison of these two different cases will lead us to a general conclusion. As it was illustrated in Section 4, the mentioned comparison needs to be done regarding each ET record's target time. Figure 9 has been provided to facilitate the conclusion. It consists of diagrams containing the spectra of the MUL009, ARC000, and ETEFs (until their target times). Within the period range $0.2T$ to $1.5T$, a significant difference can be observed between the area under the spectra of the MUL009 and the ETEF. On the other hand, in the case of the ARC000, the mentioned discrepancy is insignificant. Therefore, it can be concluded that this discrepancy is due to the incompatibility between the shape of the ground motion spectrum and the shape of ETEF (until its target time) in the selected period range.

To calculate the mean error percentages of ETEFs in estimating the values of the control parameters, Eq. (1), shown in Box I, has been employed and the results have been compiled in Table 5. It should be noted that the ETA20jn series cannot be utilized in this study due to its disability in estimating the results of 6 earthquake ground motions cases. In other words, the error percentage of this series in Table 5 is the mean of 16 items, not 22.

By observing the results indicated in Table 5 it can be concluded that the four selected series of ETEFs have significantly different accuracies (26.4% error on average) in predicting the responses of an intermediate concrete moment frame structure subjected to individual ground motions. To determine the origin of this error, the average of the values of the response acceleration spectra of ETEFs and earthquake records within the period range of $0.2T$ to $1.5T$ are compared. Table 6 indicates the mean error percentages of each series of ETEFs spectra and that of earthquake records

Table 4. Maximum values of the control parameters of the structure subjected to Endurance Time Excitation Functions (ETEFs) and earthquakes.

		Names of the single earthquake records																						**Mean error percentage**
		MUL009	**LOS000**	**BOL000**	**HEC000**	**H-DLT262**	**H-E11140**	**NIS000**	**SHI000**	**DZC180**	**ARC000**	**YER270**	**CLW-LN**	**CAP000**	**G03000**	**ABBAR–L**	**B-ICC000**	**B-POE270**	**RIO270**	**CHY101-E**	**TCU045-E**	**PEL090**	**A-TMZ000**	
Base shear X (ton_f)	**Earth.**	**5500**	**3500**	**6400**	**2700**	**2000**	**2900**	**4200**	**2500**	**2700**	**1400**	**3100**	**2700**	**4500**	**5500**	**4800**	**3400**	**4900**	**3400**	**2800**	**4100**	**2400**	**2900**	
	ETA40g	6500	4200	6500	2800	2800	4000	4900	4000	4200	1000	4200	2800	6300	4200	4200	4200	4200	4200	4200	4200	2200	2800	20
	ETA40h	5000	4000	5000	1800	1800	2400	4200	2200	2800	900	2800	1900	4300	2800	2800	2800	2800	4000	2800	3400	1700	1800	31
	ETA20inx	7800	4400	7800	3000	3000	3400	5000	3400	3400	1100	3400	3000	5100	3400	4000	3400	3400	4200	3400	4200	2600	3000	19
	ETA20jn				3200	3400	3600		3600	3900	900	3900	3400		3900	4400	3900	3900		3900	6500	2300	2900	18
Roof disp. X (cm)	**Earth.**	**65**	**21**	**35**	**35**	**15**	**17**	**21**	**32**	**27**	**9**	**38**	**16**	**45**	**16**	**13**	**37**	**25**	**37**	**26**	**17**	**20**	**15**	
	ETA40g	50	34	50	19	23	27	38	27	27	8	27	23	44	27	27	27	27	30	27	27	16	19	30
	ETA40h	39	27	39	16	16	17	27	17	19	6	19	16	34	19	19	19	19	27	19	25	12	16	42
	ETA20inx	44	28	44	20	22	22	37	22	27	9	27	22	44	27	27	27	24	27	24	27	16	20	30
	ETA20jn				17	18	21		21	21	5	21	20		21	22	21	21		21	24	13	16	31
Column C1 force (ton_f)	**Earth.**	**28**	**14**	**24**	**17**	**8**	**10**	**18**	**16**	**19**	**5**	**18**	**8**	**23**	**14**	**11**	**18**	**16**	**20**	**13**	**15**	**11**	**10**	
	ETA40g	28	18	28	10	13	15	20	15	15	4	15	13	24	15	15	15	15	17	15	15	9	10	19
	ETA40h	20	15	20	9	9	10	15	10	10	3	10	9	18	10	10	10	10	15	10	14	7	9	38
	ETA20inx	26	17	26	11	12	12	19	12	14	5	14	12	25	14	15	14	13	15	13	15	9	11	20
	ETA20jn				11	12	12		12	13	3	13	12		13	13	13	13		13	14	8	11	21

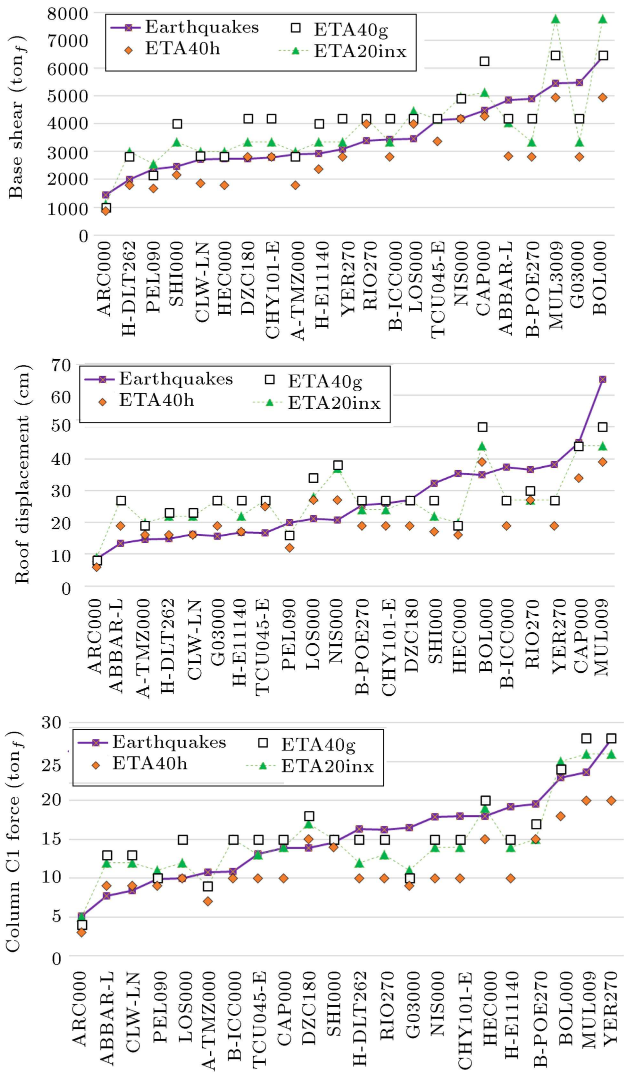

Figure 8. Overview of the values of the control parameters of the structure subjected to Endurance Time Excitation Functions (ETEFs) and ground motions.

inside the mentioned period range. Regarding Tables 5 and 6, it can be concluded that the ETA20inx series is the most appropriate ETEF series for estimating the responses of the studied structure subjected to the selected scaled earthquake records.

This conclusion is reasonable and can be predicted through the initial steps of the study. For a better understanding, Table 7 is provided, which contains the main attributes of the ETEF series used.

Among these four series of ETEFs, the ETA20inx series have the most common properties with the conditions of our project and the selected earthquake records. For instance, the template spectrum of the mentioned series is very similar to that of our project and the soil type of both is C. In addition, the optimization scope and applicability of this series can also explain why its accuracy in predicting seismic response is higher than other series. Therefore, it can be concluded that selected ETEF series and earthquake records that have the most attributes in common will provide the most similar and compatible analysis results. In fact, it is recommended that researchers produce a specific ETEF for their project to obtain the most precise and accurate results. In [19], for the first time, for time history analysis of a gravity dam, an ETEF has been generated that its response spectra and other intensity characteristics (e.g., nonlinear displacement and hysteretic energy) are compatible with a selected real ground motion.

Table 5. Total mean error of the estimated values of the control parameters in comparison to their real values (earthquake results).

ETA series	Mean error percentage
ETA20inx	24.5
ETA40h	25.1
ETA40g	27.2
ETA20jn	29

6. Conclusions

The Endurance Time (ET) method is a time history analysis method that simplifies the estimation of structural response at different seismic intensity levels Endurance Time Excitation Functions (ETEFs) play a pivotal role in the performance of the ET method. In the present study, the capability of the existing ETEFs to estimate the response of the structure under a single ground motion was evaluated. The results of the present study could be summarized as follows:

1. Various ETEF series have an average error percentage of 24 to 29 (total mean error of 26%) in estimating the responses of intermediate concrete moment frame structure located on soil type C in Tehran which is subjected to individual ground motions. It is apparent that the responses with such errors are not reliable. However, this conclusion is limited to the analysis of a single ground motion, especially when the acceleration spectrum is not smooth;

2. Error percentage of the conventional ET analysis (using the existing ETEFs) in the estimation of structural responses of various single ground motions may significantly differ from each other. For instance, the existing ETEFs can estimate the structural responses of the CAP000 earthquake with an average error percentage of 14 but in the case of the H-DLT262 earthquake, the latter parameter is equal to 42%. The magnitude of the error mainly depends on the degree of unsmoothness and turbulence of the spectrum of a single ground

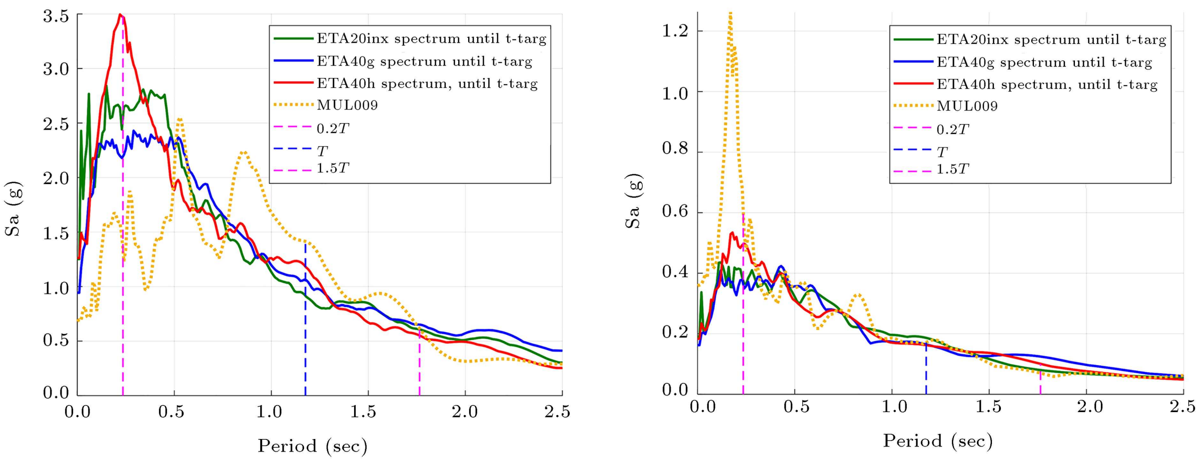

Figure 9. Comparison of the spectra of MUL009 and ARC000 earthquakes with Endurance Time Excitation Function (ETEF) series at their target times.

Table 6. Error percentages of the spectra of Endurance Time Excitation Functions (ETEFs) in comparison to each spectrum of the 22 selected ground motions.

Type of ET analysis	Error percentages		
	ETA20inx	**ETA40g**	**ETA40h**
Average error percentage of ETEF spectra in comparison to the spectrum of each of the selected earthquake records (singular earthquake recorded ET analysis)	30.2	88.4	88.6
Average error percentage of ETEF spectra in comparison to the spectrum of the average of all of the selected earthquake records (conventional ET analysis)	5.5	4.7	8.4

Table 7. Main properties of the selected series of Endurance Time Excitation Functions (ETEFs).

ETEF series	Template spectra	Optimization scope	Applicability	Notes
ETA20inx	FEMA440 20 GMs	Nonlinear	Nonlinear	Recommended for general and nonlinear analysis
ETA40g	ASCE07	Linear	Nonlinear	Covers higher intensities up to a scale factor of 4
ETA40h	FEMA440 7 motions	Linear	Nonlinear	Covers higher intensities up to a scale factor of 4
ETA20jn	ASCE07	Nonlinear	Nonlinear	Design applications

motion. Since these fluctuations are smoothed in the conventional ET analysis by using the average of multiple earthquake records, such problems do not arise in that case.

3. In this study, the target time is defined as the equalization time of the spectral mean values of ETEFs and seismic records (within the period range of 0.2T to 1.5 T). However, various methods for determining the target time do exist and are expected to have a considerable effect on the accuracy of the ET method in estimating the responses of singular earthquakes.

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