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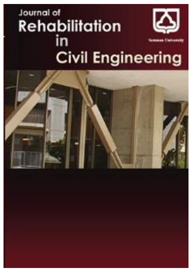

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Investigating the Effect of Earthquake Duration on Concrete Structures by Analyzing the Frequency Content of Acceleration Time History

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ABSTRACT

The occurred earthquakes in recent years have proved that in some parts of the world, they possess more duration and cause further damage to structures. Due to the fact that major cities of Iran are located in the high seismic areas and also a significant part of existing buildings are concrete structures, it is necessary to study their vulnerability under long duration earthquakes. In this study, the performance of concrete structures affected by earthquakes with different durations (from low to high) has been investigated. In order to investigate the duration of the earthquake, a new index is defined, which is the number of accelerated cycles where their period is close to the structure predominant periods (with 10% difference) and their corresponding acceleration is also higher than the plastic acceleration threshold of the structure. For this purpose, three concrete structures with, 3, 6, and 9 stories were designed with optimal sections and the predominant period and the threshold acceleration for entering nonlinear behavior were calculated. Subsequently, all three buildings were investigated in two-dimensional SeismoStruct software and nonlinear analysis was carried out considering the stiffness deterioration and strength reduction (Takeda model). Each of the 3, 6 and 9 story structures was subjected to 119 earthquake records, durations, distances, magnitudes, and different soil types. Seismic performance of structures such as relative maximum displacement and number of plastic joints were investigated. The results of the analysis show that the use of the index introduced in this study is much more efficient than other definitions of duration for damage to concrete structures. In other words, duration of an earthquake, as defined by the number of cycles whose period is near the predominant period of the structure and accelerated beyond the plastic acceleration threshold of the structure, is very consistent with the rate of damage to the concrete structure. In continuation, the effects of the height and plastic acceleration threshold on various models are discussed in detail.

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1. Introduction

The duration of strong ground motions has significant effect on damage to buildings due to the earthquakes. Many physical processes like reduction in the stiffness and strength of structures depend upon the number of loads or stress cycles during the earthquake. A short time motion, even with large amplitude, might not produce enough load cycles to cause failure of the structure. On the other hand a motion with intermediate amplitude but with long duration could produce enough loading cycles to cause damage in structures. Ground excitations induced by the events of large magnitudes and intensities and recorded reports of sites located far from the epicenter all remind us of long duration ground motions. Hence, structures built in these areas should possess data of the load bearing capacity against long duration ground motions with respect to the soil condition at the site [1].

Various researchers have studied the relationship between structural damages and duration of strong ground motions. Chai et al [2] suggested that a longer duration ground motion increases the inelastic design base shear.

Despite various studies performed on the characteristics of strong ground motion duration and different available definitions for duration, there is still need for further studies concerning the effect of earthquake duration on the structures. Not accounting for the earthquake duration in the seismic design codes, has caused rather less concern over necessity of forecasting equations to determine the earthquake duration in comparison to the damping equations used for the spectral accelerations [3]. However, nowadays, various methods have been proposed to consider the reduction of stiffness and strength. For instance, Capraro (2018) investigated the impact of subduction motions on the design, particularly the effect of duration, and evaluated the damage potential of them [4].

Chandramohan (2016) surveyed the influence of structural collapse risk and the integration in the design and assessment practices. The broad objective of this study was to evaluate the influence of ground motion duration on the structural collapse risk, and it was found to be significant to propose methods to consider for the performance assessment and design of structures [5].

2. Various types of earthquake duration

There are various methods for determining duration of severe ground motions using the characteristics and effective parameters of the seismic acceleration-duration diagram. The methods which discuss definition of the strong motion duration using the characteristics of recorded accelerograms could be categorized in three classes as follows: [6].

2.1. Bracketed duration

The simplest definition for the duration is the Bracketed Duration which is defined as the time interval between the first and last exceedance of ground acceleration with respect to threshold acceleration. In this respect, Page [7] has considered the earthquake duration based on the threshold acceleration of 0.05g. In this definition the record shape in the portion of strong motions is not taken into account and there may be two totally different earthquakes with similar threshold acceleration values which indicate equal durations [6].

2.2. Uniform duration

Another definition which considers the general characteristics of the record is called the uniform duration. This duration is the sum of time intervals at which acceleration exceeds a threshold value. Bolt [8] introduced this by defining two threshold values of 0.05g and 0.1g.

2.3. Significant duration

The basis for this third category of definitions is accumulation of seismic energy in the accelerograms. This definition is called also the significant duration. It is calculated as the square of the integral of acceleration. In most of the definitions use has been made of Arias intensity given as:

$$I_A = \frac{\pi}{2g}\int_0^T a^2(t)dt \tag{1}$$

In this relation a(t) is the acceleration at time t which is determined by the accelerogram record and IA is a measure of the total energy causing damage to the structure. The diagram depicting variation of Arias intensity with time is called Husid diagram [9]. Fig.1 shows an example of it.

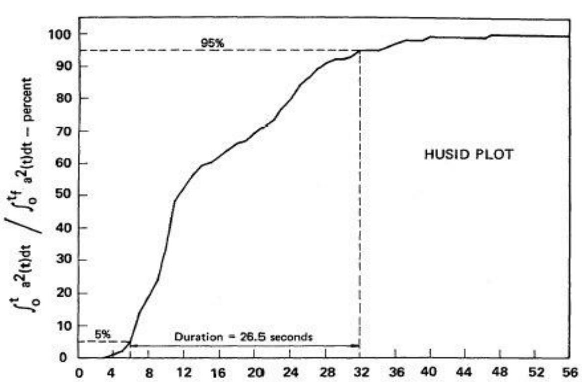


Fig. 1. Husid diagram [9].

The Husid diagram is often comprised of a low slope portion which corresponds to reaching of P waves. The middle portion has a steeper slope which corresponds to the main input energy due to S waves and surface waves. The slope of the end portion is relatively small and is associated with the bulk and surface waves which indirectly reach the accelerogram. The slope of each portion of Husid diagram is in fact the mean square of acceleration.

The significant duration is defined as the time interval which includes a certain percentage of Arias intensity. This percentage is calculated in different ways by the researchers. The most conventional definition is that presented by Trifunac-Brady based on the time elapsed between 5% and 95% of the Husid diagram.

One could find numerous duration-dependent structural engineering programs for assessment of seismic improvement in the literature. Housner [10] was one of the first researchers who proposed that structures should be designed in a way that have enough energy absorption capacity against exerted energies by the ground motion. The ground motion energy demand also is a function of intensity and duration of the earthquake. Housner also suggested that in two given ground motions with similar intensity spectrums, where the duration of one ground motion is greater than the other, the two motions may have different damage effects. Fig.2 shows that the two accelerograms have equal peak ground acceleration (PGA) values while their durations are different [1].

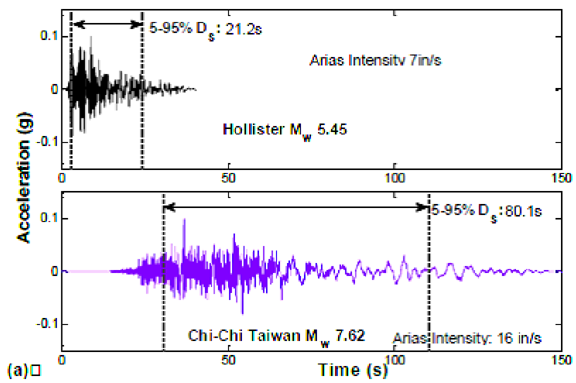


Fig. 2. Comparison of two accelerograms with similar PGAs and different durations [1].

Uang and Bertero [11] performed a comprehensive study on the energy demand of the structures under the earthquake. These studies show that the ground motion energy demand is dissipated by the structure in the form of damping and recursive elastic strain. The relations between input energy and peak spectral velocity are related to the strong motion duration. This result is confirmed by findings of Shome [12], and Rahnama and Manuel [13] which show a relationship between the ground motion duration and the input energy demand and cyclic energy (energy dissipated by the cyclic behavior of the structure which is related to the non-compensable plastic deformation of the structure).In a given structure where the induced energy is greater than the input energy, the entire input energy to the structure during the ground motion is dissipated by damping and hysteresis cyclic performance. This inelastic cyclic behavior causes negligible damage to the structure and the cumulative effects of these negligible damages cause collapse of the structure [14].

2.4. Proposed definition for the earthquake effective duration based on the accelerogram content and predominant period of the structure (cyclic duration)

Cyclic duration is based on the counting of cycles exceeding the plastic threshold acceleration which possess a period close to the structure's predominant period (±10%). In this research it was investigated and found that in low-rise structures, the number of cycles with periods close to the predominant period of the structure is significant. But for medium to high rise structures there is need for considering sum of the cycles close to a number of structure's effective periods.

Understanding the effect of ground motion duration on the cumulative damage and failure mechanism would bring us a step forward in preventing collapse due to the earthquake in the near future; also it could help us with improving the building codes.

Reinforced concrete structures are also vulnerable to various seismic excitations. Researchers have mainly concentrated on seismic vulnerability of structures under destructive earthquakes while neglecting the effect of previous earthquakes. These effects include reduction in stiffness and strength due to accumulation of damages to the construction materials under large amplitude cycles and also impact of P - Δ induced by residual displacements due to the previous earthquakes. Reduction in the stiffness and strength both significantly affect the mechanical characteristics of damaged structure. Consequently it would affect the structure response to future earthquakes [15].

The results have shown that sequences of aftershocks increase damage accumulation in the structures. Furthermore, multi-earthquake sequences with equal input energies would induce similar damage modes in the structures [16].

The reinforced concrete members may exhibit reduced stiffness and strength under cyclic inelastic deformations. In the nonlinear analysis, selection of the hysteresis model has considerable effect on precise prediction of the structure dynamic response. The selected model should provide a behavior similar to the real hysteresis behavior, where the effects of factors causing reduction in strength are included.

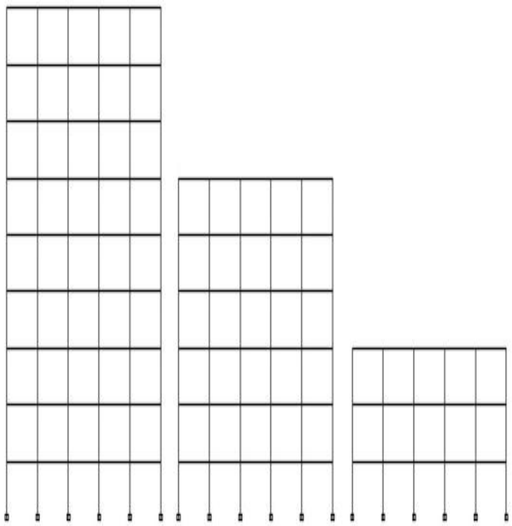
Research has shown that the deterioration parameter has a remarkable effect on the seismic damages to RC buildings. So that a loss in strength greater than 40% could make the moment resisting frame buildings unsafe, as these buildings have undergone sever and unrepairable damages [17].

The earthquake duration has considerable effect on damage to buildings, including the concrete buildings. This research attempts to study variation of the stiffness and strength in concrete buildings and presents a new definition for the duration entitled cyclic duration based on the analysis of frequency content of the accelerogram. Also this study presents a better investigation of the structure damage due to the earthquakes with different durations. This is done by including all the effective parameters on the reduction of stiffness and strength in concrete buildings and simulation of the concrete structure and its behavior using a nonlinear analysis software. Utilizing the results of these studies one could have an appropriate judgment on the residual capacity of the damaged structures due to the earthquake, for the purpose of their reuse or demolition and rehabilitation.

3. Research method

In this study, use has been made of three reinforced concrete frames with 3, 6 and 9 stories. The frames in the X direction have 5 spans with 5m length and the stories height is 3m. These 2D frames are modeled in XZ plane using the SeismoStruct 2016 Software. According to Fig. 5-1, the frames are made of reinforced concrete and the moment resisting frame system is used to resist the lateral force. The seismic loading of the structures is performed based on soil type II located in a site with severe seismicity. Design of the members is done based on ACI 318-05 Code. Loading is according to Topic No. 6 of Iranian national building regulations. The dead load, and live load of the stories and live load of the roof are taken 600, 200 and 150 kg/m^2, respectively.

The structure is first analyzed by the equivalent static method and the optimal sections are extracted. Then the structure is analyzed by the nonlinear time history method using 119 accelerograms corresponding to different earthquakes with different durations, different distances from the epicenter, and different magnitudes. The nonlinear time history analysis has been done directly under real records (not scaled records based on a target spectra related to a hazard level). Instead, we have increased time history analysis to a wide range of acceleration records with different durations.



9-story 6-story 3-story

Fig. 3. Analyzed frames.

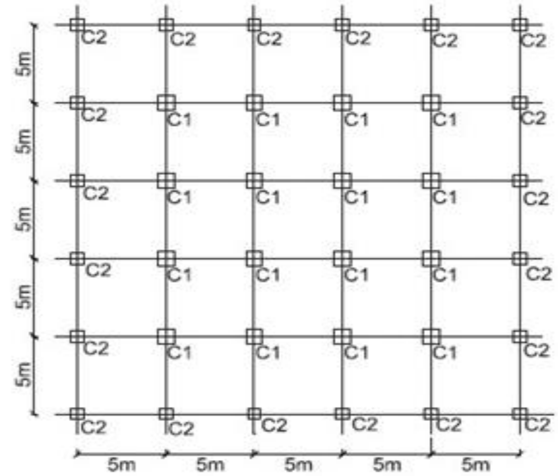


Fig. 4.1. Plan and view of the structure

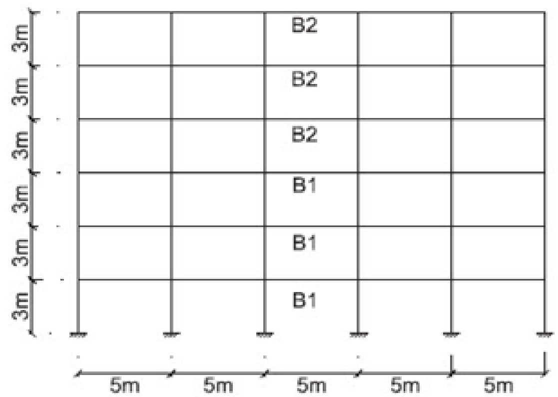


Fig. 4.2. Plan and view of the structure.

The selected records were first filtered in the frequency range of 0.2-20 Hz using the SeismoSignal software and applied on the structure using the SeismoStruct software.

For assessment of damage to the structures under long and short earthquake durations, measures like the number of formed plastic joints and maximum relative displacement were taken into the account.

Table 1. Columns details.

Story ID	Floor level	Column ID C1	Column ID C2	Description
3 Story building	Up to roof	375 x 375 8-15 M	300 x 300 4-20 M	(mm x mm) Size- Main-reinforcement
6 Story building	Up to 3rd floor	450 x 450 8-25 M	300 x 300 6 – 20 M	(mm x mm) Size- Main-reinforcement
	3rd floor to roof	450 x 450 8-20 M	300 x 300 4 – 20 M	(mm x mm) Size- Main - reinforcement
9 Story building	Up to 3rd floor	500 x 500 8-25 M	300 x 300 6-25 M	(mm x mm) Size- Main - reinforcement
	3rd floor to roof	500 x 500 6-25 M	300 x 300 6-20 M	(mm x mm) Size- Main - reinforcement

Table 2. Beams details.

Story ID	Beam ID	Size mm X mm	Middle Top (M)	Middle Bottom (M)	1/4 First-End Top (M)	1/4 First-End Bottom (M)
3 Story building	B1	300 x 450	2-20	2-20	2-20	2-20
6 Story building	B1	300 X 500	3-25	4-25	5-25	4-20
	B2	300 X 500	2-20	3-20	2-20	3-20
9 Story building	B1	300 X 500	3-25	4-25	5-25	4-20
	B2	300 X 500	3-20	3-20	3-20	3-20

4. Characteristics of investigated records

The earthquake records have been selected from Peer Berkeley website and the effective duration and PGA of the accelerograms have been extracted by the SeismoSignal software. The corresponding characteristics of the selected earthquakes have been given in Table (3).Attempt was made to select these 119 records from those exceeding 5 on the Richter Scale, having low to high durations so that approximately one record is selected per every second. The minimum duration is 2.5 seconds and the maximum duration is 96 seconds which includes a significant range of durations that are applied on 3, 6 and 9-story concrete structures.

Table 3-Characteristics of the selected earthquakes

Number Of Record	Earthquake Name	Magnitude (Mw)	5-95% Duration (sec)	Max PGA (g)
1	"Helena_ Montana-01"	6	2.5	0.16
2	"Parkfield-02_ CA"	6	3	0.36
3	"Northridge-02"	6.05	3.2	0.21
4	"Parkfield-02_ CA"	6	3.2	0.81
5	"Morgan Hill"	6.19	4.1	1.31
6	"Christchurch_ New Zealand"	6.2	4.1	1.02
7	"Christchurch_ New Zealand"	6.2	4.3	0.59
8	"Parkfield-02_ CA"	6	4.4	1.02
9	"Kobe_ Japan"	6.9	4.6	0.61
10	"Loma Prieta"	6.93	5	0.40
11	"Chi-Chi_ Taiwan-06"	6.3	5.1	0.80
12	"Parkfield-02_ CA"	6	5.4	0.43
13	"Niigata_ Japan"	6.63	5.6	1.69
14	"Niigata_ Japan"	6.63	5.6	0.83
15	"Northridge-01"	6.69	6	1.48
16	"Christchurch_ New Zealand"	6.2	6	1.62
17	"Northridge-01"	6.69	6.7	0.83
18	"Northridge-01"	6.69	6.9	1.04
19	"Parkfield-02_ CA"	6	6.9	0.71
20	"Gazli_ USSR"	6.8	7	0.74
21	"Parkfield-02_ CA"	6	7.1	1.26
22	"San Fernando"	6.61	7.3	1.06
23	"Nahanni_ Canada"	6.76	7.5	0.98
24	"Northridge-01"	6.69	8	0.52
25	"Parkfield-02_ CA"	6	8.1	0.78
26	"Iwate_ Japan"	6.9	8.3	2.44
27	"Chuetsu-oki_ Japan"	6.8	8.4	1.23
28	"Niigata_ Japan"	6.63	8.4	0.84
29	"Chuetsu-oki_ Japan"	6.8	8.5	0.68
30	"Northridge-01"	6.69	8.5	0.95
31	"Chi-Chi_ Taiwan"	7.62	8.7	0.76
32	"Duzce_ Turkey"	7.14	9	0.80
33	"Northridge-01"	6.69	9.1	1.00
34	"Parkfield-02_ CA"	6	9.4	0.84
35	"Kobe_ Japan"	6.9	9.5	0.74
36	"Bam_ Iran"	6.6	9.6	0.86
37	"Cape Mendocino"	7.01	9.7	1.90
38	"Imperial Valley-06"	6.53	9.7	0.79
39	"Chi-Chi_ Taiwan"	7.62	10	0.4

				6
40	"Chuetsu-oki_ Japan"	6.8	10.4	0.96
41	"Northridge-01"	6.69	10.7	0.89
42	"Loma Prieta"	6.93	11	0.64
43	"Chuetsu-oki_ Japan"	6.8	11.2	0.85
44	"Christchurch_ New Zealand"	6.2	11.2	0.62
45	"San Fernando"	6.61	12	0.37
46	"Superstition Hills-02"	6.54	12.3	0.82
47	"Northridge-01"	6.69	12.6	2.01
48	"Tottori_ Japan"	6.61	12.7	0.70
49	"Duzce_ Turkey"	7.14	12.77	0.79
50	"Duzce_ Turkey"	7.14	13.1	0.95
51	"Chi-Chi_ Taiwan"	7.62	13.3	0.79
52	"Chi-Chi_ Taiwan-03"	6.2	13.5	0.87
53	"Iwate_ Japan"	6.9	13.7	1.34
54	"Landers"	7.28	13.8	0.74
55	"Iwate_ Japan"	6.9	14.1	0.40
56	"Iwate_ Japan"	6.9	14.7	1.02
57	"Tottori_ Japan"	6.61	15	0.43
58	"Iwate_ Japan"	6.9	15.1	0.64
59	"Northridge-01"	6.69	15.1	0.98
60	"Tottori_ Japan"	6.61	15.9	0.75
61	"Darfield_ New Zealand"	7	16	0.97
62	"Darfield_ New Zealand"	7	16	0.97
63	"Tabas_ Iran"	7.35	16.5	1.07
64	"Iwate_ Japan"	6.9	16.6	0.74
65	"Chuetsu-oki_ Japan"	6.8	17	0.20
66	"Chuetsu-oki_ Japan"	6.8	18	0.26
67	"Chi-Chi_ Taiwan"	7.62	19.2	0.21
68	"Darfield_ New Zealand"	7	20.1	0.34
69	"Darfield_ New Zealand"	7	21.3	0.52
70	"Chi-Chi_ Taiwan"	7.62	22	0.87
71	"Chi-Chi_ Taiwan"	7.62	23	0.55
72	"Chi-Chi_ Taiwan"	7.62	23	1.14
73	"Chi-Chi_ Taiwan"	7.62	24	0.50
74	"Tottori_ Japan"	6.61	25	0.29
75	"El Mayor-Cucapah_ Mexico"	7.2	26.2	0.46
76	"Chi-Chi_ Taiwan"	7.62	27	0.29
77	"Chuetsu-oki_ Japan"	6.8	28.2	0.35
78	"Chi-Chi_ Taiwan"	7.62	28.6	0.76
79	"Manjil_ Iran"	7.37	29.1	0.53
80	"Chi-Chi_ Taiwan"	7.62	30.2	0.63
81	"Chi-Chi_ Taiwan"	7.62	30.8	0.98
82	"Chi-Chi_ Taiwan"	7.62	31.2	0.29
83	"Tottori_ Japan"	6.61	31.6	0.74
84	"Chi-Chi_ Taiwan"	7.62	32	0.18
85	"Iwate_ Japan"	6.9	33.1	0.26
86	"Chi-Chi_ Taiwan"	7.62	34	0.28
87	"Darfield_ New Zealand"	7	35.1	0.21
88	"Tottori_ Japan"	6.61	35.3	1.07
89	"Landers"	7.28	36	0.24
90	"Darfield_ New Zealand"	7	37	0.25
91	"Darfield_ New Zealand"	7	38.2	0.14
92	"Kocaeli_ Turkey"	7.51	39.4	0.09
93	"Iwate_ Japan"	6.9	40.5	0.10
94	"Iwate_ Japan"	6.9	41.2	0.12

95	"Iwate_ Japan"	6.9	42.5	0.50
96	"Kobe_ Japan"	6.9	43.8	0.28
97	"El Mayor-Cucapah_ Mexico"	7.2	44.2	0.33
98	"Iwate_ Japan"	6.9	45.8	0.22
99	"El Mayor-Cucapah_ Mexico"	7.2	46.3	0.22
100	"Iwate_ Japan"	6.9	48.3	0.38
101	"Chi-Chi_ Taiwan"	7.62	49.9	0.18
102	"El Mayor-Cucapah_ Mexico"	7.2	51.2	0.26
103	"El Mayor-Cucapah_ Mexico"	7.2	53.8	0.15
104	"Chi-Chi_ Taiwan"	7.62	54.4	0.13
105	"Kobe_ Japan"	6.9	55.2	0.19
106	"Kobe_ Japan"	6.9	56.4	0.22
107	"Iwate_ Japan"	6.9	59.1	0.11
108	"El Mayor-Cucapah_ Mexico"	7.2	60.4	0.26
109	"Chi-Chi_ Taiwan"	7.62	61.3	0.14
110	"El Mayor-Cucapah_ Mexico"	7.2	65.8	0.20
111	"El Mayor-Cucapah_ Mexico"	7.2	68.6	0.29
112	"El Mayor-Cucapah_ Mexico"	7.2	70	0.17
113	"Niigata_ Japan"	6.63	73.5	0.15
114	"El Mayor-Cucapah_ Mexico"	7.2	82.4	0.31
115	"El Mayor-Cucapah_ Mexico"	7.2	88	0.22
116	"Niigata_ Japan"	6.63	90.3	0.11
117	"Niigata_ Japan"	6.63	95.9	0.58
118	"El Mayor-Cucapah_ Mexico"	7.2	96.2	0.10
119	"Niigata_ Japan"	6.63	96.8	1.32

5. Investigating the frequency content

In this section we have dealt with the number of cycles produced within threshold acceleration range of 0.05g to 0.3g and in the range close to the dominant period (± 10%) of the structure in the 3, 6 and 9—story structures using the FORTRAN programming software. Attempt was made that by selecting different threshold accelerations they include both damage and sensitivity in all 3 structures. In continuation, a table is presented which indicates the number of cycles exceeding different threshold accelerations within the range of ± 10% difference between the cycle period of the accelerogram and the structure period.

A: Number of cycles within threshold acceleration range of 0.05g to 0.3g and with ± 10% difference between the cycle period and the dominant period of the structure in the 3-story structure.

B: Number of cycles within threshold acceleration range of 0.05g to 0.3g and with ± 10% difference between the cycle period and the dominant period and the first 3 periods of the structure in the 6-story structure.

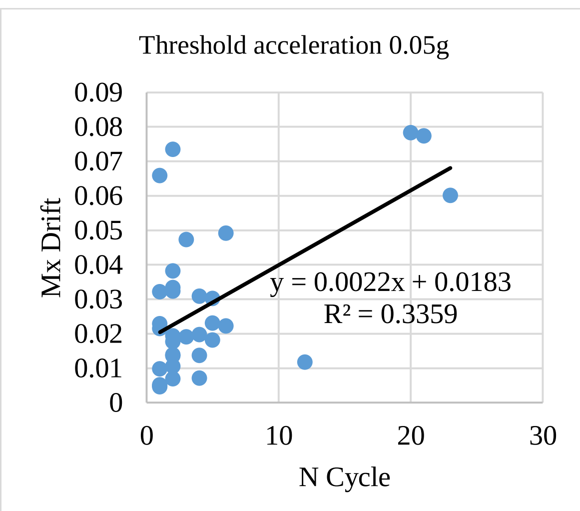
C: Number of cycles within threshold acceleration range of 0.05g to 0.3g and with ± 10% difference between the cycle period and the dominant period and the first 3 periods of the structure in the 9-story structure.

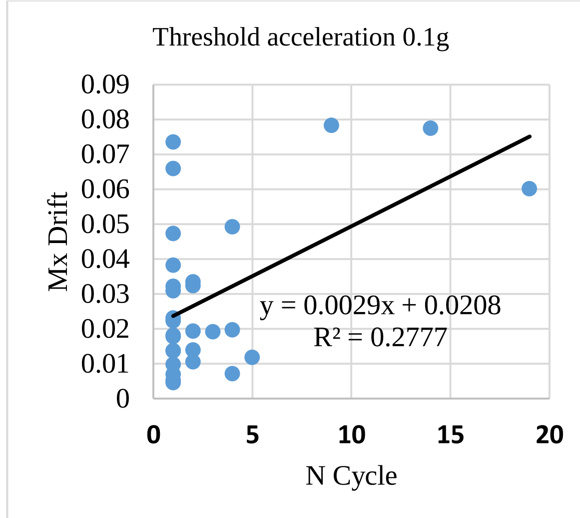
From the results of the above table which include the number of cycles exceeding different thresholds and those close to the fundamental periods of the mentioned structures, we have taken advantage for comparing the earthquake duration of structures under the introduced records. We would deal with them in continuation.

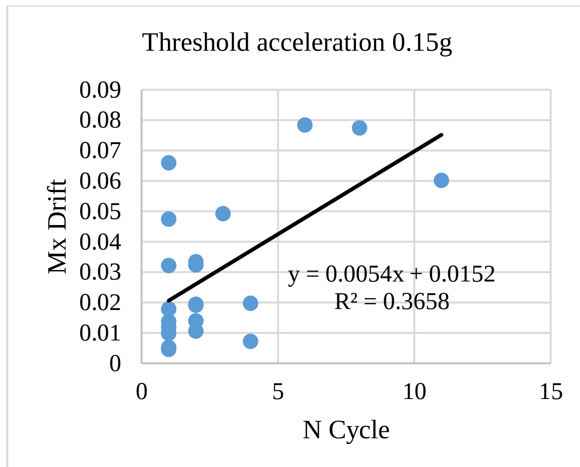
6. Investigating the range of difference between cycle period of the accelerogram and dominant period of structure

In this section we have compared the results of damage to structure based on the number of cycles and drift for the 3-story structure in the ranges of 10%, 20%, 30% and no difference between the cycle period of the accelerogram and the dominant period of the structure. It was observed that the best range is 10% difference between the cycle period of the accelerogram and the dominant period of the structure, and the corresponding diagram is given in continuation.

Number of cycles with the period range of ± 10% difference with respect to the dominant period of the 3-story building has been shown as follow:







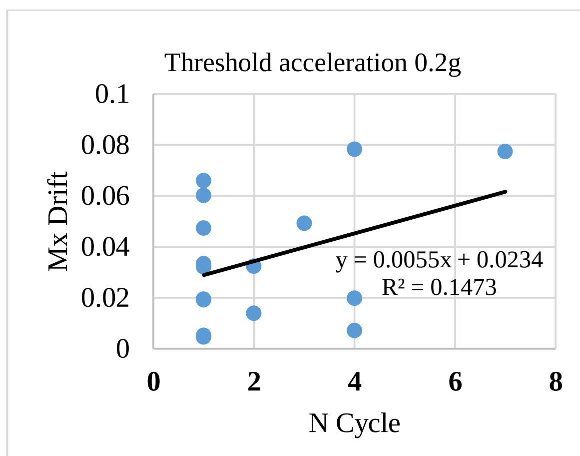


Diagram 1. investigating the range of ± 10% difference between the cycle period and dominant period of the structure.

The examination was also performed for 20% and 30% ranges and it was seen that the best range is 10% difference between the cycle period and dominant period of the structure, as it had generated the largest correlation coefficient . A summary of these 4 ranges is given in the following diagram.

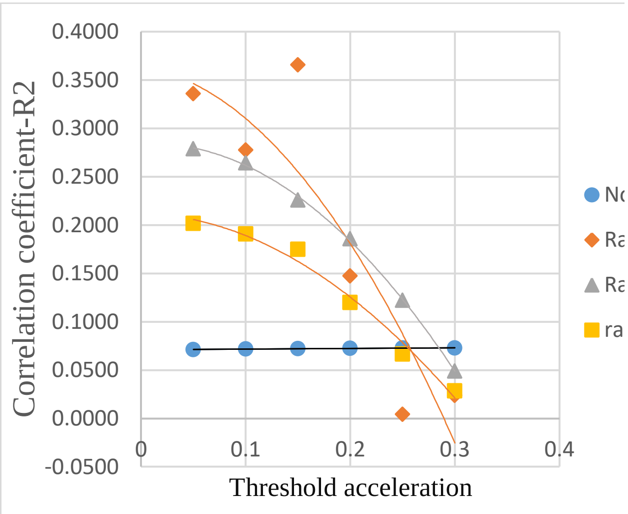


Diagram 2. Results of the comparisons made between various ranges of difference between the cycle period of the accelerogram and dominant period of the structure.

As seen from the above diagrams, it could be concluded that the largest correlation coefficient (R^2) corresponds to the range of 10% difference between the cycle period of the accelerograms and dominant period of the structure, so we would use the 10% range for the damage index. A summary of the above diagrams is given in equation (2) which indicates our explanation:

$$0.9T_i \leq T_{Cycle} \leq 1.1T_i \tag{2}$$

7. Investigation of the structure plastic threshold acceleration

In this section we have investigated the plastic threshold acceleration for the 3, 6 and 9-story structures. For this purpose we have incorporated the pushover analysis (nonlinear static analysis) in the SeismoStruct Software. To obtain the plastic threshold acceleration, we have based our work on the formation of the first LS hinge (life-safety level) and have read the corresponding target displacement and calculated the spectral acceleration (Sa) value which yielded the threshold accelerations of 0.15, 0.08 and 0.05 seconds for the 3, 6 and 9-story structures, respectively.

It should be noted that despite the calculated values for the threshold acceleration, the results of statistical analyses show that where the threshold acceleration is taken equal to 0.05g, a higher correlation coefficient is obtained concerning the relation between the cycle counts and the amount of damage. It is noteworthy that these values are much closer to each other in the 6 and 9-story structures. Following are some of analysis outputs such as record number and plastic hinges:

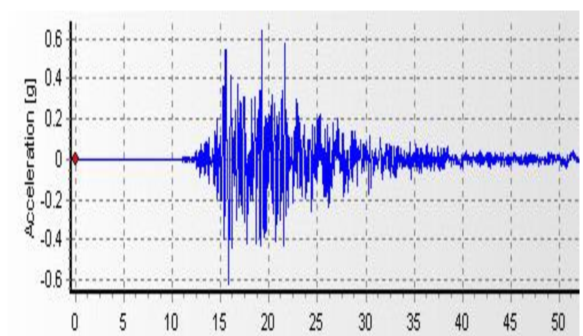


Fig. 5. Record NO.58 (Iwate_ Japan).

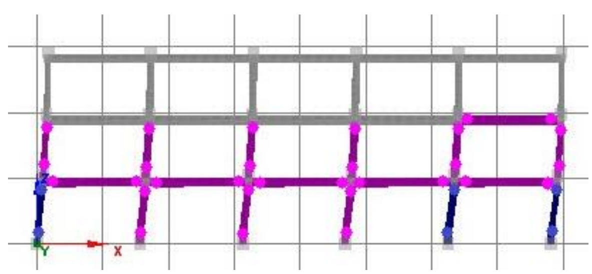


Fig. 6. IO (purple) and LS (blue) hinges of the 3-story structure.

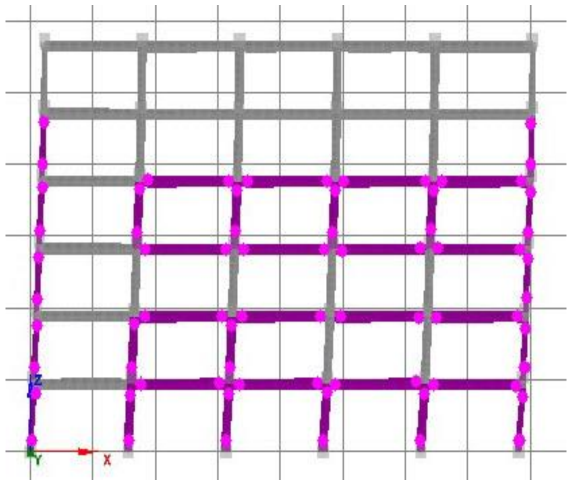


Fig. 7. IO (purple) and LS (blue) hinges of the 6-story structure.

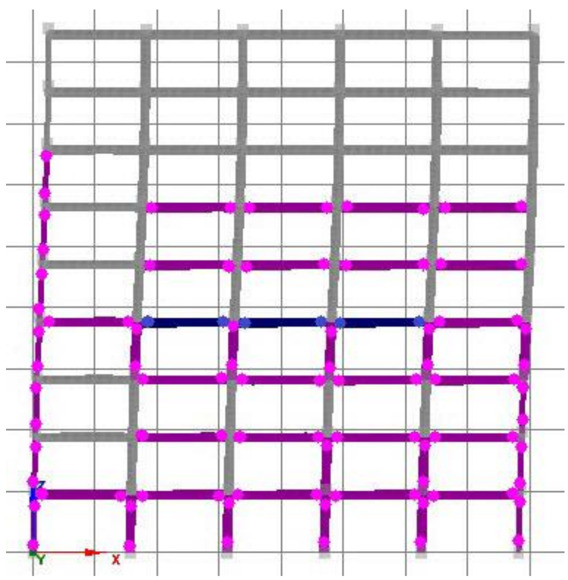


Fig. 8. IO (purple) and LS (blue) hinges of the 9-story structure.

Diagram 2 shows the relevant response spectra of all used records with different durations and the average response spectra.

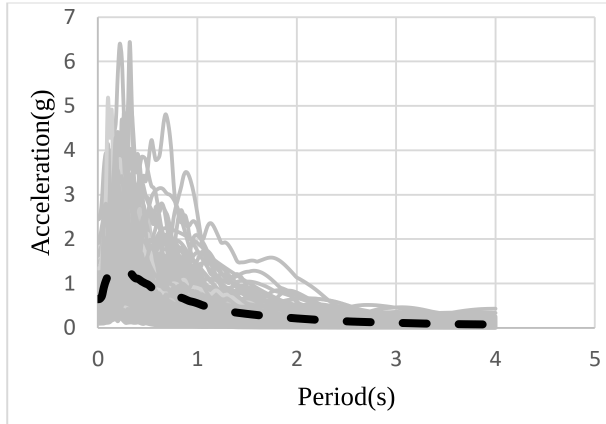
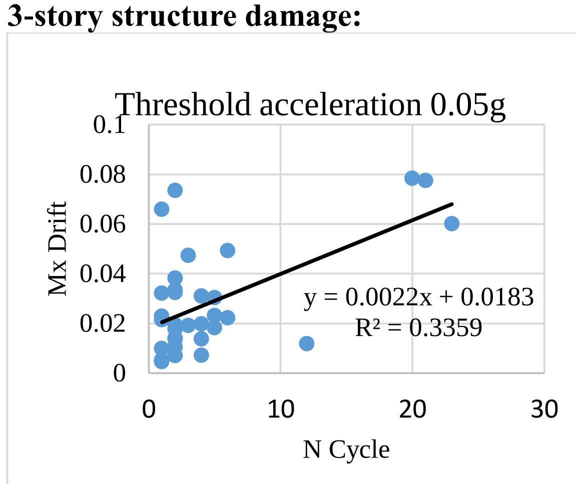


Diagram 3. Response spectra of all used records and the average.

8. Analysis Results

In this section we have investigated the results of structural analyses based on the drift values obtained for different stories. The 3, 6 and 9-story structures are separately presented together with corresponding diagrams and interpretation of the results.

3-story structure damage:



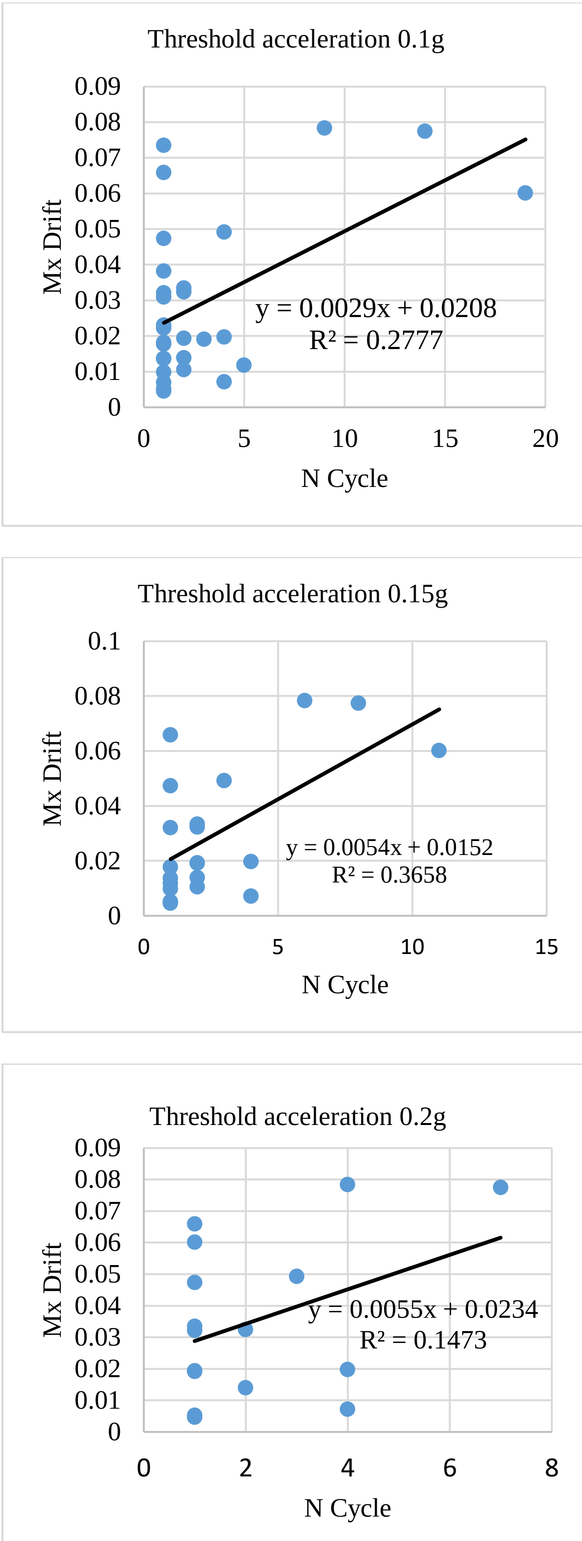


Diagram 4. Diagram depicting the number of cycles and maximum drift for the 3-story structure.

As is seen, the maximum correlation coefficient (R^2) i.e. compatibility between the cycle number and the structure drift corresponds to the threshold acceleration of 0.05g. This indicates that the maximum drift value leading to the highest rate of damage occurs at the threshold acceleration of 0.05g and in the 3-story structure.

6-story structure damage:
Following diagram shows the number of cycles and maximum drift for the 6-story structure- based on the first period of the structure:

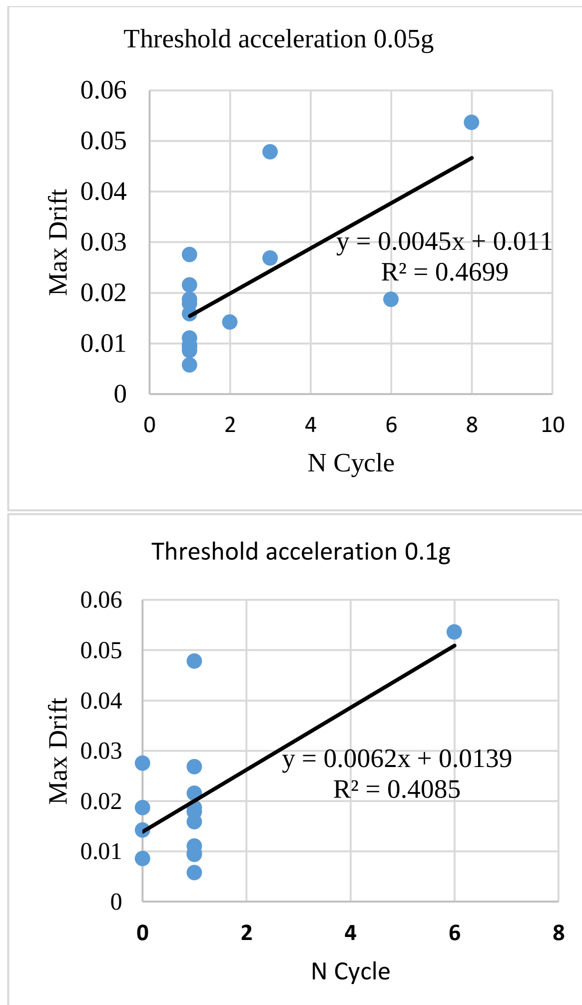
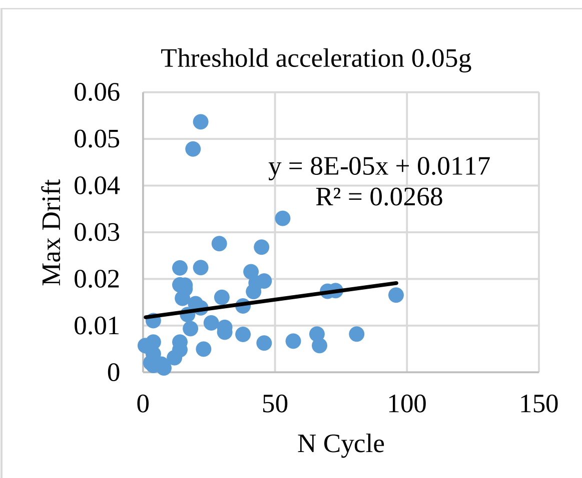
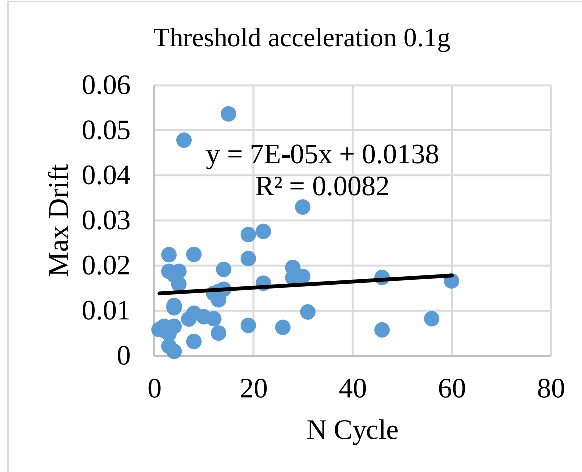
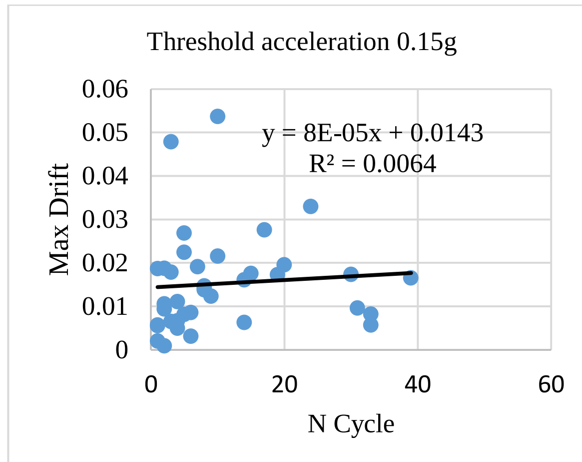


Diagram 5. Diagram depicting the number of cycles and maximum drift for the 6-story structure- based on the first period of the structure.

In the 3-story structure, the dominant period of structure to a great extent exhibits the structure behavior and a significant share of the modal mass is on this period. But in the medium to high rise structures the share of dominant period is not much, i.e. one could not present a significant relationship between increase in the cycles number and increased damage just by considering the number of cycles close to the dominant period of the structure (10% difference). Therefore in the 6 and 9-story structures the cycles close to the structure's second and third periods (10% difference) are also calculated, and by summing up the number of cycles in the three first periods of the structure, their relation with the damage intensity including the maximum peak drift was calculated and drawn as presented:







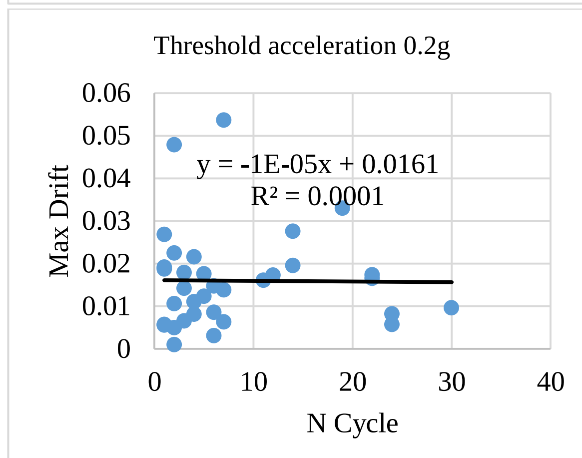
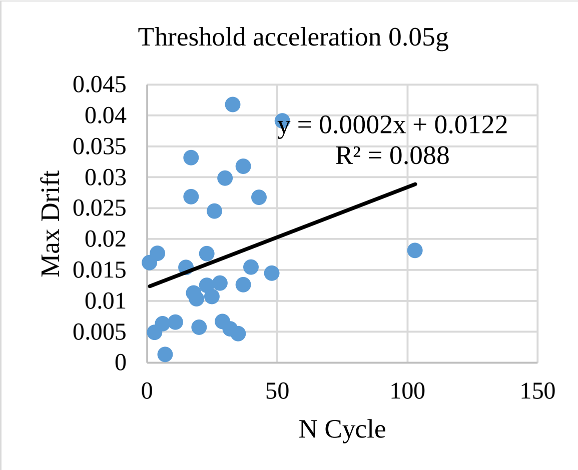
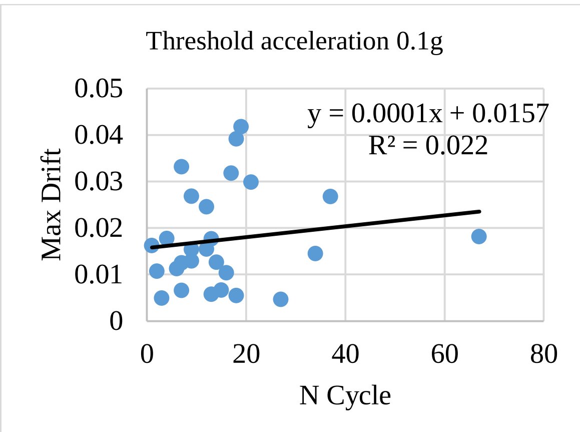
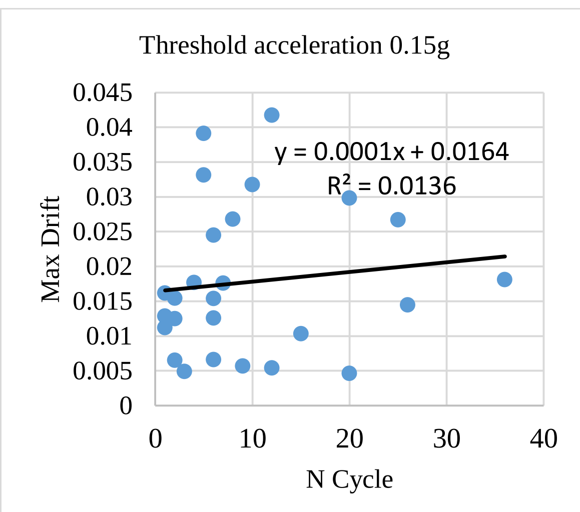


Diagram 6. Number of cycles and maximum drift for the 6-story structure-based on the first, second and third periods of the structure.

9-story structure damage:







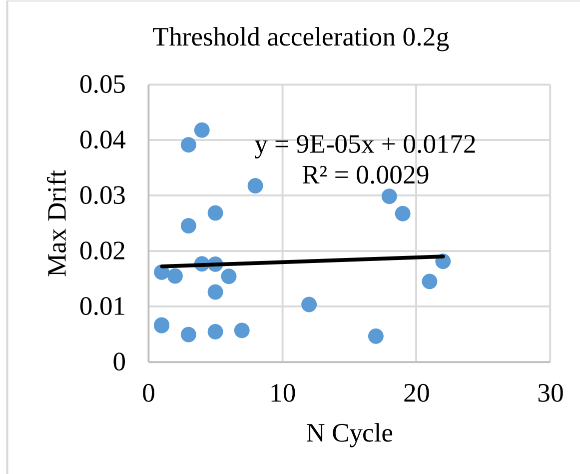


Diagram 7. Number of cycles and maximum drift for the 9-story structure-based on the first, second and third periods of the structure

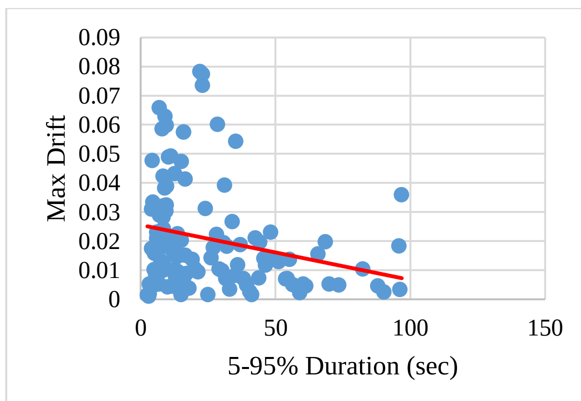
9. Comparison and analysis of different structures using the cyclic duration index

In the 3-story structure, the dominant period of structure exhibits the structure behavior to a great extent and a significant share of the modal mass is on this period. But in the medium to high rise structures the share of dominant period is not much, i.e. one could not present a significant relationship between increase in the cycles number and increased damage just by considering the number of cycles close to the dominant period of the structure (10% difference). In this thesis first the correlation between the number of cycles close to the dominant period for the 6 and 9-story structures and damage intensity were calculated but as the results were not significant, a more precise examination was performed and the number of cycles close to the dominant period of the 6 and 9-story structures was also calculated. Then, by summing up the number of cycles close (±10%) to the first three periods of the structure, their relationship with damage intensity including the maximum peak drift was calculated and drawn. This has resulted in significance of the number of cycles close to the fundamental periods and damage amount.

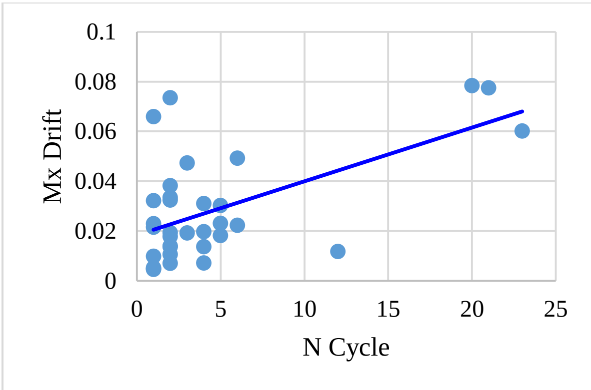
Important note: As in this thesis our goal is to work with real accelerograms, they are not scaled to a certain value because one of the shortcomings of scaling the accelerograms is alteration of their frequency content. In other words, at far distances where the cycles period of an accelerogram increases with respect to the state of being close to the epicenter, scaling of the acceleration amplitude to a specific limit (for example 0.35g) would not be realistic. Therefore, while from theoretical point of view it performs scaling with an identical maximum acceleration among several accelerograms, but the scaled accelerograms are far from being realistic. Furthermore in this study, those cycles close to the dominant period of structure are counted that exceed the plastic threshold acceleration. In other words a maximum limit has not been specified for this criterion (number of effective cycles). To reduce the error generated by the above mentioned issue, attempt was made to use a considerable number of accelerograms.
Another work that could be accounted as a suggestion for future research is to classify the records for a minimum threshold acceleration and also for a maximum limit. In other words those records should be incorporated which have relatively close PGAs which certainly have different frequency contents without applying scaling. Thus, it is predicted that the correlation coefficient corresponding to the effective cycles would considerably increase according to this definition. For example in the studied records in this research there are records with the reference earthquake magnitudes of 5 and 7 on the Richter scale, where the acceleration amplitude of each of these two accelerograms may exceed the plastic threshold acceleration of the structure per a specific period, but have different durations. In other words a strong earthquake (7 on the Richter scale) with a lower number of cycles may be less destructive than a moderate earthquake (5 on the Richter scale) but with a longer duration.

Here we have made comparison between the Arias duration and the proposed duration for the 3, 6and 9-story structures. Arias duration is in the interval of 5-95% and the proposed duration is the number of cycles exceeding a threshold of 0.05g having 10% difference with respect to the structure period. As is seen the proposed duration is directly proportional to the increased damage.

In the following diagrams comparison is made between the proposed duration and Arias duration of 5-95% for the 3, 6 and 9-story structures.

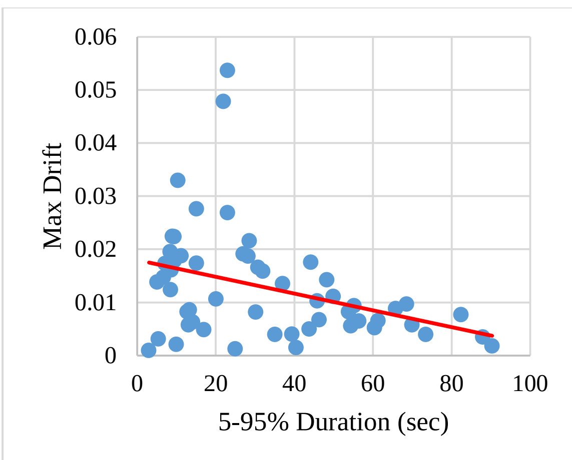


Arias duration

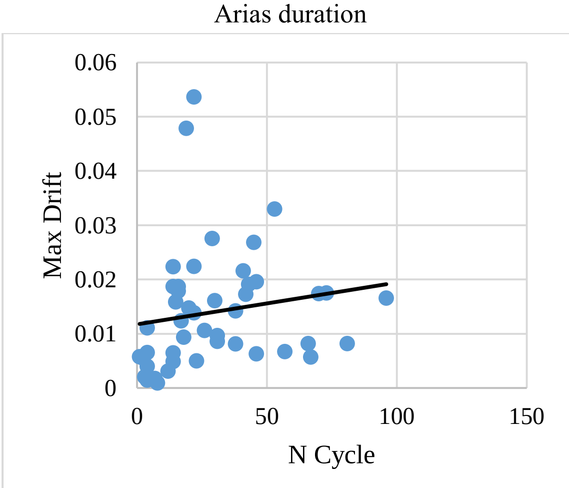


Proposed duration

Diagram 8. Comparison between Arias duration and proposed duration, based on the threshold acceleration of 0.05g for the 3-story structure

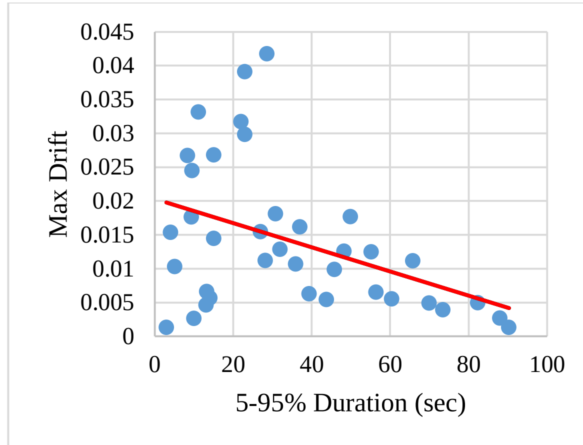


Arias duration

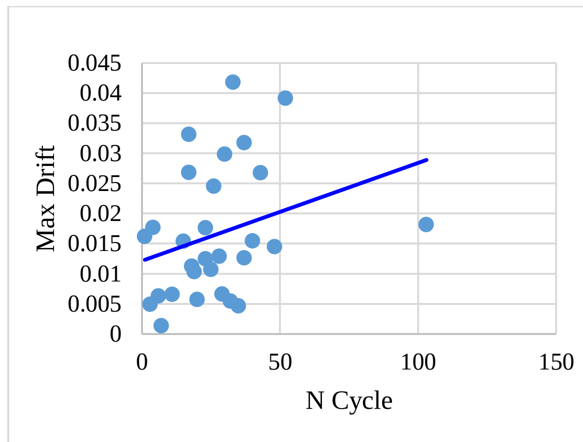


Proposed duration

Diagram 9. Comparison between Arias duration and proposed duration, based on the threshold acceleration of 0.05g for the 6-story structure



Arias duration



Proposed duration

Diagram 10. Comparison between Arias duration and proposed duration, based on the threshold acceleration of 0.05g for the 9-story structure.

It is seen that the cyclic duration could better exhibit the relation between structure damage and duration. It shows that by increase in the (cyclic) duration, damage to structure increases, too.

10. Findings

In this research we investigated the concrete structures performance under earthquakes with different durations (ranging from low to high durations). In this respect, to examine the earthquake duration, a new index was defined which is the number of accelerogram cycles which have periods close to the fundamental periods of the structure (with 10% difference) and their acceleration exceeds the plastic threshold acceleration of the structure.

For this purpose, first three concrete buildings with 3, 6 and 9 stories were designed with optimal cross sections and the dominant period and the threshold acceleration to reach the nonlinear behavior zone was calculated for them. Next, all the three buildings were linearly analyzed in two dimensional form using the elements with stiffness deterioration and strength degradation capabilities (Takeda model) in the SeismoStruct software. Each of the 3, 6 and 9-story structures was subjected to 119 records with different durations, distances from the fault, magnitudes and soil types. The seismic behavior of the structures was investigated in terms of the maximum drift, and the number of induced plastic hinges.

The summary of the results obtained in the previous sections of this research concerning investigation of the reinforced concrete performance under the effect of earthquake duration and examining frequency content of the accelerograms is given here. Also, through the experience obtained in this research some suggestions are given at the end for the future research.

11. Discussion and Conclusion

In this research, in order to investigate the effect of earthquake duration on the reinforced concrete structures, first about 3000 accelerogram records were selected with different ranges of magnitude, distance from the fault, and condition of extended site. These records had a magnitude higher than 5 on the Richter scale and Arias duration of 5-95% which were adopted from the website of Berkeley University. Among these, 119 records were selected based on Arias duration 5-95% ranging from low to high. Attempt was made to select the 119 records from the records exceeding 5 on the Richter Scale with durations ranging from low to high so that per approximately every second we had a single record. In this respect the minimum duration was 2.5 seconds and the maximum duration was 96 seconds which included a significant range of durations applied on the 3, 6 and 9-story structures.

The general results of duration analysis performed on the concrete structures are as follows:

1-The earthquake with a moderate peak acceleration and long duration induces greater damage in comparison to an earthquake with higher acceleration but shorter duration.

2-The percentage of formed plastic hinges in the frames subjected to long duration earthquakes is generally greater than that of earthquakes with shorter durations.

3-In the case of not accounting for stiffness deterioration and strength degradation, we have a lower number of the formed plastic hinges.

4-By increase in the earthquake magnitude and distance from the epicenter, the duration also increases, although the acceleration amplitude is reduced.

5-The low rise structures are sensitive and vulnerable to higher threshold accelerations and the higher structures are sensitive and vulnerable to lower threshold accelerations.

The specific results of the performed studies in this research concerning the effect of duration on the reinforced concrete structures could be stated as follows:

- The frequency content of the records is investigated and from this content the number of cycles exceeding the threshold accelerations of 0.05g to 0.3g and periods close to the structure's dominant period are calculated and interpreted by programming in Fortran Software.
- Examining the proposed cyclic duration and Arias duration of 5-95% it was concluded that the proposed cyclic duration (based on the analysis of frequency content of the accelerogram), the relation between increased damage of the structure and increase in duration could be stated with higher precision. Also in the 3-story structure the dominant period of the structure to a large extent indicates the structure behavior and a significant share of the modal mass is on this period. But in moderate to high rise structures the share of dominant period of structure is not much, meaning that just by considering the number of cycles close to the dominant period of the structure (10% difference), one could not derive a significant relation between increase in the number of cycles and increase of damage.
- In this research, first the correlation between a number of cycles close to the dominant period of the 6 and 9-story structures and damage intensity were calculated. But as the results were not significant enough a more precise investigation was performed and the number of cycles close to the second and third periods of the structure was also calculated and by summing up the number of cycles close (±10%) to the first three periods of the structure, their relation with damage intensity was calculated and drawn in terms of the maximum peak drift. This resulted in significance of the total number of cycles close to the fundamental periods which exceeded a threshold acceleration and damage in all the structures. It is clear that with a higher number of cycles with periods close to all the structure modes (modes with 90% participation of the modal mass) we could obtain better results.

It should be noted that using drift as a real variable was a very good criterion in determining the relationship between durability and damage. It is clear that the number of plastic hinges formed in the structures is another good criterion, but this criterion may cause the fragility of the proposed relationship. The criterion of the number and level of plastic joints can be developed in future researches.

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