Influence of ground motion duration on the structural response at multiple seismic levels

Mojtaba Harati\textsuperscript{1}, Mohammadreza Mashayekhi\textsuperscript{2}\textsuperscript{*}, Morteza Ashoori Barmchi\textsuperscript{2} and Homayoon E. Estekanchi\textsuperscript{2}

\textsuperscript{1}Department of Civil Engineering, University of Science and Culture, Rasht, Iran
\textsuperscript{2}Department of Civil Engineering, Sharif University of Technology, Tehran, Iran

Abstract

This paper aims to investigate the effects of motion duration on the structural seismic demands, seeking potential correlations between motion durations and structural responses at several seismic levels. Three seismic levels with 100 years, 475 years, and 2475 years earthquake return periods (RPs) are first considered for correlation computations. Spectrally matched ground motions are employed to isolate the contribution of duration from the effects of ground motion amplitudes and response spectral shape. Four single degree of freedom systems derived from four real reinforced concrete structures are studied, where both degrading and non-degrading equivalent SDOF systems are included for structural modeling. Results show a positive correlation between motion duration and structural displacement demand and this correlation increases with an increase in earthquake RP. It is also investigated whether or not this positive correlation has an impact on the incremental dynamic analysis curves. The spectrally matched ground motions are divided into two distinct groups in this case: short-duration and long duration ground motions. The comparison of incremental dynamic analysis of these two groups reveals that long-duration ground motions can cause up to a 20 percent decrease in the collapse capacity of considered structures.

Key Words: Strong ground motion duration, nonlinear dynamic analysis, degrading structures, spectral matching, statistical correlation, and wavelet

\textsuperscript{*}Corresponding: Mohammadreza Mashayekhi, Research Associate, Sharif University of Technology, Tehran, Iran. Email: mmashayekhi67@gmail.com


1 Introduction

Post-earthquake field reports show that damages in the structural members of the observed building type systems can be pertinent to the duration of the induced earthquakes as well as high nonlinear cycles endured by the elements of the damaged structural systems before the failure. It is also established by a growing body of the research in this area that the duration of the earthquake may have a meaningful effect on the structural performance of built infrastructures. Numerous researchers have worked on the seismic response of different structures regarding the influence of motion duration. Their studies revealed that seismic responses of the structures under earthquake loadings with deteriorative behaviors, including RC frames [1–5], concrete dams [6–8] and masonry buildings [9], are directly influenced by the duration of ground motions. It means that structures with degrading behaviors are more vulnerable to motion duration, so more structural and non-structural damages would be expected to occur at places whose constructions are subjected to long-duration earthquakes [10,12]. Besides, it is shown that structures subjected to long-duration ground motions have a collapse capacity equal to 80 percent of the one obtained for the same structures that are exposed to short-duration motions [11]. As a result, accumulated damage indices which are partially or completely composed of the hysteretic cyclic energy of the earthquakes such as Pak-Ang damage index as well as extreme damage indices such as peak floor drifts are shown to have positive correlations with the motion durations [5,12,13].

Although it is shown that there is a positive correlation between motion duration and different damage induces, current seismic codes generally offer a record selection procedure through which ground motions are mainly selected in such a way that their response spectrum is adequately compatible with a predefined target response spectrum [14]. In this case, some rules are prescribed by the codes to ensure the aforementioned response spectrum compatibility. Moreover, the minimum duration length of the earthquake is not explicitly dictated or ever recommended by many seismic codes around the world—such as ASCE07 (2010) [15] and current US rehabilitation provisions (e.g. ASCE/SEI 41-17 (2017) [16] and FEMA-356 (2000) [17]). However, there are some seismic provisions that put a limit on the required minimum length of motion duration for use in the response time history analysis. For example, Chinese Code for Seismic Design of Buildings [18] necessitates a bracketed motion duration which is
equal to or more than 5–10 times of the fundamental period of the structure. Also, a similar regulation can be found in Iranian National Building Code (INBC) by which structural engineers are forced to select earthquake records with strong motion duration at least equal to 10 sec or more than 3 times of the fundamental period of the structure. It is important to note that the minimum strong motion duration recommended by INBC can be of any definitions for the duration of the earthquakes.

In contrast to the above-mentioned studies that mainly focused on the correlation of motion duration and damage indices considering a specific hazard level—for example, the DBE seismic level or the MCE, this paper attempts to show the effects of motion duration on the structural seismic demands at different seismic hazard levels up to a point where a complete collapse of the structures occurs. Therefore, our study includes different hazard levels which are meaningful when structural seismic performance is the case. To this purpose, statistical correlation computations are considered to include the potential effects of considering different seismic hazard levels in such investigations.

2 Research methodology

In this paper, first the correlation of motion duration with structural seismic demands—for building type systems with and without degrading behavior—is considered using a devised research framework which is based on spectrally matched ground motions that are uniformly adjusted to be at the same seismic levels. The structural seismic demands required for correlation assessments are calculated by an IDA as well as a nonlinear response time history procedures. The record selection procedure essential for these analyses is prepared based on the regulations posed by INBC. In this case, the selected records are matched to a target spectrum to diminish their variability related to frequency content as well as spectral amplitudes. In order to diminish uncertainties and variability associated with the duration length of the ground motions and include its effect on the response analysis (or on the median IDA curves), earthquake ground motions are divided into two distinct groups—namely the short- and long-duration sets. Details about spectral matching procedure and policy regarding selected duration definition and the division of the records into two groups come in the next sections.
These numerical dynamic analyses are performed on the equivalent SDOFs which are subjected to scaled matched ground motions. In this case, all adjusted ground motions, both from short- and long-duration sets of motions, are scaled to the desired seismic levels. Moreover, earthquake RPs serve as a means to change the levels of intensity measures (IM) in the response analysis. Statistical correlation procedures are performed at three distinct levels of seismic excitations. Each of these seismic levels corresponds with an earthquake RP. For example, earthquake RPs of 100, 475, and 2475 years represent the service level earthquake (SLE), design basis earthquake (DBE) and the maximum considerable earthquake (MCE), respectively. RPs and scaling factors for the ground motions are obtained from hazard curves of the design spectrum of INBC considering different soil classes defined in the code, as indicated in Figure 1, where class 3 soil—compatible with the soil category of the considered site in this study—is chosen for the calculation of RPs. It is essential to add that above-mentioned SDOFs are modeled utilizing pushover curves of multi-degree RC building types. Characteristics of these SDOFs are also mentioned in the following section of the paper.

![Graph](image)

**Figure 1.** INBC design spectrum hazard curves for different soil types.

While two measurements of interest—the seismic demands at specific seismic level and duration of the selected motions—are independently generated and found in each computer simulation, it is possible to estimate the related correlation coefficient using the Pearson product-moment correlation estimator:
\[ \rho_{x,y} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \]

where \( x_i \) and \( y_i \) are the components of vector \( X \) and \( Y \), which are related to the two measurements of interest respectively; \( x \) and \( y \) are the means of vector \( X \) and \( Y \), and \( \sum \) it represents summation over the number of items pertinent to the duration utilized motions or over components of the vector related to the seismic demands obtained for the whole number of applied ground motions all of which are at a specific seismic hazard levels.

3 Definitions of motion duration

There are more than 30 definitions for motion duration—or duration of strong ground motion—in the literature, but some of them are more commonly accepted and used by the earthquake engineering community. Among the defined available definitions in the literature, bracketed duration, uniform duration as well as the significant duration are more repeatedly used in the field of earthquake engineering. The bracketed duration of motion delivers the total time left between the first and last acceleration excursions which are greater than a specific predefined threshold. The definition pertinent to the uniform duration is all related to the sum of the elapsed time intervals considering the same aforementioned threshold level set on the acceleration [19]. But the definition related to significant duration is somehow different from the bracketed and uniform duration. This definition of the motion duration takes use of a well-known integration-based accumulative intensity measure, the so-called Arias Intensity (AI). Significant duration is denoted by \( D_{x-y} \) hereafter, which is defined as the time interval during which the normalized AI moves from a minimum (x\%) to a maximum (y\%) threshold. And so, the \( D_{5-95} \) means the time interval as buildup accumulation energy of the earthquake goes up from 5 to 95 percent. It is of the essence to add that some studies show that the CAV can be also considered as an alternative for the AI to assess the effect of the motion duration on structural responses (e.g., EPRI (1988) [20], Cabañas et al. (1997) [21]). This is due to the fact that both of these intensity measures, the CAV and AI, are capable of capturing and showing the cumulative energy of the ground motions.
Both of the CAV and AI are defined as the time integral of a form of acceleration function profile as can be seen in Equation (2) and (3), where the $|a(t)|$ is the absolute value of the acceleration function of the ground motion at time $t$, $[a(t)]$. Also, $t_{\text{max}}$ and AI is the total duration of ground motion and the total AI calculated for the entire duration of the ground shakings.

\[
AI = \frac{\pi}{2g} \int_{0}^{t_{\text{max}}} [a(t)]^2 \, dt \\
CAV = \int_{0}^{t_{\text{max}}} |a(t)| \, dt
\]

While there are many definitions for the motion duration as indicated before, the definition for the significant duration is selected as a duration-related parameter in this paper because it is a continuous time interval as far as the characteristics of ground acceleration are concerned; therefore, this definition for duration of an earthquake is more convenient for the time history analysis. The process pertinent to the calculation of a form of significant duration, the $D_{5-95}$ parameter, for the Loma-Prieta earthquake of 1989 is depicted in Figure 2. According to the figure and as mentioned earlier, the significant duration ($D_{5-95}$) is the time interval during which the buildup energy of the normalized AI moves from a minimum (5%) to a maximum (95%) threshold. The times associated with the mentioned minimum and maximum thresholds are defined by $t_x$ (here 8sec) and $t_y$ (here 17sec), respectively.
Figure 2. The procedure required to compute the D5-95 parameter of a recorded ground motion

4 Selection of earthquake records

4.1. Characteristics of the selected motions

In this study, first 200 ground motions selected by Heo et al. (2011) [22] are taken as a source of the record selection procedure. Then some of these ground motions are nominated and divided into two different subsets using a devised mechanism which is described in section 4.3. Heo et al. (2011) [22] used these 200 motions in the dynamic analysis which aimed to compare amplitude scaled and spectrum-matched ground motions for seismic performance assessment. In their study, unscaled ground motions that drive the structure into the nonlinear range was of interest, therefore, a subset of 200 ground motions from Pacific Earthquake Engineering Research (PEER) Next Generation Attenuations (NGA), whose PGA exceeded 0.2g was used in the aforementioned simulation. Acceleration spectra of these ground motions are shown in Figure 3.
Figure 3. Acceleration spectra of 200 ground motions

As can be seen in Figure 3, dispersion of acceleration spectra of these ground motions is very noticeable which can also cause a considerable dispersion in the structural responses. This variability can be attributed to the amplitude and frequency content of the ground motions. As far as the effect of motion duration is concerned, this source of variability should be minimized. In order to reduce this type of variability, ground motions acceleration spectra are matched with a target spectrum.

4.2. Spectral matching procedure

To remove and diminish the influence of spectral amplitudes of ground motions from the characteristics of the selected motions, earthquakes are matched to a target response spectrum. Hence, all of these motions only differ in terms of their duration as well as the non-stationary characteristics they inherited from original earthquake records. Spectral matching procedure modifies the original acceleration time history to match the entire range of target spectrum with minimal alteration of the velocity displacement history of the record. The time-domain spectral matching procedure proposed by Hancock et al. (2006) [23] is adopted in this study. The main assumption of this method is that the peak response does not change due to wavelet adjustment.
Given N target spectral points to match, the spectral misfit is defined by the difference between the target spectral value \( Q_i \) and the initial time series spectral value \( R_i \)

\[
\Delta R_i = (Q_i - R_i) P_i
\]  

(4)

where \( P_i \) is the polarity of the peak response of the oscillator. Hancock et al. (2006) [23] shows that the response of an adjustment time series should be equal to \( \Delta R_i \)

\[
\Delta R_i = \sum_{j=1}^{N} b_j f_j(t)
\]  

(5)

where \( f_j(t) \) is a set of adjustment functions and \( b_j \) is the set of amplitudes of the adjustment functions. The modified amplitude of the responses to the wavelet is determined by not only the misfit at each spectral point but also neighboring spectral points

\[
b = C^{-1} \delta R
\]  

(6)

Each component of a square matrix C is the amplitude of the wavelet response for the j-th spectral point at the peak oscillator time \( t_i \) of the initial time series response for i-th spectral point.

In this study, the target spectrum is the median of the spectra of the selected ground motions. The comparison of acceleration spectra of the original and matched time histories together with the associated target spectra, acceleration and displacement target spectra extracted from the original time series, are also presented in Figure 4 and Figure 5, respectively. Figure 5 indicates that the ground motions are well matched to the target spectra with a minimal change seen in the initial time histories of the ground motions. Acceleration spectra of matched ground motions versus the target spectrum of original ground motions, as shown in Figure 5 (a), demonstrate an acceptable match.
Figure 4. Spectral-related characteristics of the selected ground motions: a) acceleration spectra versus the target spectrum; b) displacement spectra and displacement target spectrum
Figure 5. Spectral-related characteristics of adjusted ground motions: a) matched acceleration spectra versus the target spectrum; b) matched displacement spectra and displacement target spectrum
4.3. Dividing ground motions into long- and short- sets

In order to investigate the possible effects of motion duration on the seismic demands of the structures, spectrally equivalent ground motions are divided into two different sets based on the regulations of INBC in this regard. These specifications force structural engineers to select earthquake records with strong motion duration equal to 10 sec or more than 3 times of the fundamental period of the structure. In this case, the first set of motions includes earthquake records with significant strong motion duration between 10 to 15 sec. And the second set of ground motions contains records that have a significant duration more than 15 but less than 40 seconds. The first group of motions can represent the short-duration earthquakes while the second one is related to the dataset for the long-duration ground motions. It is worth to re-mention that all of these ground motion records, both from short and long sets, are matched to a target response spectrum. So, except for the duration-related sources of variability, these motions are almost unified in terms of amplitude-based intensity measures such spectral accelerations in different ranges of vibrational periods.

5  Structural modeling

The equivalent SDOF systems used for this study are created and modeled based on the bilinear pushover curves derived by Mashayekhi et al. (2019) [24], where four RC building type structures—three-, five-, eight- and twelve-stories—are numerically modeled and considered. In their study, the general characteristics of these structures including the number of stories, bay width, height length, and the total height of the structures are adopted according to the structural details reported by Korkmaz and Aktaş (2006) [25]. After that, the nonlinear static pushover curves of all considered RC structures are first computed and then converted to bilinear pushover curves. These curves help us find the essential characteristics of the equivalent SDOF systems. Table 1 shows the extracted characteristics of bilinear pushover curves required to build the equivalent SDOF systems of this present study.
Table 1. Characteristics of bilinear pushover curves required to model the equivalent SDOF structures

| Model ID | Fy (KN) | Seismic weight of mode 1, W (KN × e+3) | Fy/W | Fundamental Period, T1 (sec) |
|----------|---------|----------------------------------------|------|-----------------------------|
| 1003     | 500     | 2.04                                   | 0.24 | 0.61                        |
| 1005     | 800     | 3.4                                    | 0.23 | 0.69                        |
| 1008     | 815     | 5.24                                   | 0.1592 | 1.22                      |
| 1012     | 1100    | 8.16                                   | 0.1374 | 1.4                        |

Two types of equivalent SDOF system, one with degrading behavior and the other one without degradation, are modeled in Opensees software [26] to investigate the potential effects of motion duration on the seismic demands of the selected structures. In this case, structural SDOF systems with different periods of vibration as specified in Table 1, which are extracted from afore-mentioned MDOF building types, are selected for this purpose. The inelastic SDOF systems with degrading and non-degrading behavior are modeled using bilinear and Ibarra-Krawinkler hysteretic model [27], respectively. The employed hysteretic models for both degrading and non-degrading SDOF systems are displayed in Figure 6. For degrading and non-degrading models, different $F_y/W$ parameters are applied as indicated in Table 1, where $W$ is the seismic weight of the equivalent SDOF systems and $F_y$ stands for the yield strength. Factors associated with the hardening as well as post-capping stiffness, $\alpha_s$ and $\alpha_c$, are selected to be 0.006 and -0.02, respectively. Residual strength is also 0.01 of the yield strength ($\lambda=0.01$).
Figure 6. Employed hysteretic models: a) bilinear elastoplastic model utilized for non-degrading SDOF system; b) backbone curve of the Ibarra-Krawinkler used for degrading SDOF system [27]

6 Numeral results

In this section, numerical results are presented. The response time history analysis essential for the statistical correlation procedure is accomplished at three seismic levels. The required seismic levels to study the correlation of motion duration with structural seismic demands at different levels of excitation are determined through earthquake RPs as described in the research methodology section. Next, the dynamic analysis of the structures subjected to the spectrum-matched ground motions, both from short- and long-duration sets, at multiple levels of excitation are performed through an IDA analysis. The results associated with the IDA procedure of all considered equivalent SDOFs are presented and compared to each other. It is worth mentioning that structural displacement demand is taken as the engineering demand parameter for both types of employed analyses, the IDA and time history analysis.

In order to quantify and get an insight into the relationship of motion duration and structural seismic demands, a statistical correlation procedure as described in the methodology section of this paper is performed at three levels of seismic excitation. As mentioned earlier, each of these seismic levels corresponds with an earthquake RP which is defined before. The ‘Seismic Level 1’ is chosen in a way that an RP of 100 years is considered, a seismic hazard level at SLE. The next seismic levels, the ‘Seismic Level 2’ and ‘Seismic Level 3’, are at the earthquake RPs of
475 (DBE) and 2475 (MCE) years, respectively. Correlation of significant duration with structural displacement for model 1008, which is modeled with a non-degrading SDOF, are computed at three aforementioned seismic levels and shown in Figure 7 (a) to (c). The vertical red line in this figure demonstrates the threshold posed between short- and long-duration sets. As can be apparently recognized, the correlation of motion duration with structural displacement demand can increase at the upper seismic levels. For example, the correlation coefficient of significant duration and computed seismic structural demands is nearly equal to zero for the first considered seismic level, the Seismic Level 1.
Figure 7. Correlation of motion duration with structural displacement for an 8-story non-deteriorating SDOF at three seismic levels: a) RP=100 years; b) RP=475 years; c) RP=2475 years
Correlation of motion duration and structural displacement of model 1008, which is modeled with a degrading SDOF system, are depicted in Figure 8. The same increasing trend for correlation of motion duration and structural displacement demands, as observed in non-degrading SDOF model, can be also seen in this structure with a degrading manner. In this case, the computed correlation coefficient goes up from 0.1103 to 0.1632 from Seismic Level 1 (RP=100 years) to the Seismic Level 2 (RP=475 years), respectively. The correlation coefficients calculated for three considered seismic levels of this degrading model is more than the ones obtained for structures modeled without degradation. Therefore, the effect of motion duration on the displacement structural responses of degrading structures is more pronounced. These findings, the ones both from correlation studies of degrading and non-degrading structural systems, can confirm this matter that the influence of duration on the structural seismic demands is much more significant and evident if the selected structures experience more nonlinearity.
Figure 8. Correlation of duration with structural displacement for an 8-story degrading SDOF at three seismic levels: a) RP=100 years; b) RP=475 years; c) RP=2475 years
The same results, as described above for 8-story equivalent SDOFs, are found for the rest building types that are modeled and incorporated in this study. Correlation coefficients between duration and structural displacements of these structures are condensed and reported in Table 2 and 3. As can be seen in these tables, the same trend for correlation coefficients—as observed so far between duration and structural seismic demands of an 8-story building—is found for the rest buildings type models in use, the structures with 3 to 12 stories. In general, the correlation coefficients increase with an increase in the seismic level of the taken earthquake inputs. As indicated in Table 2, it is interesting to find out that the correlation coefficient in the Seismic level 1 (at the SLE) is negative for the non-degrading SDOFs with 3 and 12 stories.

Table 2. Correlation coefficients between duration and structural displacement demands of non-degrading (equivalent) SDOFs

| Seismic Level | 3-Story SDOF | 5-Story SDOF | 12-Story SDOF |
|---------------|--------------|--------------|---------------|
| 1             | -0.0915      | 0.00351      | -0.0151       |
| 2             | 0.0952       | 0.0951       | 0.1126        |
| 3             | 0.102        | 0.1249       | 0.1329        |

Table 3. Correlation coefficients between duration and structural displacement demands of degrading (equivalent) SDOFs

| Seismic Level | 3-Story SDOF | 5-Story SDOF | 12-Story SDOF |
|---------------|--------------|--------------|---------------|
| 1             | 0.0903       | 0.1042       | 0.1103        |
| 2             | 0.1311       | 0.1439       | 0.1429        |
| 3             | 0.1502       | 0.1527       | 0.1627        |

Figure 9 demonstrates single IDA curves, calculated for each applied ground motion, as well as the median response IDA curves of an 8-story frame which is modeled utilizing an equivalent non-degrading SDOF system. These response curves, shown in Figure 9 (a) and (b), are the outcomes of the IDA analyses that are performed up to a seismic level equal to the SA of 3 g for both of these equivalent SDOF systems, the degrading and non-degrading ones. Figure 10 also displays single IDA curves, which are computed for each applied ground motion, as well as the median response IDA curves of an 8-story RC structure with deteriorative manner. The single
IDA curves for both sets of motions, the short and long sets of ground motions, are computed using an equivalent degrading SDOF system. The median response curves, obtained for each set of motions, represent the behavior of the considered structure under each group of applied ground shakings.

Figure 9. Single IDA curves and the median response of an 8-story structure using a non-degrading SDOF system: a) for short-duration motions b) for long-duration motions

Figure 10. Single IDA curves and the median response of an 8-story structure using a degrading SDOF system: a) for short-duration motions b) for long-duration motions
The median IDA response curves, for both sets of taken ground motions, are figured out and presented in Figure 11 for all employed equivalent SDOF structures. These SDOFs are created with the introduced non-degrading model and can be an appropriate response estimator for structures that do not have deteriorative manner. As can be witnessed in the Figure 11, (a) to (c), at the lower levels of seismic excitation, the median IDA response curves for both sets of motions are the same while they get separated at the upper seismic levels once structures enter the regions associated with high nonlinear cycles. Contrary to the results obtained for structures under short-duration motions, structural seismic demands of non-degrading structures generally increase when they are subjected to long-duration motions. The increased seismic displacement observed in these structural systems, which are exposed to the long-duration set of ground motions, can be related to the further number of nonlinear cycles these building type structures experience during the long-duration earthquakes.
Figure 11. The IDA curves of short-duration motions versus the long-duration motions utilizing non-degrading SDOFs: a) for a 3-story building b) for a 5-story building c) for an 8-story building d) for a 12-story building

The median IDA response curves, for both sets of ground motions, are also computed and shown in Figure 12 for all considered equivalent degrading SDOF systems. As can be seen in this Figure 12, (a) to (c), at the lower levels of seismic excitation, the median IDA response curves for both sets of ground motions are coincident while they detach from each other at the upper seismic levels. In these seismic levels, structures are under conspicuous nonlinear deformations. Therefore, given the fact that linear models are not capable of capturing the structural behavior in the nonlinear regions, they are not able to demonstrate the potential effects of motion duration on structural seismic demands. As a general rule, seismic demand imposed on
the considered structural systems increase when they are exposed to long-duration motions, especially at the higher levels of seismic excitation. The median IDA curve obtained for long-duration set of motions display a noticeable drop-down trend compared to the IDA curve calculated for the short set of motions. This drop-down can reach 20 percent in the 5-story building type of this study as depicted in Figure 12 (b). It means that the collapse capacity of this structural system, the 5-story building, show a 20 percent decline if it is subjected to long-duration motions. The observed behavior of these structural systems, exposed to long-duration motions, can be attributed to more nonlinear cycles these structures experience compared to buildings subjected to a short set of ground motions. Moreover, the induced nonlinear cycles can weaken the structural members and thus further increase the associated peak deformation demands of the considered structures.
Figure 12. The IDA curves of short-duration motions versus the long-duration motions utilizing degrading SDOFs: a) for a 3-story building b) for a 5-story building c) for an 8-story building d) for a 12-story building

7 Conclusion

This paper examines the influence of applying different seismic levels on the results of correlation-based assessments conducted between motion duration and structural seismic demands. Structural seismic demands are determined through an IDA as well as a nonlinear time history analysis. Spectrally matched ground motions are employed in these analyses to investigate the potential effects of motion duration on the structural responses, isolating the
contribution of earthquake duration from the effects of ground motion amplitudes and response spectral shape. For computing linear correlation coefficients between motion duration and structural response, three seismic levels are determined in a way that each of them is compatible with an earthquake return period (RP). Four single degree of freedom systems, which are derived from four real reinforced concrete structures, are considered to model required equivalent SDOFs—degrading and non-degrading models. The results are listed below:

- Although it seems obvious to find out that correlation coefficients approach to zero or even negative value in non-degrading systems at low RPs, positive correlation coefficients equal to 10 percent have been witnessed in degrading SDOFs at the same seismic levels.

- It is revealed that correlation of motion duration with structural seismic demands do not remain unchanged and increase with earthquake RPs where more nonlinearity is expected to happen in the selected structures, both for degrading and non-degrading SDOFs.

- It is revealed that long-duration motions can cause up to 50% larger peak deformation demands compared to the corresponding seismic demands imposed by the short-duration ground motions.

- It is shown that a drop-down trend in the median IDA curves of the degrading SDOFs are found when they are exposed to long-duration ground motions. The collapse capacity of the structures under such long excitations can get declined by 20 percent in some cases.

8 Acknowledgment

The authors would like to thank all the efforts accomplished by the staffs in the center of High-Performance Computing (HPC) of the Sharif University of Technology for providing a robust and fast platform to run our simulations of this research.
9 References

[1] J. Han, X. Sun, Y. Zhou, Duration effect of spectrally matched ground motion records on collapse resistance capacity evaluation of RC frame structures, Struct. Des. Tall Spec. Build. 26 1–12 (2017). doi:10.1002/tal.1397.

[2] M. Raghunandan, A.B. Liel, Effect of ground motion duration on earthquake-induced structural collapse, Struct. Saf. 41 119–133 (2013). doi:10.1016/j.strusafe.2012.12.002.

[3] A. Belejo, A.R. Barbosa, R. Bento, Influence of ground motion duration on damage index-based fragility assessment of a plan-asymmetric non-ductile reinforced concrete building, Eng. Struct. 151 682–703 (2017). doi:10.1016/j.engstruct.2017.08.042.

[4] R. Chandramohan, J. Baker, W, J. Deierlein J, Quantifying the influence of ground motion duration on structural collapse capacity using spectrally equivalent records, Earthq. Spectra. 32 927–950 (2016).

[5] J. Hancock, J.J. Bommer, Using spectral matched records to explore the influence of strong-motion duration on inelastic structural response, Soil Dyn. Earthq. Eng. 27 291–299 (2007). doi:10.1016/j.soildyn.2006.09.004.

[6] G. Wang, S. Zhang, C. Zhou, W. Lu, Correlation between strong motion durations and damage measures of concrete gravity dams, Soil Dyn. Earthq. Eng. 69 148–162 (2015). doi:10.1016/j.soildyn.2014.11.001.

[7] Ioannis M.TaflampasConstantine C.SpyrakosIoannis A.Koutromanos, The effects of strong motion duration on the dynamic response and accumulated damage of concrete gravity dams, Soil Dyn. Earthq. Eng. 45 112–124 (2013). doi:10.1016/j.soildyn.2012.11.011.

[8] C. Wang, H. Hao, S. Zhang, G. Wang, Influence of Ground Motion Duration on Responses of Concrete Gravity Dams, J. Earthq. Eng. 2469 1–25 (2018). doi:10.1080/13632469.2018.1453422.

[9] J.J. Bommer, G. Magenes, J. Hancock, P. Penazzo, The influence of strong-motion duration on the seismic response of masonry structures, Bull. Earthq. Eng. 2 1–26 (2004). doi:10.1023/B:BEEE.0000038948.95616.bf.

[10] M. Mashayekhi, H.E. Estekanchi, Significance of effective number of cycles in Endurance Time analysis, Asian J. Civ. Eng. (Building Housing). 13 647–657 (2012).

[11] M. Mashayekhi, M. Harati, H. Estekanchi, Effect of ground motion duration on incremental dynamic analysis results, Submitted. (2019).

[12] M. Sarieddine, L. Lin, Investigation Correlations between Strong-motion Duration and Structural Damage, Struct. Congr. 2013. 2926–2936 (2013). doi:10.1061/9780784412848.255.

[13] H.E. Mashayekhi, M. R., Harati, M., Estekanchi, Estimating the duration effects in structural responses by a new energy-cycle based parameter, Submitted. (2019).
[14] E.I. Katsanos, A.G. Sextos, G.D. Manolis, Selection of earthquake ground motion records: A state-of-the-art review from a structural engineering perspective, Soil Dyn. Earthq. Eng. 30 157–169 (2010). doi:10.1016/j.soildyn.2009.10.005

[15] ASCE/SEI 7-10, Minimum design loads for building and other structures, American Society of Civil Engineers: Reston, VA, 2010.

[16] ASCE/SEI 41-17, Seismic evaluation and retrofit of existing buildings (41-17), (2017).

[17] FEMA-356, Prestandard and Commentary for the Seismic Rehabilitation of Buildings, (2000).

[18] GB50011-2010 Code, Code for Seismic Design of Buildings, Ministry of Housing and Urban-Rural Development of the People’s Republic of China, (2010).

[19] J.J. Bommer, A. Marytínezpereira, The effective duration of earthquake strong motion, J. Earthq. Eng. 3 127–172 (1999). doi:10.1080/13632469909350343.

[20] EPRI, A criterion for determining exceedance of the operating basis earthquake, Report No. EPRI NP-5930, Palo Alto, California, (1988).

[21] M. Cabañas, L., Benito, B., Herráiz, An approach to the measurement of the potential structural damage of earthquake ground motions, Earthq. Eng. Struct. Dyn. 26 79–92 (1997). doi:10.1002/(SICI)1096-9845(199701)26.

[22] Y. Heo, S.K. Kunnath, F. Asce, N. Abrahamson, Amplitude-scaled versus spectrum-matched ground motions for seismic performance assessment, J. Struct. Eng. 137 278–288 (2011). doi:10.1061/(ASCE)ST.1943-541X.0000340.

[23] J. Hancock, J. Watson-Lamprey, N. a. Abrahamson, J.J. Bommer*, A. Markatis, E. McCoyH, R. Mendis, An improved method of matching response spectra of recorded earthquake ground motion using wavelets, J. Earthq. Eng. 10 67–89 (2006). doi:10.1080/13632460609350629.

[24] M. Mashayekhi, M. Harati, H. Estekanchi, A new strong ground motion duration parameter and investigating its correlation with nonlinear responses, Submitted. (2019).

[25] Korkmaz A. Aktaş E., Probability based seismic analysis for r/c frame structures, J. Fac. Eng. Archit. Gazi Univ. 21 55–64 (2006).

[26] F. McKenna, Open System for Earthquake Engineering Simulation (OpenSees) version 2.4. 4 MP [Software], (2014).

[27] L.F. Ibarra, R.A. Medina, H. Krawinkler, Hysteretic models that incorporate strength and stiffness deterioration, Earthq. Eng. Struct. Dyn. 34 1489–1511 (2005). doi:10.1002/eqe.495.