Duration-dependent inelastic response spectra and effect of ground motion duration

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SUMMARY:
During the last decade, the international structural design community has shown a major interest in performance-based seismic design. Seismic performance is related to damage levels when the structure is subjected to earthquake ground motion of specified intensity. Current seismic design codes allow a structure to develop inelastic deformations and large inelastic deformations can be expected to occur in such structures at the design level earthquake as the force levels specified by most seismic design codes are considerably lower than that expected in elastic structures. During earthquakes, structures are thus expected to dissipate a large amount of seismic energy under the reversed cyclic loading through inelastic deformation or damage. The damage in structures depends on various factors, such as the load-deformation characteristics of the structure, the yield strength and the intensity and duration of the ground motion. It seems that the design spectra currently included in most of the current seismic design codes do not take into account the effect of duration of the ground motion although the potential of cumulative damage during long duration earthquake is generally recognized. Yielding structures under a long duration ground motion undergo an increased number of reversals of inelastic deformations and the accumulation of damage may significantly affect the overall performance of the structure. Recent major earthquakes (e.g., the 26th December 2004, Sumatra; 27th February 2010, Chile; and the 11th March 2011, Japan) have produced very long duration ground motions up to several minutes and thus emphasize the need of the present study. In this paper, inelastic response spectra are developed for ground motions which are characterized by long duration. The effect of duration is investigated by nonlinear dynamic analysis with the help of the conventional approach of constructing inelastic seismic response spectrum using a reduction factor. Effect of long duration of the earthquake ground motion is considered through the seismic energy imparted to the structure and performance of the structure is estimated by using an energy-based cumulative damage model.

Keywords: Ground motion duration, Inelastic response spectra, Performance based seismic design, Seismic energy

1. INTRODUCTION

After the unexpectedly high economic loss and cost of repair during the 1989 Loma Prieta and 1994 Northridge earthquakes the international structural design community has shown a major interest in performance-based seismic design with the basic objective to design structures that respond in a more reliable manner during earthquake shaking. The performance targets can be displacements and a limit state or damage state. Current seismic codes allow designing most of the buildings for base-shear considerably lower than the elastic base-shear associated with the expected shaking that can occur at that site. Thus, the buildings are expected to suffer damage during strong ground shaking and large inelastic deformations can be expected. Insufficient lateral strength can result in excessive structural damage, and thus, improper structural performance. During earthquakes structures dissipate a large amount of seismic energy under the reversed cyclic loading through inelastic deformation or damage. The design base-shear coefficients currently included in seismic design codes do not seem to take into account the effect of several variables (e.g. ground motion duration) that should have be considered. As a result, the design base-shear coefficients may be insufficient to adequately control structural damage on ductile structures subjected to ground motions exhibiting large energy content. The damage in structures depends on various factors, such as the load-deformation characteristics of the structure, the yield strength and the intensity and duration of the ground motion.

Yielding structures under a long duration ground motion undergo an increased number of reversals of inelastic deformations and the accumulation of damage may significantly affect the overall performance of the structure. Although the potential of cumulative damage during long duration ground motion is generally recognized (Chai et al. 1998 and Chai 2005), it seems that the design spectra currently included in most of the current seismic design codes do not take into account the effect of ground motion duration.

Iervolino et al. (2006) concluded that duration of ground motion is statistically insignificant to displacement ductility, but it considerably affects hysteretic ductility. Handcock and Boomer (2006) did a comprehensive literature review on influence of strong-motion duration on structural damage. Handcock and Boomer (2006 and 2007) concluded that damage measures related to cumulative energy usually find a positive correlation between strong-motion duration and structural damage, but the damage measures using maximum response (maximum drift or displacement) generally do not find strong correlations between duration and damage. Lin et al. (2010) concluded that the strong-motion duration does not have effects on the drifts when the seismic excitations are scaled to spectral acceleration at the fundamental building period. Tremblay (1998) developed design spectra based on simulated ground motion time histories for subduction earthquakes for four different sites in British Columbia. Chai and co-authors (1998, 2000 and 2005) developed duration dependent inelastic seismic design spectra using the spectral input energy, damaging part of which is dissipated by the plastic strain energy capacity of the structure. They adopted a bilinear equivalent velocity spectrum, which is dependent to the ground-motion duration, to obtain spectral energy input. They adopted the equivalent velocity spectrum with a constant value beyond characteristic period (Chai and Fajfar 2000). Constant value of equivalent velocity spectrum beyond characteristic period is expected for ground motions characterized by small duration and decreasing value of equivalent velocity spectrum beyond characteristic period is more evident for earthquake ground motions characterized by long duration (Kuwamura and Galambos 1989).

The objective of this paper is to develop duration dependent response spectra for long duration ground motions. First a single-degree-of-freedom (SDOF) structure is studied to see the effects of the strong-motion duration on the peak response quantities as well as on energy based performance of the structure. Then the effect of strong-motion duration is shown on the response spectra. The effect of duration is considered directly through inelastic (hysteretic) seismic energy which is a part of the input seismic energy imparted to the structure. An approach to include strong-motion duration effect on performance-based seismic design is also discussed.

2. ENENGY BALANCE EQUATION

For a structure the following energy balance equation holds true at any time during ground motion duration (Riddell and Garcia 2001):

$$E_K + E_D + E_H + E_S = E_I \tag{2.1}$$

In the equation (2.1) E_K , E_D , E_H , E_S , E_I are kinetic energy per unit mass, energy per unit mass dissipated by viscous damping, hysteretic energy per unit mass, elastic strain energy per unit mass and energy imparted to the structure per unit mass, respectively. When the system comes to rest at the end of the ground motion, the kinetic energy and elastic strain energy vanishes. As a result, at the end of the ground motion, equation (2.1) becomes

$$E_D + E_H = E_I \tag{2.2}$$

Hysteretic energy E_H is dissipated by the inelastic behavior of the structure and this part of the input energy causes damage to the structure. During strong ground motion, structure undergoes inelastic excursion below the maximum lateral displacement capacity of the structure. In such cases, the structure can be significantly damaged by low-cycle fatigue. Such duration related damage or cumulative damage is reflected in the hysteretic energy (Benavent and Zahran 2010). In this study, hysteretic energy E_H is directly used to develop the duration dependent response spectra.

3. DURATION MEASURE

In this study, strong-motion duration is defined by "significant duration" which is based on the accumulation of energy in the accelerogram represented by the integral of the square of the ground acceleration (Arias intensity, Arias, 1970). Here significant duration is defined as the interval over which 5 and 95% of the Arias intensity is accumulated (D5-95).

$$Arias\ intensity = \frac{\pi}{2g}\int_0^{T_d} a_g^2\,(t)dt \tag{3.1}$$

where, g is the acceleration due to gravity, a_g is the ground acceleration and T_d is the total duration of the ground motion.

4. DAMAGE MEASURE

In order to investigate the performance of the structure during severe earthquake, the well-known Park and Ang (1985) damage model as used in IDARC (Valles et al. 1996) is used here which is defined as linear combination of the maximum displacement and the dissipated hysteretic energy. The Park and Ang damage index (Di) is defined in the following way:

$$Di = \frac{\mu-1}{\mu_m-1} + \beta\frac{E_H}{f_Y\mu_m u_Y} \tag{4.1}$$

Here, maximum ductility demand, $\mu = u_m/u_Y$ where, u_m is peak deformation of elastoplastic system due to ground motion and u_Y and f_Y are yield deformation and yield strength of the elastoplastic system, respectively. Available ductility capacity, $\mu_m = u_{um}/u_Y$, where u_{um}= ultimate displacement capacity of the structure under monotonic loading. Here, β is strength deterioration parameter for structural damage, the experimental value is ranged between -0.3 to +1.2, with a median of about 0.15. In this study, the strength deterioration parameter (β) is taken as 0.15.

5. NONLINEAR RESPONSE ANALYSIS OF A BUILDING STRUCTURE

In order to investigate the effect of strong motion duration, performance of a SDOF structure is investigated for peak response quantities (peak storey drift and peak floor acceleration). In this investigation, the structure is modeled using SAP2000 (CSI 2009). Fundamental natural period of the structure is, T=1.0s. Ten seed ground motions are selected from PEER NGA ground motion database (PEER 2011) with different durations which are shown in Table 5.1. In the selection process for the ground motions, no restriction is considered for magnitude, site-to-source distance and site conditions in order to obtain records of a wide range of durations. The ten seed ground motions of Table 5.1 are modified using the computer code RSPMATCH (Abrahamson, 1998) to match a target response spectrum which is the 5% damped spectra as used by Hancock and Bommer (2007) for a median-plus-one-standard-deviation design scenario for an Mw 7 strike-slip earthquake at a soft soil site 5 km from the surface projection of the fault rupture. The target spectrum and the spectra for the 10 ground motions scaled to the target spectrum are shown in Figure 5.1. The significant duration of the 10 spectrally matched ground motions are shown at the last column of the Table 5.1.

Table 5.1. List of ten seed ground motions

Year	Earthquake Name	Station Name	Earthquake Magnitude	Record Sequence Number	D5-95 (s)	Closest distance to rupture plane (km)	Vs30 (m/s)	D5-95(s) after modification
1995	Kobe- Japan	Takarazuka	6.9	1119FN	5.1	0.3	312	17.65
1992	Cape Mendocino	Petrolia	7.01	828FN	16.2	8.2	712.8	26.52
1999	Chi-Chi-Taiwan	TCU120	7.62	1545FN	32.6	7.4	459.3	36.47
1999	Chi-Chi-Taiwan	TCU141	7.62	1553FN	52.2	24.2	209.2	60
1999	Chi-Chi-Taiwan-03	TCU059	6.2	2613FN	65.9	52.2	230.3	68.9
1999	Chi-Chi-Taiwan	CHY012	7.62	1185FN	80.3	59	198.4	66.26
2002	Nenana Mountain-Alaska	Anchorage - K2-05	6.7	2065FP	99.8	269.6	284	112.68
2002	Denali-Alaska	Anchorage - NOAA Weather Fac.	7.9	2102FN	116	275.1	274.5	117.69
2002	Denali-Alaska	Anchorage - Dowl Eng Warehouse	7.9	2096FP	129.4	270.3	360	136.54
2002	Denali-Alaska	Anchorage - K2-04	7.9	2099FN	143.5	273.6	279.4	162.24

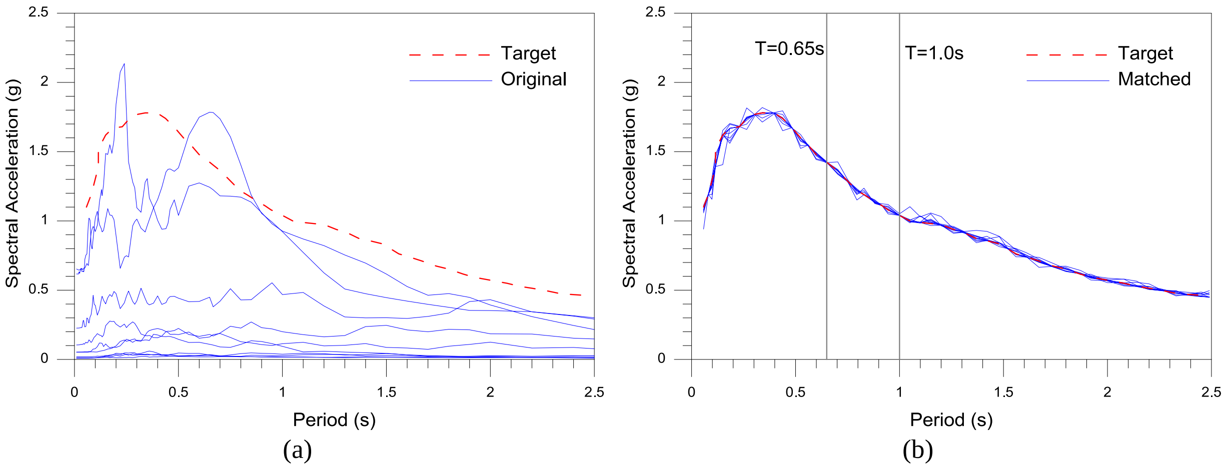
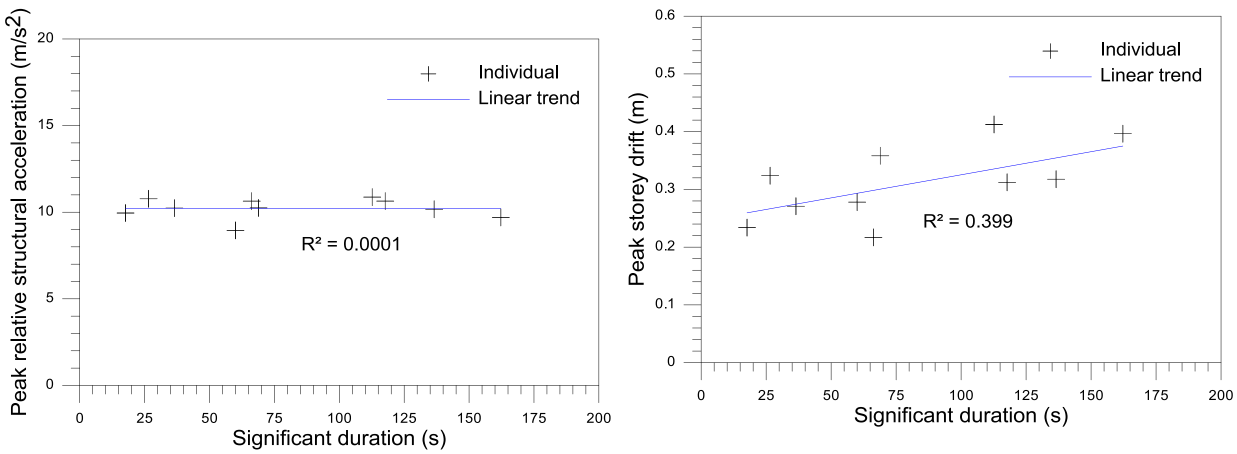
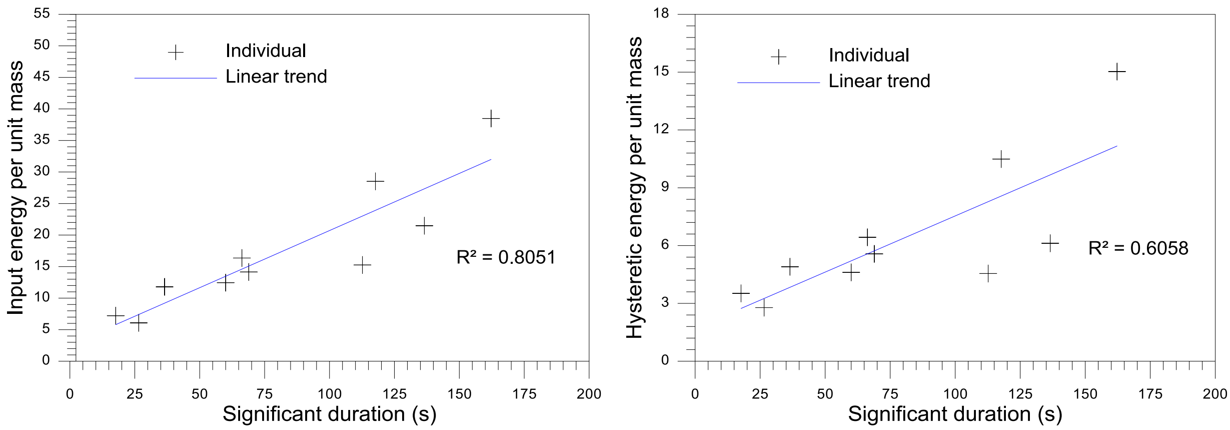


Figure 5.1. Target spectrum and (a) original spectra, (b) matched spectra of the 10 ground motions scaled using spectrum matching method to the target spectrum



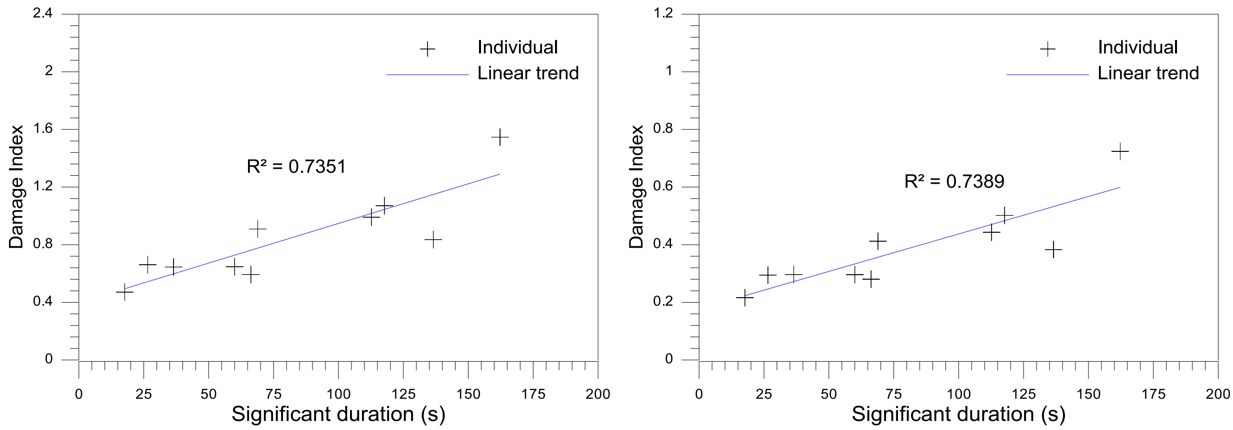
Structural acceleration Storey drift

Figure 5.2. Peak relative structural acceleration and storey drift for 10 spectrally matched ground motions for a T=1.0s structure



Input energy Hysteretic energy

Figure 5.3. Input and hysteretic energy for 10 spectrally matched ground motions for a T=1.0s structure



(a) μ_m=4 (b) μ_m=8

Figure 5.4. Damage Index for 10 spectrally matched ground motions for a T=1.0s structure with different ductility capacities (μ_m)

In this investigation, Bouc-Wen hysteretic model (Wen 1976 and CSI 2009) is used which is extensively utilized in structural dynamics research to describe the hysteretic behaviour of concrete and steel structures (Park et al. 1985, Goda et al. 2009 and Foliente et al. 1995). In the present investigation, a quasi-bilinear hysteretic model is used. Post yield stiffness ratio is taken as zero. To investigate the effect of duration on the peak response quantities, the nonlinear response history analysis is performed considering a yield strength which is 50% of the elastic strength required (fy is 50% of fe). Peak structural acceleration and storey drift for 10 spectrally matched ground motions and the trend line for peak response quantities are shown in Figure 5.2. From the results, it can be seen that the duration does not have significant effect on peak structural acceleration response quantities which almost remain same even for long duration ground motions. Unlike the earlier studies by Hancock and Bommer (2007) and Lin et al. (2010), this study finds that the peak storey drift has prominent correlation with the duration, which increases with the increase of the duration of ground motion. The effect of duration is more prominent for input and hysteretic energy quantities which can be seen from Figure 5.3. The effect of duration on damage index (which takes into account both the hysteretic energy and peak deformation) is shown in Figure 5.4, which increases with duration. As a result, the seismic performance of a structure under a long duration ground motion can be inferior compared to a small duration ground motion. It can be seen from Figure 5.2- Figure 5.4 that correlation between ground motion duration, input energy, hysteretic energy and damage index is more prominent (as the slope of trend line is much stiffer) compared to the correlation between ground motion duration and peak responses (as the slope of trend line is more flat).

6. DURATION DEPENDENT RESPONSE SPECTRA

From the section 5, it is established that the ground motion duration has an adverse effect on the performance of structure. Considering strong motion duration, in this section, duration dependent response spectra are developed. In this investigation, E_H is used in equation (4.1) to develop duration dependent response spectra assuming that the structure reaches ultimate limit state (damage index, Di=1). An iterative procedure is used which is as follows:

1. A SDOF nonlinear structure of unit mass, a specific natural period and damping ratio=0.05 is considered. Bouc-Wen hysteretic model (Wen 1976 and CSI 2009) is used here to describe the hysteretic behaviour of the structure. Structures with various available ductility capacities (μ_m) are considered. Strength deterioration parameter (β) is taken as 0.15.
2. An earthquake ground acceleration time history is selected. Elastic strength demand (f_e) is calculated.
3. The value of yield strength (f_y) is obtained by searching for which the structure reaches ultimate limit state (Di=1). An iterative procedure can be used by gradually reducing the yield strength from the elastic strength demand ($f_y= f_e-\Delta f$). In each iteration, nonlinear time history analysis is performed to find out u_m and E_H. The iterative procedure is continued till the computed Di is within 2% of the target Di. For various f_y values the iteration may converge. In such cases, the largest value of the f_y is taken. Once the iterative procedure is converged to Di=1, base-shear coefficient is calculated.
4. These steps are repeated for structures with various natural periods.

In order to show the effect of ground motion duration, three ground motions are considered of different durations. Among the three, the smallest duration ground motion is from Gazli earthquake, USSR (1976) recorded at Karakyr (NGR record sequence number is 126FN). The medium duration ground motion is from Chi-Chi earthquake, Taiwan (1999) recorded at TCU053 (NGR record sequence number is 1493FP). The long duration ground motion is from Sumatra earthquake (10 April, 2005) recorded at BTDF, Singapore (at 111425 hrs GMT). These ground motions are modified to match the target spectrum using spectral matching method using the computer code RSPMATCH (Abrahamson, 1998). Here, the target response spectrum is the same spectrum as used in section 5. In order to obtain records of a wide range of durations, no restriction is considered on the seismological characteristics of the ground motions. Comparison of 5% damped target spectrum and the spectra from three selected records with different durations is shown in Figure 6.1. The 5-95% significant duration for the three modified time histories are 10.56s, 34.68s and 226.76s and thus they are termed as small, medium and long duration ground motion, respectively. The original and the modified time histories for the long duration motion used for this investigation are shown in Figure 6.2.

Duration dependent response spectra and the effect of ground motion duration are shown in Figure 6.3 for two different ductility capacities (μ_m). The effect of the ground motion duration is clearly seen in the long period region. A clear difference in the spectral ordinates is seen between the three ground motions although their elastic spectral ordinates are the same (Figure 6.1). In Figure 6.4, the reduction factors for base-shear co-efficient and trend are shown for all 13 ground motions for T=0.65s and 1.0s structures for two different ductility capacities (μ_m). For the T=0.65s structure, the trend is not very clear. But, for the T=1.0s structure, the results clearly indicate that the reduction factors decrease with the increase of duration of ground motions. It indicates, for small duration ground motion the structure can be designed for much lower value of base-shear coefficient compared to long duration ground motion which requires much higher values of base-shear coefficient.

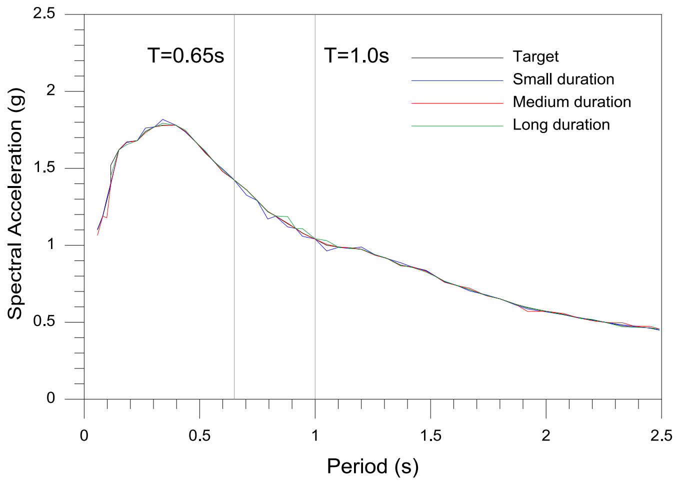
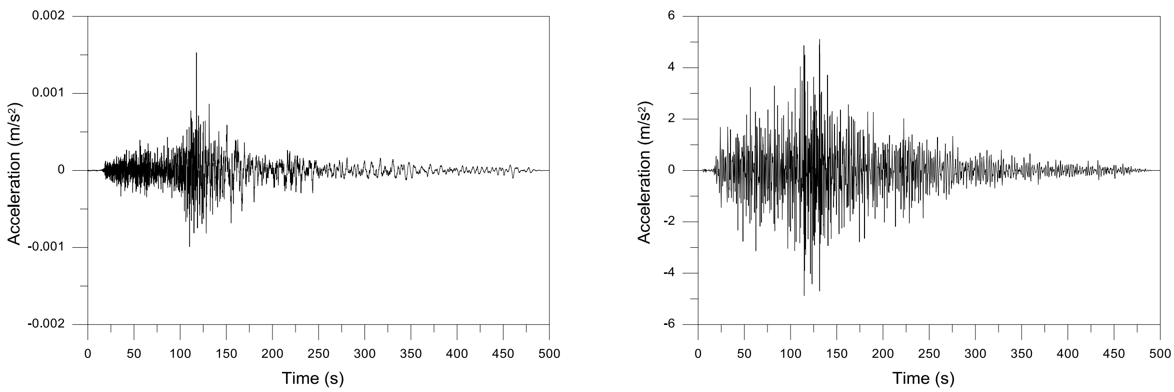
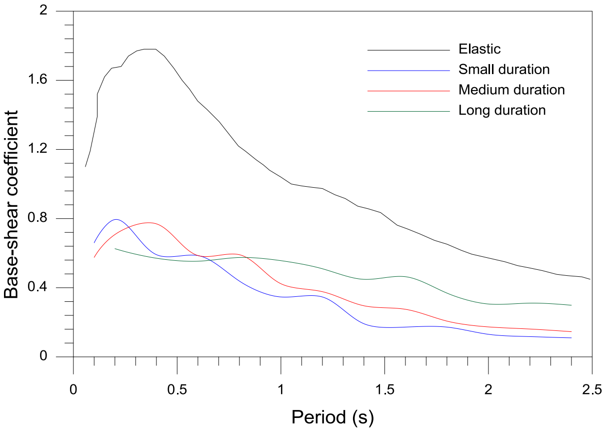


Figure 6.1. Target spectrum and matched spectra of the 3 ground motions scaled to the target spectrum

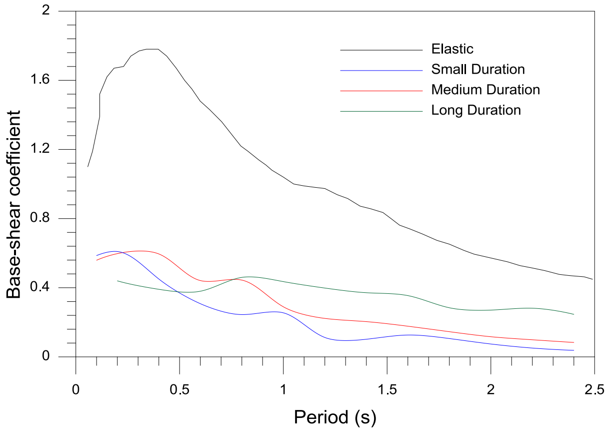


(a) before spectral matching (b) after spectral matching

Figure 6.2. Typical acceleration time series for the long duration ground motion

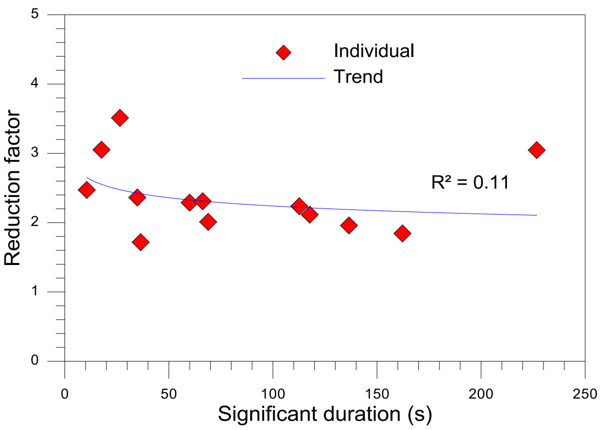


(a) μ_m=4

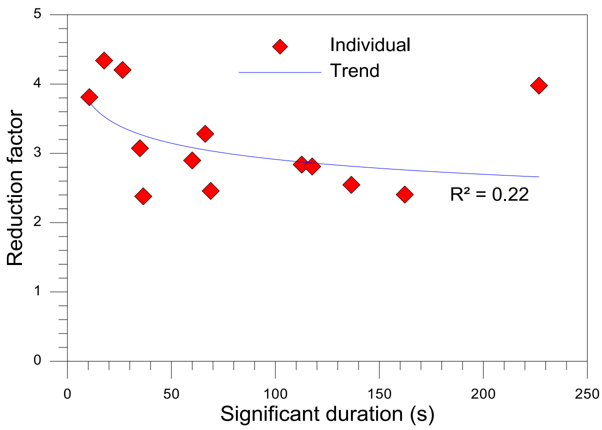


(b) μ_m=8

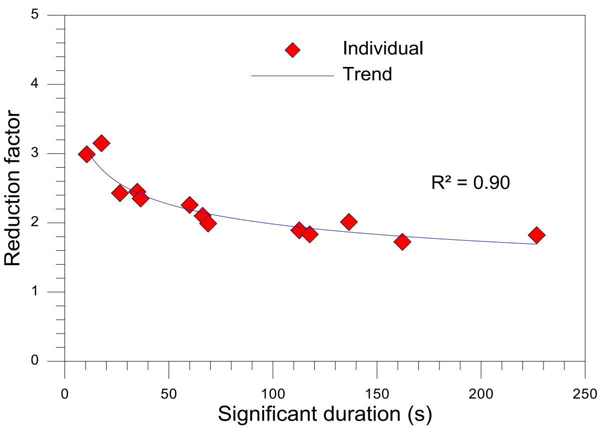
Figure 6.3. Elastic and duration dependent response spectra for two different ductility capacities (μ_m)



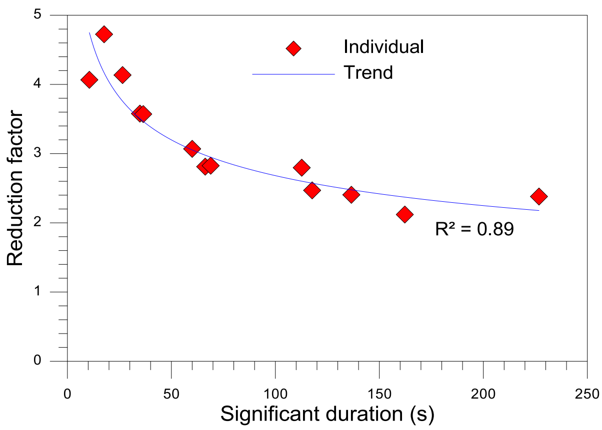
(a) T=0.65s, μ_m=4



(b) T=0.65s, μ_m=8



(c) T=1.0s, μ_m=4



(d) T=1.0s, μ_m=8

Figure 6.4. Effect of ground motion duration on reduction factors for base-shear co-efficient for 13 spectrally matched ground motions for two different structures with two different ductility capacities (μ_m)

7. DURATION DEPENDENT RESPONSE SPECTRA FOR PERFORMANCE-BASED EARTHQUAKE ENGINEERING

One of the main objectives of performance-based earthquake engineering is to produce structures which will achieve reliable performance objectives during stated levels of seismic hazard. The performance objective may be a level of displacement or a damage state. As it is seen that duration can be one of the factors in the design, the effect of duration should be included in the performance-based seismic design. Many of the earlier studies defined different damage states based on the damage index. The structure will have no damage for Di <0.1; minor damage for 0.1≤Di≤0.25; moderate damage for 0.25≤Di≤0.40; severe damage for 0.4≤Di≤1.0 and collapse for Di≥1.0 (Williams and Sexsmith 1995). Thus, it is possible to create damage performance based duration dependent spectra for design of new structures by modifying the target damage index which has been taken as unity in section 6 for the ultimate limit state in order to produce duration dependent response spectra.

It is also possible to know the performance of existing structures based on the damage index. Table 7.1 shows the performance of three existing structures for three ground motions of different durations. It can be seen that although the three ground motions produce same elastic spectra (Figure 6.1), structural performance can be very different for the three ground motion cases. The 1.0s and 2.0s structures perform well during the small duration ground motion (damage indexes are 0.146 and 0.23, respectively). But severe damage occurs under the long duration motion (damage indexes are 0.738 and 0.785, respectively). The effect of duration on damage index for a T=1.0s structure is shown in Figure 5.4 for 10 other ground motions (with, fy=50% of fe). Similar finding is also seen there.

Table 7.1. Performance based assessment of existing structures (for μ_m=4)

Structure property, Period (s)	Ground motion duration	Damage Index (Di)
0.6s (fy=45% of fe)	Small duration	0.626
	Medium duration	0.693
	Long duration	0.734
1.0s (fy=65% of fe)	Small duration	0.146
	Medium duration	0.212
	Long duration	0.738
2.0s (fy=60% of fe)	Small duration	0.230
	Medium duration	0.341
	Long duration	0.785

8. SUMMARY AND CONCLUSIONS

The effect of ground motion duration on the peak responses, performances of structures and inelastic response spectra is discussed. It is found that the peak acceleration response usually does not find strong correlation with duration, but, the peak storey drift usually has well defined correlation which increases with the increase of ground motion duration. The input energy due to the ground motion increases with the increase of duration and so are the hysteretic energy and damage index. As a result, the performance of structure is dependent on the duration of the ground motion which is more susceptible to damage as duration increases. In this investigation, an iterative procedure is used to incorporate the strong motion duration effect on the inelastic response spectra and duration dependent inelastic response spectra are developed. Effect of ground motion duration is considered through the hysteretic energy which is a part of the seismic input energy imparted to the structure. Performance of the structure is evaluated by using energy-based Park and Ang damage model. Spectrally matched ground motions are used to show the effect of ground motion duration on the seismic base-shear co-efficient. Very small duration to very long duration ground motions are considered to study the effect of duration. The investigation finds that the ground motion duration shall be incorporated for the design of structures as long duration ground motions require much higher value of base-shear coefficients compared to small duration motions. For the specific target spectrum and the ground motions used in this investigation, the effect of duration is more prominent for structures with natural periods T>0.80s. Recent studies have emphasized performance based seismic design of structures which is dependent on damage levels in the structure. Procedure to develop performance based duration dependent spectra for design of new structures and duration dependent performance analysis of existing structures are also discussed. It is shown that the same structure can perform very poorly if the ground motion duration increases. The results from this investigation are from a non-strength/stiffness reducing damage model. The effect of ground motion duration can be even more serious for a strength/stiffness reducing damage model.

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