CONTRASTING DISPLACEMENT DEMANDS OF DUCTILE STRUCTURES FROM TOHOKU SUBDUCTION TO CRUSTAL EARTHQUAKE RECORDS

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Abstract

With the impending Cascadia subduction zone event affecting the Pacific Northwest, this study utilized the vast number of records from the great 2011 Tohoku earthquake to better understand the effects that duration and magnitude of a large subduction event has on ductile structural response. A metric using cumulative plastic deformation was developed and utilized in the analysis elastic perfectly plastic SDOF systems in order to contrast the response to a representative set of crustal earthquakes. The results indicate that damage to structures of the same design ductility would be significantly higher in the low natural periods, a range corresponding to regular highway bridge structures.

Introduction

Modern structural design philosophies rely on the inelastic response of structures for resisting earthquake ground motion. Deployment of seismological technology coupled with the frequent occurrence of earthquakes has resulted in robust databases of crustal ground motions. Several studies have been conducted using records from these databases to investigate various aspects of the inelastic demands on structures (Ruiz-Garcia and Miranda 2003, 2007, Krawinkler et al. 2003, Medina and Krawinkler 2003, Ibarra and Krawinkler 2011). Large magnitude subduction zone events, however, are recognized to display distinct differences in acceleration magnitude, shaking duration, and accelerogram frequency content as compared to crustal earthquakes. Understanding the structural response differences to such earthquakes is paramount to furthering the development of engineering practices, particularly for regions such as the Pacific Northwest coast of the United States, which lies near the Cascadia subduction zone.

The Cascadia subduction zone is the over 1000km long boundary between the Juan de Fuca and North American plates. Geological evidence has shown that 13 significant earthquake events have occurred in the past 3000 years (Goldfinger et al. 2008). The most notable of which, the M9.0 earthquake of 1700, produced a tsunami large enough to reach Japan (Atwater et al. 2005). Historical evidence combined with comparisons of the Cascadia fault to other subduction zones has led geologists to conclude that a megathrust earthquake in the Cascadia subduction zone is impending (Heaton and Kanamori 1984). This creates an even greater need for the more thorough understanding of the differences in structural response resulting from large subduction zone earthquakes.

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Due to the lack of available large magnitude subduction zone ground motion records, researches wishing to analyze the structural demands of such earthquakes had to resort to records of smaller accelerations, conducted studies with the few ground motions available, or utilized simulated records. Both simulated records and the use of attenuation relationships required ground motions to be scaled, which can produce biased results (Luco and Bazurro 2007). Atkinson and Boore (2003) also stated that an earthquake of magnitude 8.0 or greater would result in a significant hazard increase compared to ground motions of lower magnitude, indicating the need for a study of the specific structural effects of large magnitude earthquake events.

The recent occurrence of the 2011 Tohoku earthquake (M9.0) provided an opportunity to learn from one of the largest known earthquakes. The quantity of large magnitude subduction zone records increased to the extent that a study could be performed using recorded time history accelerations, removing the bias caused by scaled and simulated records. Structural demand requirements produced by the Tohoku earthquake do not necessarily extend to the Cascadia subduction zone, but by performing this study, knowledge of the potential differences between Cascadia and crustal earthquakes can begin to be compiled. An elastic perfectly plastic single degree of freedom (SDOF) system was used to quantify the difference in demands resulting from crustal and the Tohoku subduction zone earthquake.

Earthquake Record Selection

Ground motions were selected with the intention of isolating the variations in structural response of more common crustal earthquakes to those from the Tohoku subduction earthquake. A representative crustal and two subduction zone sets were used for these purposes. FEMA P695 (2009) describes a far-field record set that was compiled using similar selection criteria to previous studies utilizing crustal ground motions (Krawinkler et al. 2003, Richards and Uang 2004, Richards et al. 2007, Medina and Krawinkler 2003, Ibarra and Krawinkler 2011) and was chosen as the representative crustal set, containing 22 records ranging in magnitude from M6.5 to M7.4.

Two subduction zone sets were compiled using records exclusively from the 2011 Tohoku M9.0 earthquake available from the Kyoshin Network (K-Net). The first set contained records with PGA greater than 0.9g, while the second contained records between 0.2g and 0.9g referred to as the Tohoku1 and Tohoku2 sets, respectively. This resulted in sets of 16 records for the Tohoku1 set and 100 records for the Tohoku2 set. Additional Tohoku records were available from the associated Kiban-Kyoshin Network (Kik-Net), but as the two networks cover a similar geographical area, using only records from the K-Net database was deemed to be appropriate. The locations for the recording stations used are shown in Figure 1. The PGA bounds of the Tohoku2 set reflected a range similar to that of the Crustal set, which had PGA between 0.2g and 0.82g. The resulting elastic response spectral shapes of the Crustal and Tohoku2 sets were also similar, while the Tohoku1 set contained the higher PGA range and subsequently higher spectral accelerations. Maintaining the division in the Tohoku sets allowed the effects of response spectral shape on the displacement demand to be analyzed.

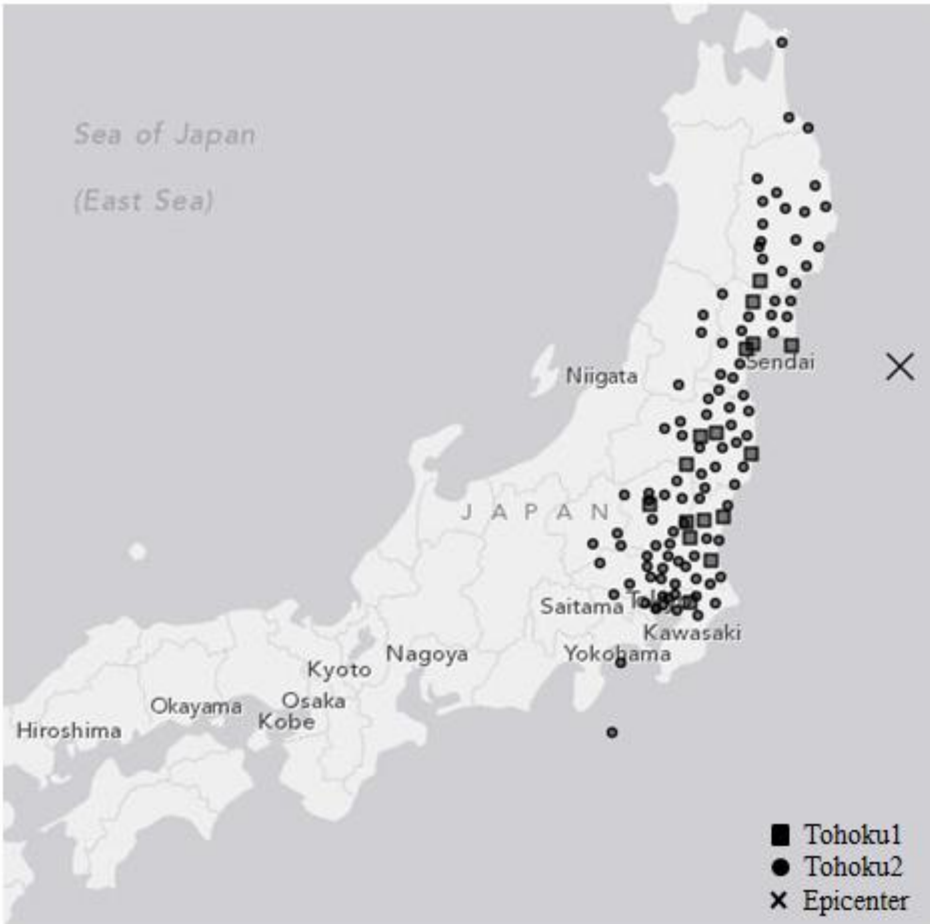
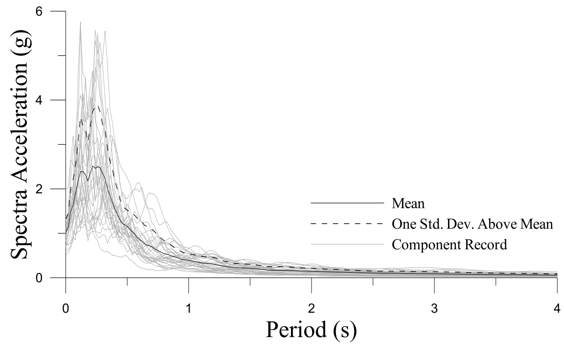


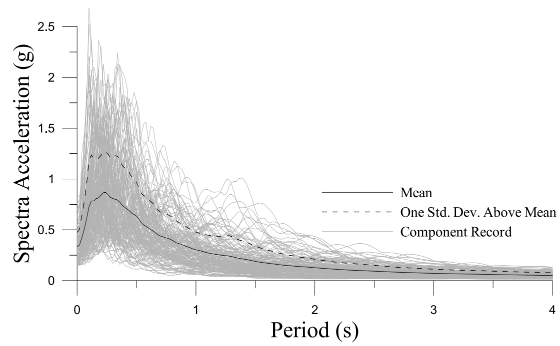
FIGURE 1: TOHOKU RECORDING STATION LOCATIONS

In each of the record sets, two horizontal component records were used for each ground motions. Vertical components were not used. For the purposes of this study, component records were not rotated or combined, but treated as two separate ground motions. Imposed criteria for all sets were based on the component record that contained the higher PGA from each location, but both components were used in analysis regardless of PGA. This reflected the selection and analysis methods employed by the procedure set forth in FEMA 695 (2009).

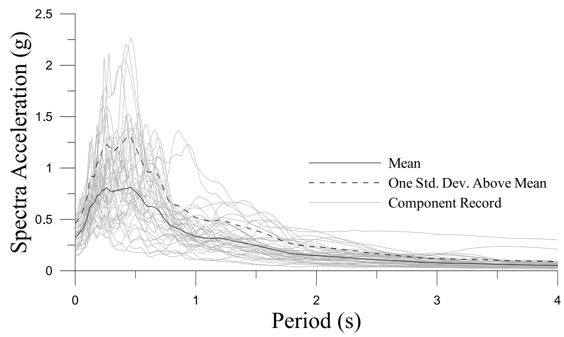
Evaluation of the elastic response spectra of each record set led to the observation that each set contained a small number of records or components of records fell well above the mean at some point in the spectra. Any component that exceeded three standard deviations above the mean at more than one point of the elastic response spectra was removed to avoid potential skewing of the results. Elastic response spectra following the removal of these outliers are shown in Figure 2, upon which all of the subsequent analyses and result interpretation had been based.



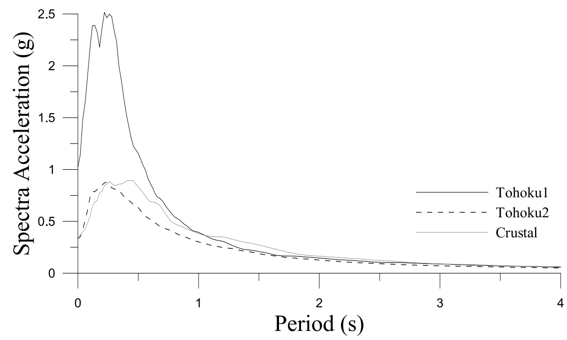
a.) Tohoku1 Set



b.) Tohoku2 Set



c.) Crustal Set



d.) Mean Comparison

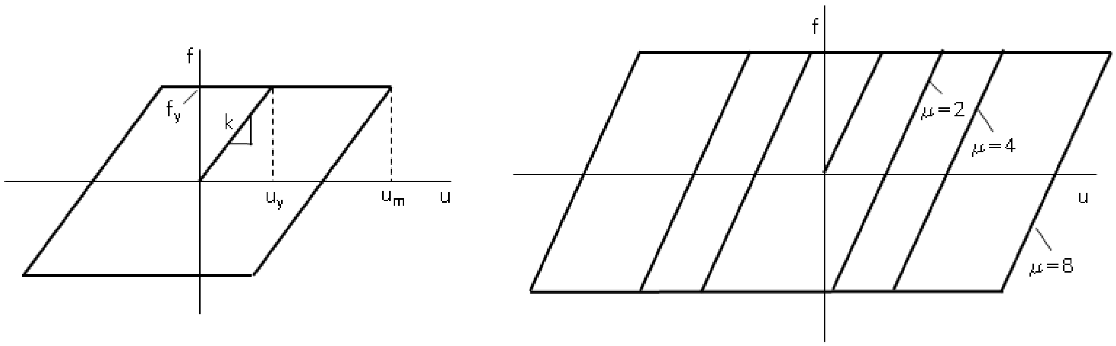
FIGURE 2: ELASTIC RESPONSE SPECTRA (5% CRITICALLY DAMPED)

<u>Inelastic Response Demand</u>

Inelastic structural demand from each set of earthquakes was conducted by means of a constant ductility approach, which utilized an elastic perfectly plastic SDOF system as shown in Figure 3. The constant ductility analysis procedure used in this study was related to the inelastic response spectra procedure used by Murukami and Penzien (1975). Time history analyses of the SDOF system over a range of natural periods up to 4s at 0.02s increments was conducted for each of the earthquake ground motions using OpenSees (2010). At each period and for each earthquake record, the yield strength of the structure that produced the desired ductility value was found through an iterative process, in effect having an individual ductility design for each of the earthquake records. The ductility, μ, was defined as

$$\mu = \frac{u_m}{u_y}$$

where u_m=max displacement and u_y=yield displacement. Inelastic responses were calculated at ductility values of 2, 4, and 8 as this was considered to represent a wide range of ductile structural responses. Although not directly corresponding to the response modification factor R contained in the current bridge design specifications in the USA (AASHTO 2010), the ductility value is closely related. Throughout the process, mass of the system remained constant, while the stiffness, *k*, was calculated based on the desired period. Yield force was represented by f_y.



a.) General Characteristics

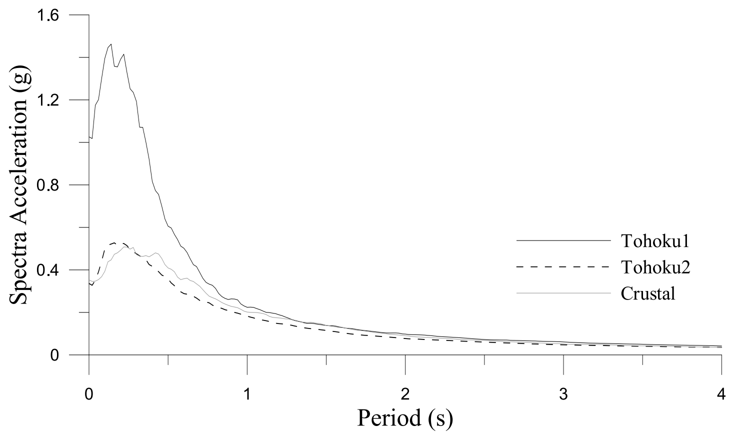
b.) Cyclic Hysteresis

FIGURE 3: ELASTIC PERFECTLY PLASTIC SDOF HYSTERETIC CHARACTERISTICS

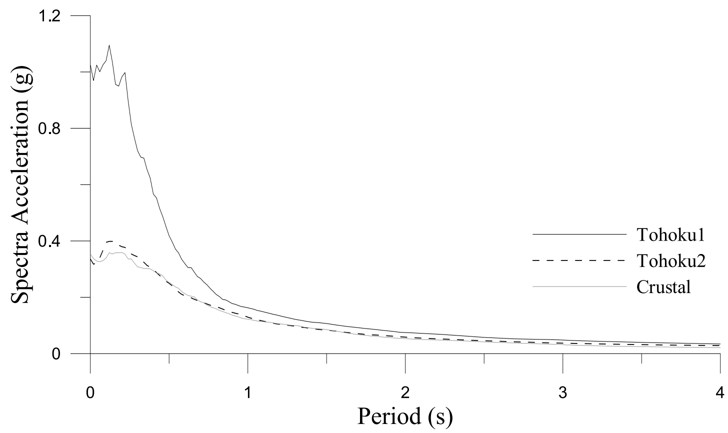
Resulting mean inelastic acceleration response spectra are shown for each record set at each considered ductility value in Figure 4. The mean of the Tohoku1 response was consistently higher than the other two record sets, which is a direct reflection of the higher acceleration content of that set. The Tohoku2 and Crustal sets, however, resulted in very similar values despite the differences in fault type and magnitude of the earthquake events.

Cumulative Plastic Displacement Demand

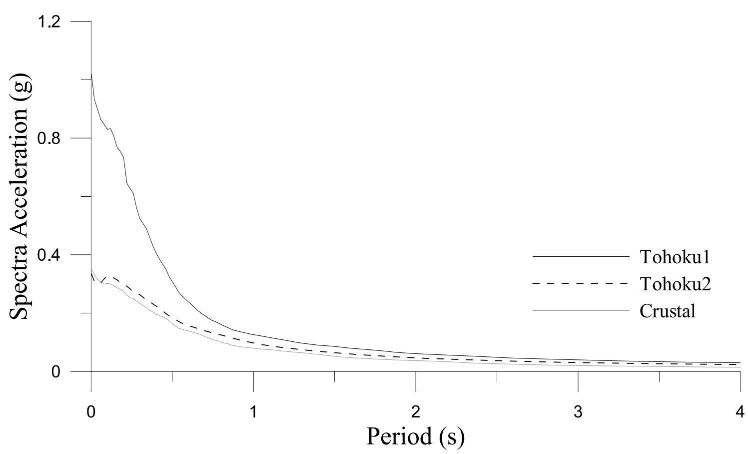
Force based seismic design is evolving toward displacement based design from the research realm to practice, whereby a number of states including Oregon have adopted Guide Specifications (AASHTO 2009) to more appropriately capture the structural behavior. Hence, a displacement based metric was needed to compare the seismic demand between record sets that would take into account the longer duration of subduction zone records and allow for comparison between ground motions of various magnitudes and spectral acceleration contents. This was achieved by calculating the total cumulative plastic displacement demand over the duration of the response.



a.) Ductility 2



b.) Ductility 4



c.) Ductility 8

FIGURE 4: MEAN INELASTIC ACCELERATION RESPONSE SPECTRA (5% CRITICALLY DAMPED)

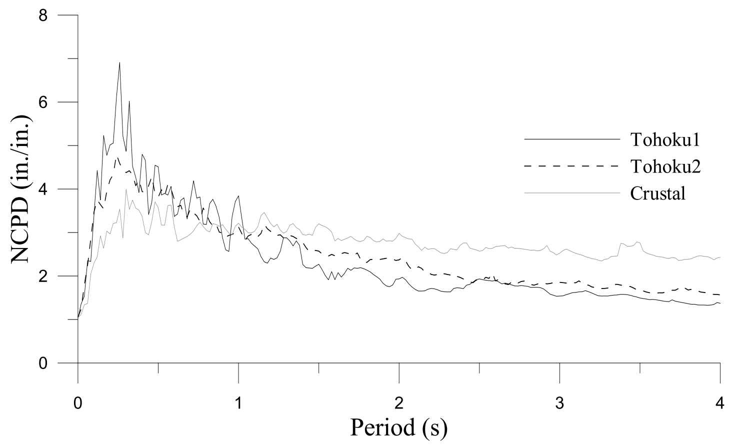
To calculate cumulative plastic displacement, elastic displacement was first removed from the total displacement leaving only the plastic displacement, u_p, at each time increment of the analysis, i. Adding the incremental differences of plastic deformation produced the cumulative plastic displacement, U_p, for each earthquake record at each structural period as

$$U_p = \sum_{i=1}^{n} \left\| (\Delta u_p)_i \right\|$$

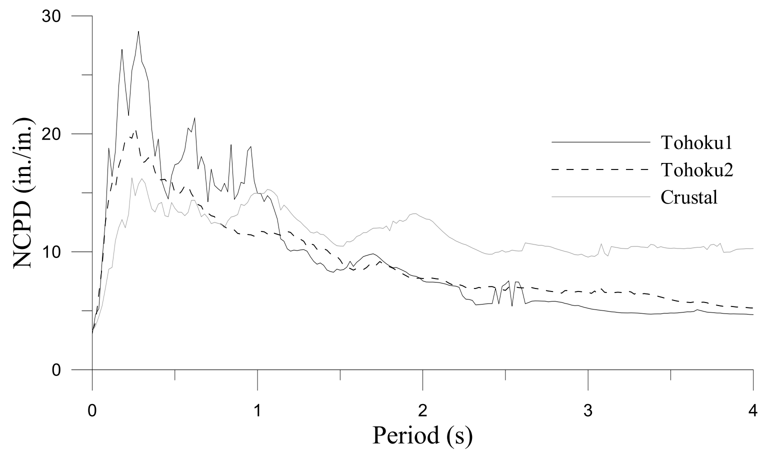
Normalizing this value by the yield displacement provided a quantifiable measure of the inelastic displacement demand imposed on the structure. Since the structures were designed to a set ductility value, i.e. to a specific inelastic displacement demand, the differences in the normalized cumulative plastic displacement (NCPD) indicate the amount of plastic demand imposed. The results can be presented for each earthquake by plotting the data over the period range at each ductility value. These plots are referred to as normalized cumulative plastic displacement spectra and are shown in Figure 5 for each of the ductility levels.

Differences in the resulting cumulative displacement demand exhibit different characteristics for low and high periods. At periods less than approximately 1.0s, the NCPD from both Tohoku sets was higher than the Crustal set. This difference in demand was more pronounced with increased structural ductility. The largest difference between the means of the Tohoku1 set was 42% higher than that of the Crustal set at ductility 2 and increased to 55% higher at ductility 8. This means that for structures designed to the same ductility, the Tokoku1 earthquake accumulates significantly more plastic deformation as lower period structures. The Tohoku1 set resulted in 31% more demand than the Tohoku2 set at ductility 2 and increased to require 44% more at ductility 8. The differences in NCPD between the Tohoku sets at lower periods were less than the differences between their ductility spectra, especially for the higher levels of ductility.

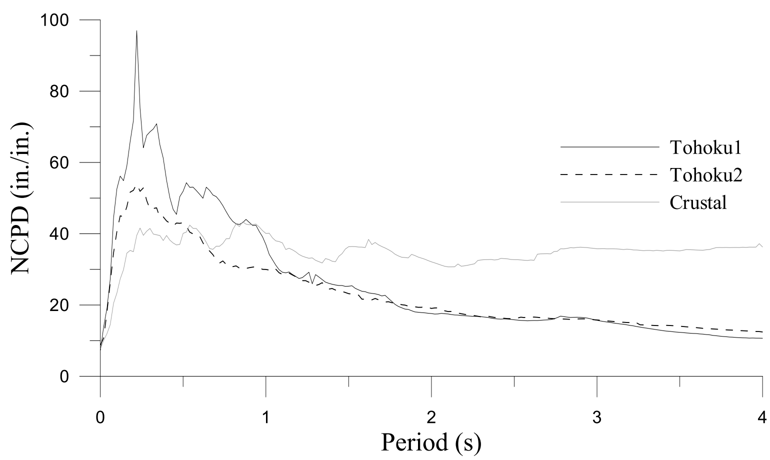
At periods higher than approximately 1.0s, the Tohoku sets produced lower normalized cumulative displacement demand than the Crustal set. This difference increased as the period increased and was more pronounced at higher ductility values. For the analysis period of 4.0s, the mean NCPD from the Crustal set was 43%, 54%, and 71% higher than that required by the Tohoku1 set for ductility values 2, 4, and 8, respectively. Despite the differences in spectral accelerations, the mean NCPD between the Tohoku sets remained within approximately 14% for all ductility values. This means that despite the longer duration of the records, the response cumulates significantly less plastic deformations for high period structures.



a.) Ductility 2



b.) Ductility 4



c.) Ductility 8

FIGURE 5: MEAN NCPD SPECTRA

Structures designed to current practice could be assumed to be able to withstand the cumulative displacement demand imposed by the Crustal set. Plastic displacement can be related to damage with accumulation of plastic displacements resulting from reversing motion resulting in more damage than through simple monotonic loading. With these considerations, the earthquake records from the Tohoku subduction zone earthquake were shown to impose higher damage for low period and lower damage for high period structures. Most highway bridges exhibit periods corresponding to the low period range in this study and would therefore be subjected to higher plastic demands than would be expected from Crustal earthquakes. As this study only investigated one subduction zone earthquake event, extending the conclusions to subduction zone earthquakes in general is not possible. Nonetheless, the differences in demand do suggest that special considerations need to be made for ductile structures in geographic areas such as the Pacific Northwest where large magnitude subduction zone earthquake is a significant part of the design hazard.

Summary and Conclusions

The structural demands of earthquake records from the great Tohoku earthquake were quantified through the development of a cumulative plastic displacement metric, which allowed a meaningful response comparison of a range of ductile structures. Using a SDOF elastic perfectly plastic system, the demand differences of the earthquakes were able to be evaluated using a constant ductility approach, thereby removing the need to scale recorded ground motions. By contrasting the response using the large dataset available from the Tohoku earthquake to that of a representative Crustal earthquake set, several observations and conclusions were made.

- At low structural periods, the accumulation of plastic deformations from the Tohoku subduction earthquake was significantly higher than those resulting from the representative Crustal set. The difference was amplified in response of structures of higher ductility and in records of high peak ground acceleration.

- At high structural periods, the accumulation of plastic deformation from the Tohoku subduction earthquake was significantly lower than from the representative Crustal set, despite similarities in the ductile response spectra in that range. The difference was amplified for higher ductilities.

- Based on the above observations, the differences in response spectra and in the earthquake duration of the Tohoku subduction earthquake are not sufficient in capturing the cumulative damage.

Results suggest that for the great Tohoku subduction earthquake, there are potentially significant differences in damage from the accumulation of inelastic deformations. For regular highway bridges, larger damage would be expected in structures responding to the same design ductility. To confirm that this effect extends to other subduction events, further data from other large magnitude events would be needed. Nonetheless, based on the available data, similar outcomes would be expected in regions affected by the Cascadia subduction.

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