Evaluation of Seismic Displacement Demands from Ground Motions Recorded in Recent Earthquakes

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SUMMARY:
A detailed assessment of seismic displacement demands computed from a selected number of ground motions recorded during recent earthquakes is presented. Ground motions recorded during the Mw 8.8 February 27th, 2010 Chile earthquake, the Mw 7.0 September 4th, 2010 Darfield, New Zealand earthquake, the Mw 6.3 February 22nd, 2011 Christchurch, New Zealand earthquake and during the Mw 9.0 March 11th, 2011 Tohoku, Japan earthquake are examined. Results include linear and inelastic spectra for SDOF systems and generalized interstory drift spectra for MDOF systems. It is shown that despite its moderate magnitude some of the most demanding ground motions are those from the 2011 Christchurch, New Zealand earthquake. The most damaging records from these earthquakes are identified and further evaluated. It is shown that displacements demands on inelastic systems are smaller to those of elastic systems for periods corresponding to peaks in the elastic displacements spectrum. Implications on seismic design criteria are discussed.

Keywords: displacement demands, strong ground motion, SDOF systems, nonlinear response

1. INTRODUCTION

There is a consensus among the earthquake engineering community that damage in structural elements, and to many kinds of nonstructural components, are primarily the result of lateral deformation demands induced by earthquake ground shaking in the structure. As a consequence, modern performance-based assessment methodologies for design and evaluation of existing structures (e.g. FEMA 356, 2000) rely on the estimation of peak lateral displacement demands that engineered-structures could suffer under seismic excitation.

Very recently, strong earthquakes have occurred around the word, some of them affecting important urban cities. Among them, the Mw 8.8 February 27th, 2010 Chile earthquake, the Mw 7.0 September 4th, 2010 Darfield, New Zealand earthquake, the Mw 6.3 February 22nd, 2011 Christchurch, New Zealand earthquake and during the Mw 9.0 March 11th, 2011 Tohoku, Japan. Earthquake ground motions recorded during these events provide a good opportunity to examine displacement demands in structures.

The main objective of the study reported in this paper was to perform a detailed assessment of seismic displacement demands computed from ground motions recorded during recent earthquakes. In particular, peak elastic and inelastic displacement demand spectra, inelastic displacement ratio spectra which allow the estimation of displacement demands in inelastic systems from the displacement demands on elastic systems, and generalized interstory drift spectra (GIDS) are computed and discussed. A generalized interstory drift spectrum is a new kind of spectrum that provides information of the peak rotation demand of a continuous system as a function of the fundamental (first) period of vibration of the system, which provides estimates of interstory drift to multi-story buildings responding elastically to earthquakes.

2. EARTHQUAKE GROUND MOTIONS CONSIDERED IN THIS STUDY

This study employs selected earthquake ground motions (EQGMs) recorded worldwide during recent strong earthquakes such as the Mw 8.8 February 27th, 2010 Chile earthquake, the Mw 7.0 September 4th, 2010 Darfield, New Zealand earthquake, the Mw 6.3 February 22nd, 2011 Christchurch, New Zealand earthquake and during the Mw 9.0 March 11th, 2011 Tohoku, Japan earthquake. For this purpose, EQGMs were downloaded from the Center for Engineering Strong Motion Data (CESMD 2012). Table 2.1 reports selected EQGMs that were examined in this study.

Table 2.1 Earthquake ground motions considered in this study

Earthquake	Date	Mw	Station	Component	PGA (cm/s^2)
Maule, Chile	2/27/10	8.8	CON	L	393.2
			CON	T	280.5
			COT	T	613.8
Darfield, NZ	9/4/10	7.0	HVSC	S64E	606.6
			CCCC	N64E	224.5
Christchurch, NZ	2/22/11	6.3	HVSC	S64E	1163.6
			CCCC	N64E	473.9
Tohoku, Japan	3/11/11	9.0	MYG004	NS	2699.9
			MYG004	EW	1268.4
			MYG012	NS	758.4
			MYG012	EW	1969.2
			IBR003	NS	1597.6
			IBR003	EW	1185.9
			FKS004	EW	568.4
			IBR001	EW	399.6
			IWT019	NS	316.2

Fig. 2.1shows typical EQGMs recorded during the 2011 Tohoku earthquake. The National Research Institute for Earth Science and Disaster Prevention (NIED) in Japan identified four distinct characteristics in the EQGMs, which reflects that three main fault slips, sometimes also referred to as sub-events, occurred in this earthquake (NIED, 2010). These selected waveforms illustrate several distinct time modulations as follows: (1) first sub-event is dominant (Fig. 2.1a); (2) both sub-events are dominant (Fig. 2.1b); (3) the second sub-event is dominant (Fig. 2.1c); and (4) the first phase is not clearly visible (Fig. 2.1d). Regardless of the particular features, these records show very long ground motion duration. It should be noted that EQGMs having the larger peak ground acceleration (PGA) occurred in records where both sub-events are predominant (e.g. PGA=2933 cm/s2 at MYG004 station, PGA=2019 cm/s2 at MYG012 station, and PGA=1845 cm/s2 at IBR003 station).

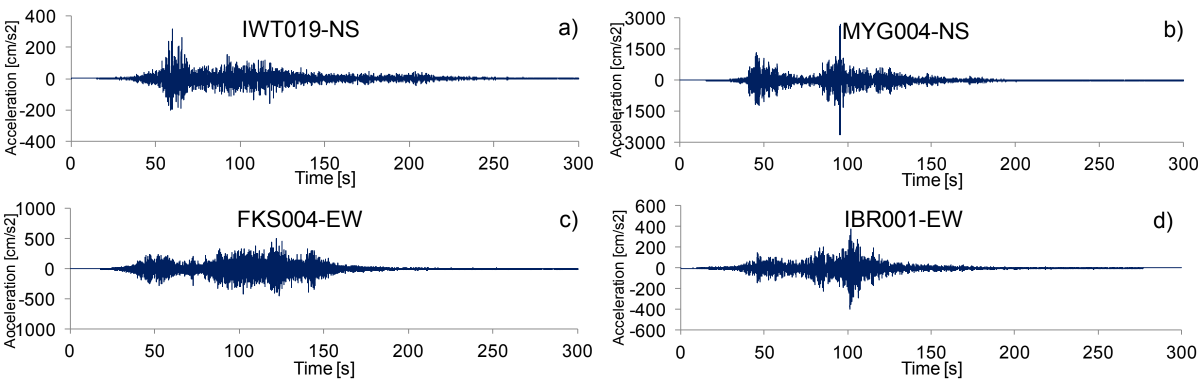

Figure 2.1. EQGMs recorded during the 2011 Tohoku earthquake showing distinct characteristics: a) first phase is predominant, b) both phases are predominant, c) the second phase is predominant, d) the first phase is not visible.

Figure 2.2 illustrates selected EQGMs recorded during the 2010 Chile earthquake, the 2010 Darfield earthquake, and the 2011 Christchurch earthquake. EQGMs shown in Fig. 2.2a and 2.2b recorded the largest PGA during the 2010 Chile since stations were located at the closest epicentral distance. The Constitución record shows similar ground motion features than other EQGM's recorded during past earthquake such as the 1985 Viña del Mar earthquake (i.e. long duration wave forms with high-frequency content), however the Concepción records is characterized by long duration low frequency content resembling some of the characteristics observed in the SCT station recorded in Mexico City during the 1985 Mexico earthquake.

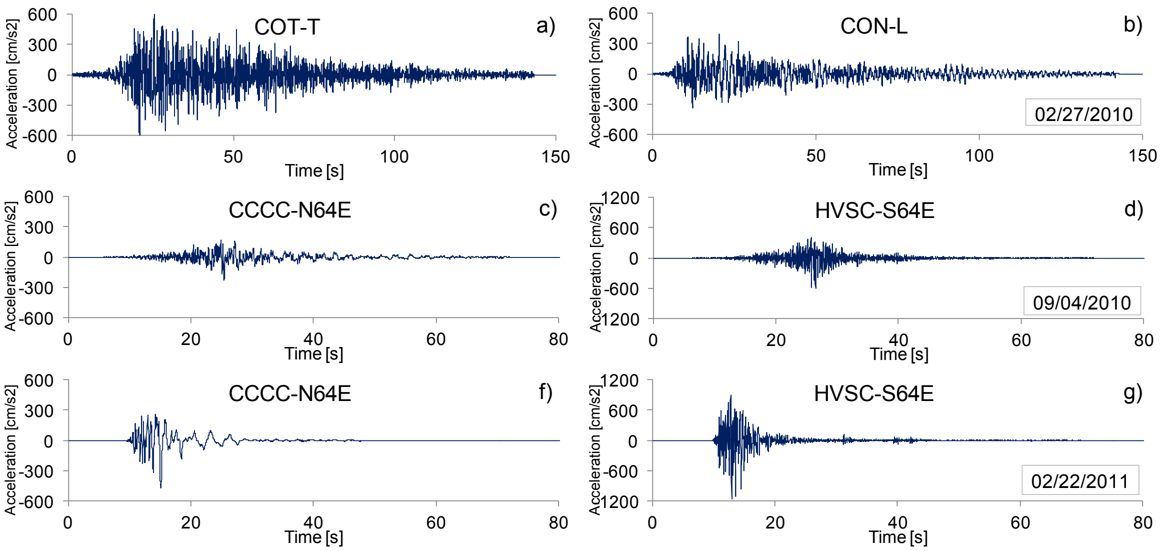

Figure 2.2 EQGMs recorded during the 2010 Chile earthquake, the 2010 Darfield earthquake, and the 2011 Christchurch earthquake: a) Constitución station (Comp. T), b) Concepción station (comp. L), c) Christchurch Cathedral station (N64E), d) Heathcote Valley Primary School station (comp.S64E), e) Christchurch Cathedral station (N64E), d) Heathcote Valley Primary School station (comp.S64E).

It should be noted that an unusual seismic scenario occurred during the seismic events that struck New Zealand last 2010 and 2011. Following the September 4, 2010 Canterbury earthquake (Mw=7.0), a second strong event (Mw=6.3) occurred on February 22, 2011 essentially below the city of Christchurch. Unlike typical mainshock-aftershock sequences, some stations recorded greater PGAs due to the aftershock than those from the mainshock. This situation can be partially explained since the stations were located at a shorter epicentral distance from the aftershock epicenter than that from the mainshock epicenter (e.g. Christchurch Cathedral station had a distance from the mainshock fault rupture of 38 km, while it was 6 km from the aftershock epicenter). For instance, Fig. 2.2c and 2.2e show EQGMs recorded during the mainshock, while Figs. 2.2d and 2.2f illustrates their corresponding EQGMs gathered during the aftershock.

3. LINEAR ELASTIC SPECTRAL ORDINATES

Figure 3.1 shows a comparison of spectral acceleration and displacement demands computed from linear single-degree-of-freedom systems with 5% damping ratio when subjected to the EQGMs illustrated in Fig. 2.1. It can be seen that records with two waveform phases lead to the largest elastic acceleration and displacement demands in a wide spectral region. A further look at elastic spectra for six records with two distinct sub-events in the waveform EQGMs is illustrated in Fig. 3.2. It can be observed that these records trigger high acceleration demands at short periods of vibration, but elastic displacement demands become larger as the period of vibration become longer.

Five percent damped elastic acceleration and displacement response spectra computed for six earthquake ground motions corresponding to the four earthquakes are shown in Figures 3.3a and 3.3b, respectively. It can be seen that EQGMs recorded at MYG004 station lead to large spectral

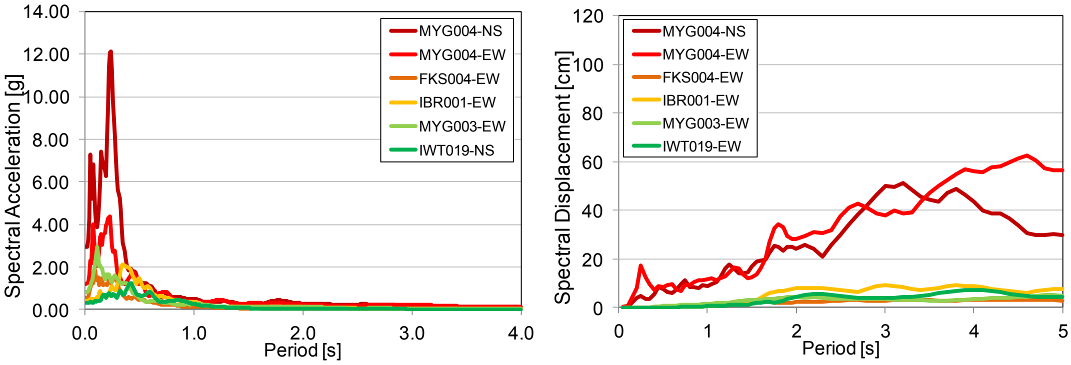

Figure 3.1 Comparison of 5% damped elastic response spectra computed from six EQGMs recorded during the 2011 Tohoku earthquake: (a) Acceleration response spectra; (b) Displacement response spectra.

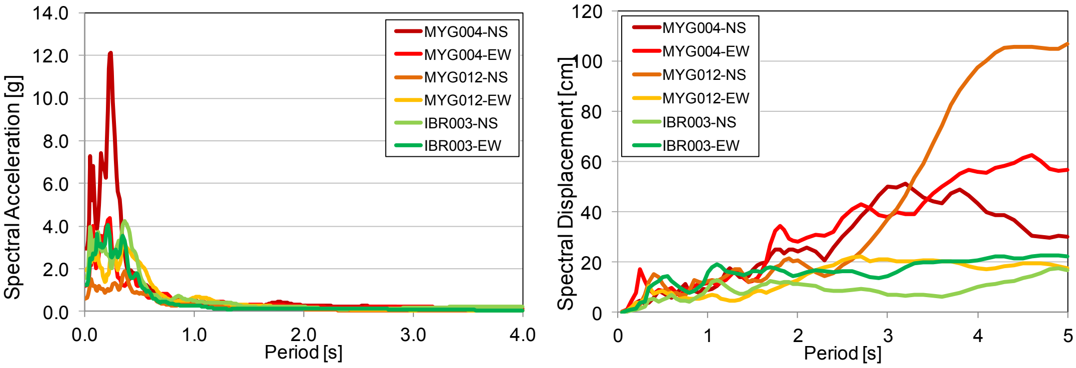

Figure 3.2 Comparison of elastic response spectra computed from six EQGMs having two distinct waveform sub-events recorded during the 2011 Tohoku earthquake: (a) Acceleration response spectra; (b) Displacement response spectra.

acceleration ordinates, particularly high for low periods of vibrations around 0.3s, but EQGMs recorded at the Concepción (CON) station during the 2010 Chile earthquake and at the CCCC station during the 2011 Christchurch earthquake produced unusually high spectral acceleration ordinates for systems with periods of vibration between 1 and 2 seconds. Among this group of EQGMs, the largest spectral displacement ordinates (approximately 110 cm) are due to the CON-L record at approximately 2s. It should be noted that the record CCCC gathered at the NZ aftershock has two distinct spectral peaks one that lead to peak displacement of approximately 57 cm for a period of 1.5s and approximately 88 cm for a period of 3.2s. It is interesting to note that despite the large magnitude of the Japan earthquake displacement demands are relatively small compared to some of the ones observed in the other earthquakes. For example despite of the large PGAs and spectral acceleration demands, records from MYG004 station produce spectral displacement demands that large significantly smaller than those of the CCCC record obtained in the Mw 6.3 Christchurch earthquake for periods between 0.4 and 4.0s.

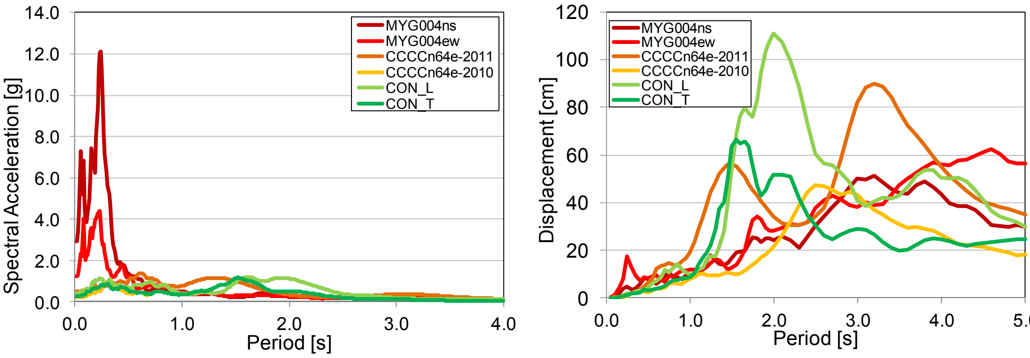

Figure 3.3 Comparison of 5% damped elastic response spectra computed from EQGMs recorded during the last four most damaging earthquakes: a) Acceleration response spectra, b) displacement response spectra.

4. INTERSTORY DRIFT DEMANDS IN ELASTIC SYSTEMS (GIDS)

Miranda and Akkar (2006) extended Iwan's drift spectrum (Iwan, 1996) to consider continuous systems that can range to flexural beams to shear beams with intermediate cases which combine both shear and flexural lateral deformations. The new spectrum, referred to as Generalized Interstory Drift Spectrum (GIDS) provides estimate of interstory drift ratios in multi-story buildings responding elastically.

Figure 4.1 shows GIDS computed for shear beams (α=650) for selected ground motions recorded during the 2010 and 2011 New Zealand earthquakes and from the 2010 Maule Chile for 5% damped systems with fundamental periods of vibration between 0.05 and 5.0s. A reference height of the model is used as previously done by Iwan (1996) and by Miranda and Akkar (2006). It can be seen that despite their moderate magnitudes of the New Zealand earthquake these ground motions produce large lateral deformation demands in multi-story buildings. For the CCCC N64E record in the 2011 displacement demands in SDOF were characterized by a second large 'hump' for periods of vibration of 3.0 s. It is shown here that for MDOF system much larger deformation demands occur for systems with fundamental period of vibration of 1.5s. The COT record is characterized by high demands in the short period region while the Concepción (CON) records are characterized by high deformation demands for structures with periods of vibration between 1.5 and 2.5s.

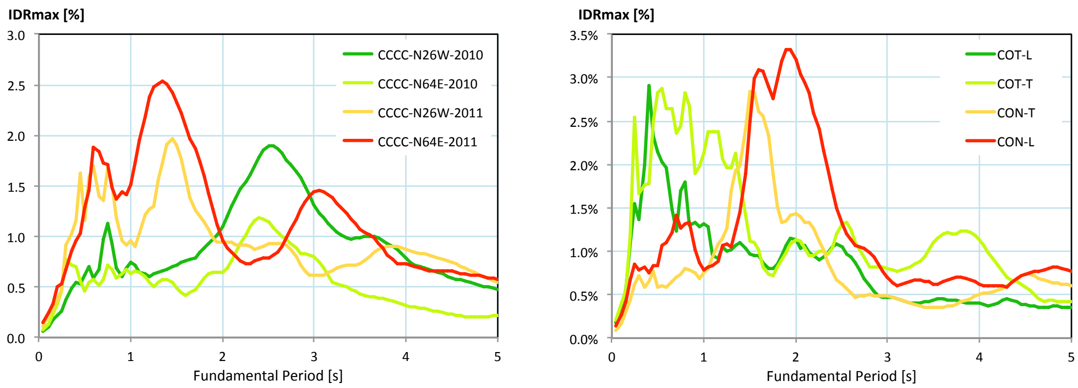

Figure 4.1. Generalized Interstory Drift Spectra (GIDS) computed for EQGMs recorded in the 2010 Darfield and 2011 Christchurch earthquakes (on the left) and for EQGMs recorded during the 2010 Maule, Chile (on the right).

Figure 4.2 presents GIDS for two records obtained in the city of Miyagi during the 2011 Tohuku, Japan earthquake. These ground motions are characterized by very high PGA which also result in very high deformation demands for structures with fundamental periods of vibration less than 0.4s, however, for longer periods deformation demands produced by these records are significantly lower than those shown in figure 4.1 for the New Zealand earthquakes and the 2010 Chile earthquake.

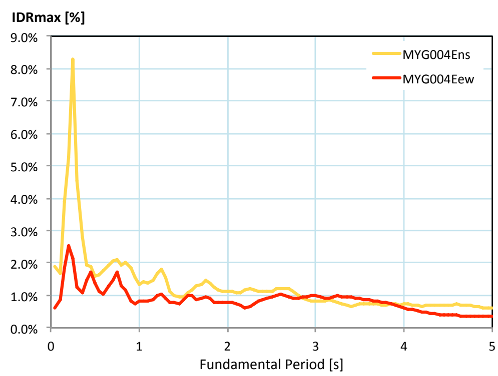

Figure 4.2. Generalized Interstory Drift Spectra (GIDS) computed for EQGMs recorded in the city of Miyagi during the 2011 Tohuku earthquake.

5. NONLINEAR SDOF DISPLACEMENT DEMANDS

Structures are typically designed for lateral strengths that will lead to yielding in the event of severe ground motions. Therefore it is also interesting to look at displacement demands in nonlinear SDOF systems. For this purpose, Fig. 5.1 illustrates displacement time-histories computed from elastic and inelastic (elastoplastic behaviour with a strength of one third of that required to remain elastic) SDOF systems having T=2.0s and 1.5s when subjected to EQGMs recorded at CON station (comp. L) and CCCC station (comp. N64E), respectively. From Fig. 3.3, it can be seen that T=2.0s corresponds to the peak in the elastic displacement spectrum of the CON record, while T=1.5s correspond to the first 'hump' in the elastic displacement spectrum of the CCCC record. In can be seen that displacement demands in the inelastic systems are considerably smaller (e.g. the ratio of peak inelastic displacement to peak elastic displacement is about 0.51 and 0.64 for CON and CCCC records, respectively) than the displacement demands in the elastic systems. Although this may appear "surprising" based for example on the equal displacement approximation (Veletsos and Newmark, 1960) it is consistent with our previous observations from other earthquakes (Ruiz-García and Miranda, 2004, 2006; Ruiz-García, 2011) where we have noted that for systems with periods of vibration that are near the predominant period of the ground motion, in the case of records obtained in soft soil sites, or near the pulse period, in the case of near-fault records affected by forward directivity, the displacements demands of inelastic systems are on average smaller than those of their elastic counterparts. This observation has very important implication in earthquake resistant design and in earthquake loss estimation because it means that damage for structures in these circumstances would be smaller and in some cases significantly smaller than those that would be inferred by using displacement demands of elastic systems. To the best of our knowledge, with exception of the Mexico City Building Code, codes do not take into account this important observation.

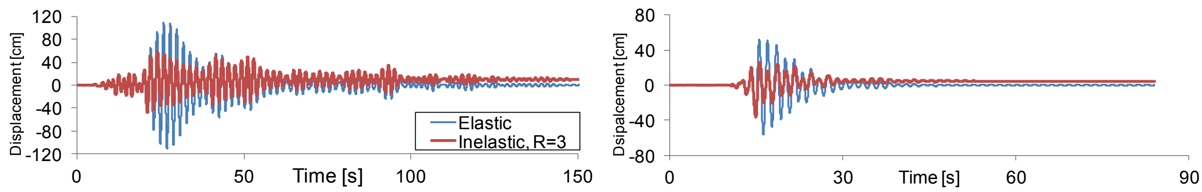

Figure 5.1. Comparison of elastic and inelastic displacement time-history (R=3) computed from two EQGMs: (a) Concepción (CON) station; (b) Christchurch Cathedral (CCCC) station.

Next, Fig. 5.2a illustrates peak inelastic displacement demands computed from the selected Japanese records with different waveform characteristics. It can also be seen that the EQGMs with two predominant phases recorded at MYG004 station (Fig. 2.1) lead to the largest peak inelastic displacement demands. A comparison of peak inelastic displacement demands computed from selected 'strong' EQGMs from the various recent earthquakes is shown in Fig. 5.2b. It can be seen that the EQGMs recorded at the Concepción (CON) station during the 2010 Chile earthquake lead to the largest peak inelastic displacement demands over a wide spectral region in spite of having smaller peak ground acceleration than that of MYG004 records.

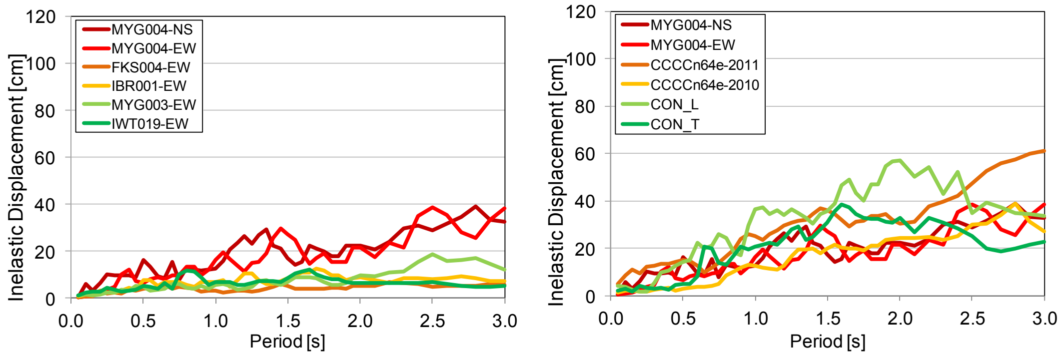

Figure 5.2. Inelastic displacement spectra for the selected earthquake ground motions (R=3): a) Selected Japanese records, b) selected EQGMs

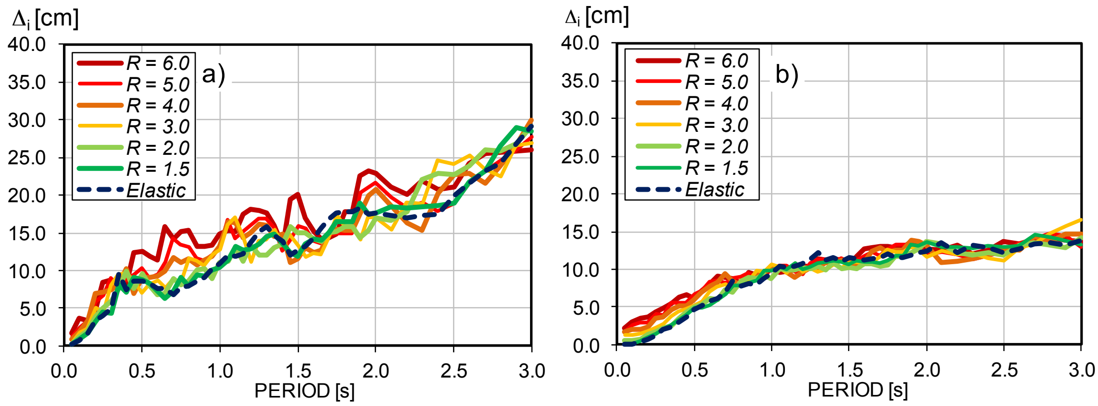

Figure 5.3. Inelastic displacement spectra for the selected earthquake ground motions (R=3)

Figure 5.4 shows median peak inelastic displacement demands computed from a set of 34 EQGMs recorded in the same stations during the 2010 Darfield earthquake and the 2011 Christchurch earthquake. For comparison purposes, the median peak elastic displacement demand is also shown in the corresponding figure. An important observation is that peak inelastic displacements computed from the combined 2010/2011 sequence of New Zealand earthquakes is larger than the inelastic displacement demands than any of the two events separately, highlighting the importance of seismic sequences. Furthermore, over wide range of periods, median inelastic displacement demands are larger than median elastic displacement demands.

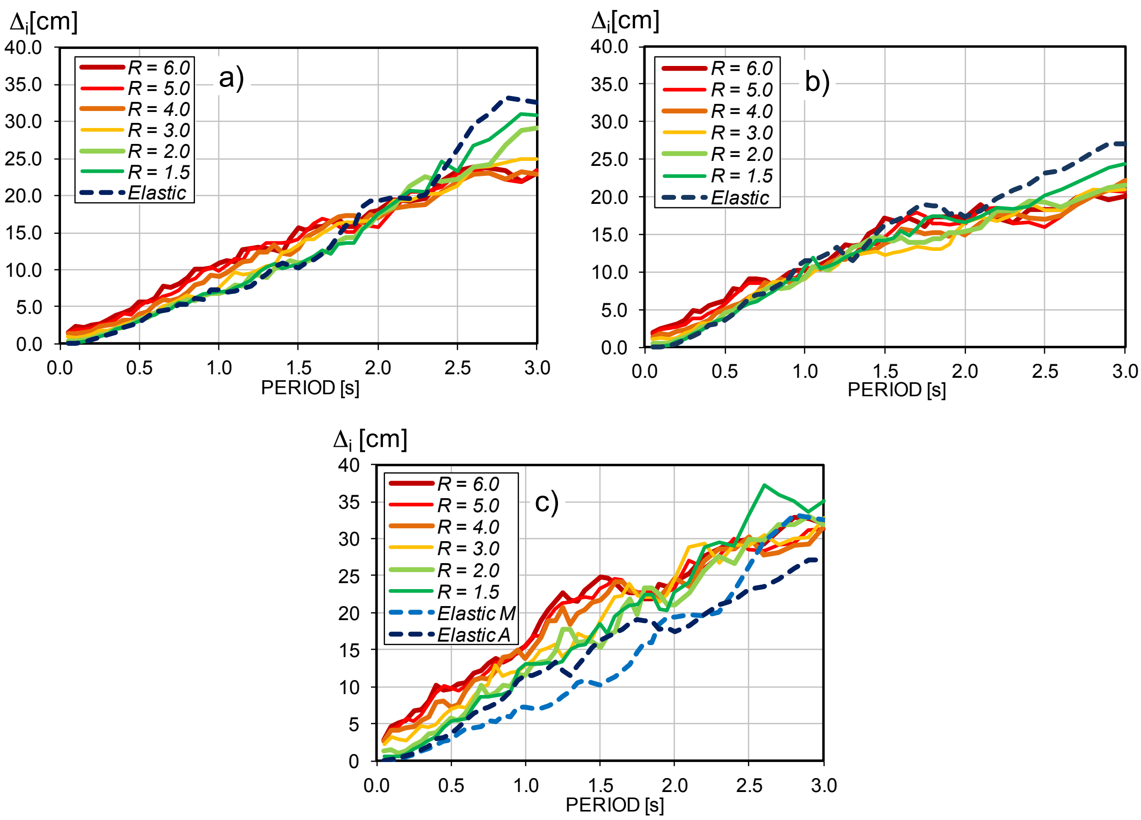

Figure 5.4. Peak inelastic displacement demand spectra for sets of EQGMs recorded in: a) 2010 Darfield earthquake, b) 2011 Christchurch earthquake, and c) sequence 2010/2011

Probabilistic seismic hazard analysis, typically only provide information about displacement demands of linear elastic SDOFs, therefore it is particularly important to be able to estimate inelastic displacement demands from information (conditioned on) displacement demands on elastic systems. This can be achieved through the use of inelastic displacement ratios, C_R, which are defined as the peak lateral inelastic displacement demand divided by the peak lateral elastic displacement demand of SDOF systems with the same mass and same initial stiffness (i.e. same period of vibration) when subjected to a given earthquake ground motion (Ruiz-Garcia and Miranda 2003). This ratio allows the estimation of peak inelastic displacement demands from their elastic counterparts of SDOF systems. Fig. 5.5 shows C_R spectra computed from four EQGMs recorded in recent strong earthquakes. These spectra show that for individual ground motions the "equal displacement approximation" may not lead to an adequate estimation of inelastic deformations in a wide spectral regions.

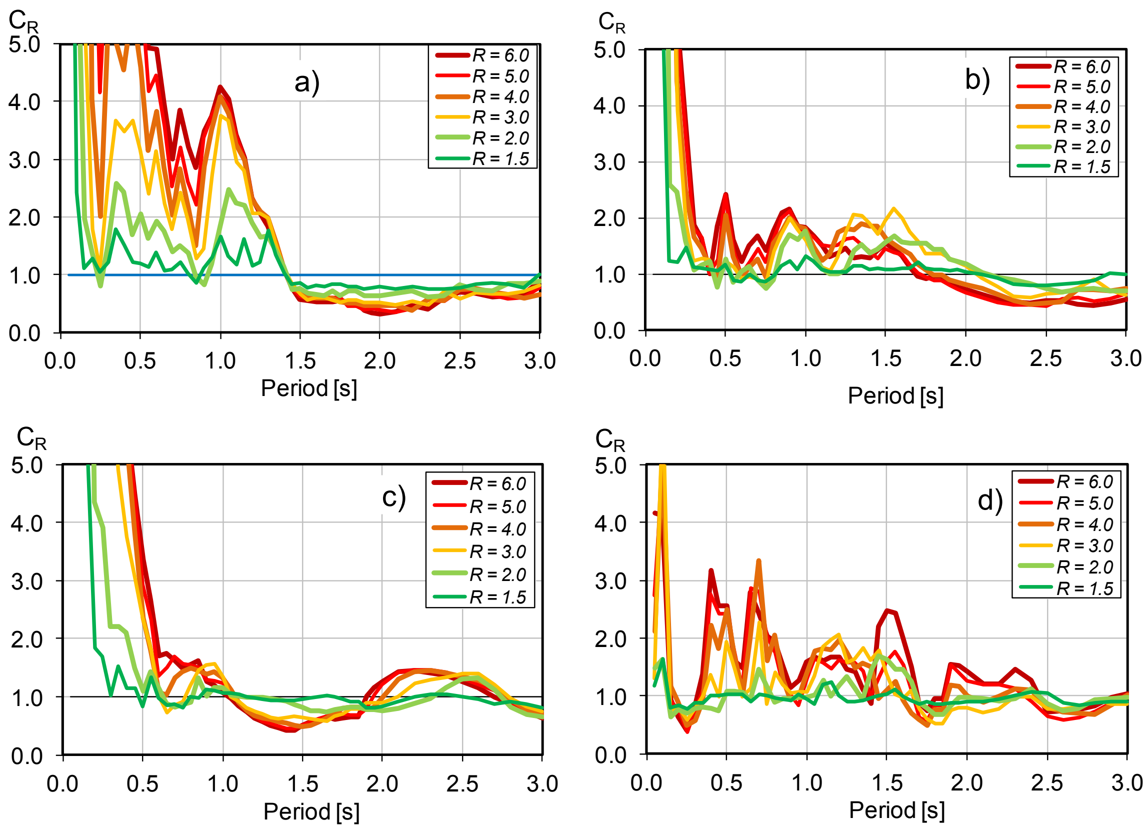

Figure 5.5. Inelastic displacement spectra for selected EQGMs: a) CON-L (2010 Chile earthquake), b) CCCC-N64E (2010 Darfield earthquake), c) CCCC-N64E (2010 Christchurch earthquake), and d) MYG-004 (2011 Tohoku earthquake)

Median inelastic displacement ratios computed for a set of 38, 34, and 34 earthquake ground motions recorded during the 2010 Chile earthquake, the 2010 Darfield, and the 2011 Christchurch earthquakes, respectively are shown in Figures 5a-5c. It can be seen that the trend is different, although it should be recall that records from the 2011 Christchurch earthquake could include near-fault effects. The results shown in the figures confirm that "equal displacement approximation" does not hold for a wide spectral region, which is particularly true for the ratios computed from the 2010 Canterbury earthquake.

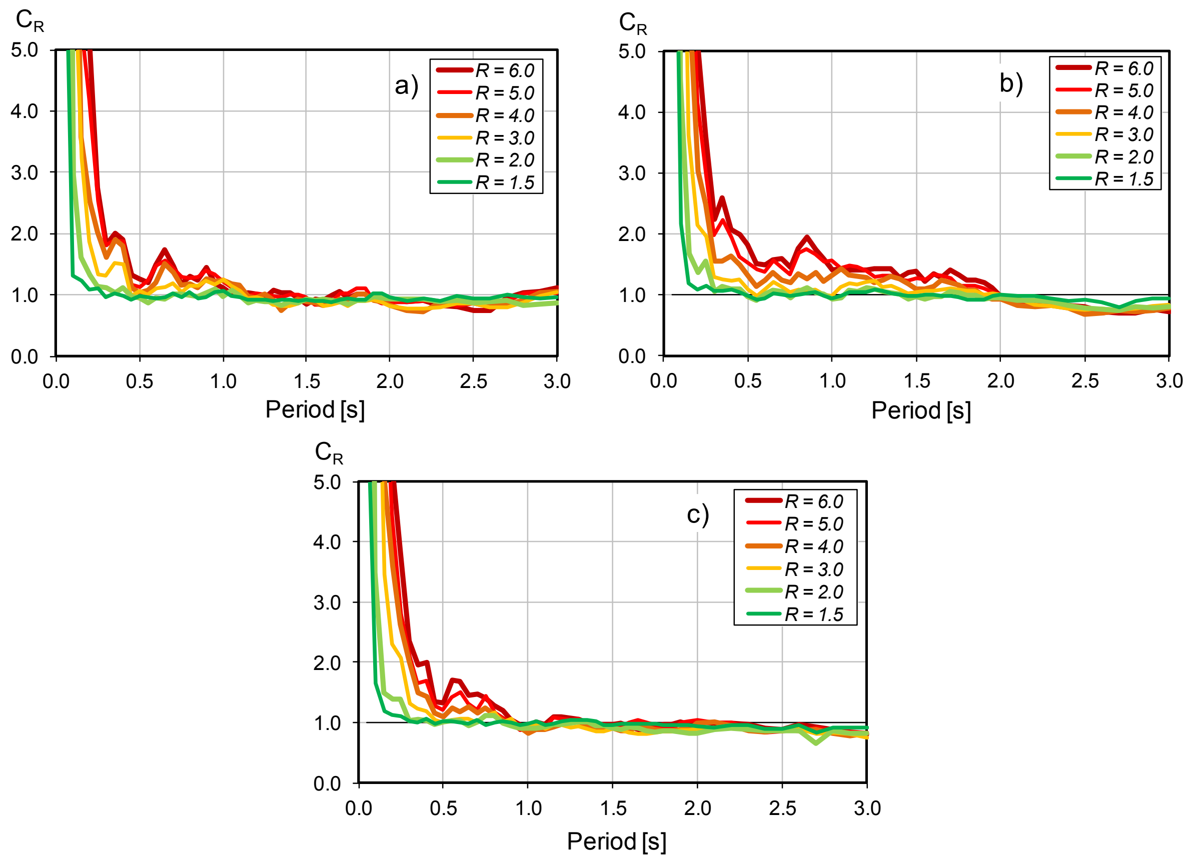

Figure 5.6. Median inelastic displacement spectra for three sets of EQGMs recorded in: (a) 38 records from the 2010 Chile earthquake; (b) 34 records from the 2010 Darfield earthquake; and (c) 34 records from the 2011 Christchurch earthquake

6. CONCLUSIONS

The research reported in this paper examined elastic and inelastic displacement demands computed from a selected number of ground motions recorded during the Mw 8.8 February 27th, 2010 Chile earthquake, the Mw 7.0 September 4th, 2010 Darfield, New Zealand earthquake, the Mw 6.3 February 22nd, 2011 Christchurch, New Zealand earthquake and during the Mw 9.0 March 11th, 2011 Tohoku, Japan earthquake. From the results of this investigation, the following conclusions are drawn:

- Many of the Japanese records are characterized by very long durations and by having two predominant sub-events in the waveforms. Several of these records have extraordinary PGAs and produced very large spectral acceleration demands at short periods of vibration. However, displacement demands in many of these records are relatively small which partially explains the low level of damage produced by ground shaking in this earthquake despite its large magnitude.
- Several of the records from the 2010 Maule Chile earthquake produced large displacement demands. Of particular interest is the record obtained in the city of Concepción at the CON recording station where a narrow band ground motion that resembles the one measured at the SCT station in Mexico City during the 1985 Mexico City earthquake was obtained. This ground motion produced very large displacement demands for periods around 2s.
- The New Zealand earthquake produced a rich set of ground motions. Of particular interest is the set of ground motions obtained in the 2011 Christchurch event, which produced several near-fault records with very large displacement demands. Comparison of displacement demands from the 2010 and 2011 explain, to a great extent, the limited level of damage that occurred in the 2010 earthquake and the large amount of damage in the city of Christchurch in the 2011 event despite the much smaller magnitude of the second event.

- Consistent with prior observations made by the authors using records from other earthquakes, records obtained in these recent earthquakes show that systems with periods of vibration that are near the predominant period of the ground motion, in the case of records obtain on soft soil sites, or near the pulse period, in the case of near-fault records affected by forward directivity, the displacements demands of inelastic systems are on average smaller than those of their elastic counterparts. This observation has very important implications in earthquake resistant design and in earthquake loss estimation because it means that damage for structures in these circumstances would be smaller and in some cases significantly smaller than those that would be inferred by using displacement demands of elastic systems..
- Results from inelastic systems subjected to the sequence of acceleration time-histories recorded during the 2010 Darfield and the 2011 Christchurch earthquake led to inelastic displacement demands larger than those subjected only to either one or the other event highlighting the importance of earthquake sequences.

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