Preliminary Assessment of Ground Motion Duration Effects on Structural Collapse

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SUMMARY:
The 2010 M8.8 Chile and 2011 M9.0 Tohoku earthquakes are reminders of the potential for large magnitude earthquakes to produce ground motions with long durations. While it is generally recognized that long duration ground motions are more damaging than shorter duration motions, previous research on duration effects are inconclusive, and current design practice does not explicitly consider duration effects. This paper summarizes preliminary results of a study to assess the significance of ground motion duration effects on structural collapse. First, the findings of a preliminary investigation to identify the ideal duration metric for the evaluation of structural response are described, where the ideal duration metric is one which is uncorrelated from spectral acceleration and free from peculiarities in response spectra and acceleration record characteristics. Finally, the effects of ground motion duration on the collapse capacity of a 3-story steel special concentrically braced frame are presented.

Keywords: Strong-motion duration, structural collapse, non-linear dynamic analysis, ground motion records

1. BACKGROUND AND MOTIVATION

The effect of strong motion duration on structural response is a topic which has been of significant interest in the literature. While this effect has been widely studied, the findings have been mixed, suggesting that the effect of duration depends on the response parameter. It has been found that peak response parameters are insensitive to duration, while energy-based parameters show some dependency on it, as indicated in Bommer et al. (2004) and Iervolino et al. (2006). There has also been little agreement about the most suitable duration metric for assessing structural response. Reed and Kassawara (1990) found that Cumulative Absolute Velocity (CAV) was the measure most closely correlated to structural damage, while Manfredi (2001) found that I_D was a reliable parameter for estimating seismic cyclic damage potential.

Due to these mixed conclusions, current code provisions tend to ignore duration and rely on peak response measures. Furthermore, because of the limited long-duration records available, nonlinear dynamic analyses and loading protocols tend to use record sets which include moderate duration motions only. FEMA P695 (FEMA, 2009) presented a methodology for the quantification of the collapse capacity of several building archetypes, defined as the median spectral acceleration of a ground motion set causing structural collapse. This set consists of (22) record pairs taken from the PEER-NGA database for moderate duration events with magnitudes between M6.5 and M7.6. Similarly, many loading protocols, such as the Steel-SAC (SAC, 2000) and the Wood-CUREE protocol (CUREE, 2000), consider the equivalent cumulative damage imposed by inelastic cycles of ground motions when determining loading histories, but include no explicit consideration of duration, utilizing record sets of moderate duration events only.

The occurrences of the 2010 M8.8 Chile and 2011 M9.0 Tohoku earthquakes, however, suggest that large magnitude, long duration ground motions have the potential of inflicting significant structural damage, particularly in structures which experience large inelastic deformations. It is important to note that many studies performed to date have used analysis models which do not explicitly capture cyclic strength and stiffness degradation or cumulative damage. These modeling parameters may show a higher correlation between structural response and strong motion duration. It can be argued, therefore, that the effect of duration should be further examined and the inclusion of duration in code provisions reassessed.

The objectives of this study are three-fold. First, the authors wish to identify a robust measure of ground motion duration that accounts for the damaging effects on structural response. Second, this study aims to evaluate the influence of duration on structural collapse through analytical models that utilize degrading material models. Finally, if a statistical correlation is determined between duration and structural response, the authors will assess appropriate ways to incorporate duration into performance-based design provisions. This paper presents preliminary results of a study investigating the duration metrics presented in the literature and identifying the ideal duration metric for evaluating structural response. The results of a “pilot” study of a 3-story steel special concentrically braced frame (SCBF) are also presented.

For the remainder of this paper, the authors will use the term “large magnitude crustal” earthquakes to refer to M6.5 to M8.0 events that might be seen in shallow crustal earthquakes and the term “large magnitude subduction” earthquakes to refer to events like the 2010 Chile and 2011 Tohoku earthquakes.

2. DEVELOPMENT OF PRELIMINARY LONG DURATION GROUND MOTION SETS

To determine the effect of strong motion duration on structural response, ground motion sets of varying durations are used in this study through nonlinear time history analyses. These ground motion sets include both "long" duration records and “standard” records used to benchmark any change in structural response.

2.1 Benchmark Record Sets

Several existing record sets comprised of "moderate" duration, large magnitude crustal records are used as benchmarks in this study and include the FEMA P695 far-field set and several of the PEER Transportation Research Program sets (PEER, 2011). The FEMA P695 set is included as it has been used for collapse evaluation in several studies, including ATC 76 (NIST, 2010) and ATC 84 (NIST, 2012). This set was also specifically designed to be neither structure- nor site-specific and contains records from the PEER-NGA database for large magnitude crustal earthquake events, similar to the PEER Transportation sets.

2.2 Long Duration Records

Ground motion records have been collected from several large magnitude subduction events that exhibit "long" duration characteristics, including the 2011 Tohoku, the 2010 Chile, the 1985 Santiago and the 1985 Michoacan earthquakes. The records from the 2011 Tohoku earthquake were collected courtesy of K-NET and Kik-net available at <http://www.kyoshin.bosai.go.jp/kyoshin/quake/index_en.html>. The records from the 2010 Chile earthquake were collected courtesy of Universidad de Chile (CESMD, 2012). The records from the latter two earthquakes were collected courtesy of COSMOS Virtual Data Center available at <http://db.cosmos-eq.org/scripts/default.plx>. To minimize any earthquake event-based bias, records from various large magnitude crustal events have also been selected from the PEER-NGA Database available at <http://peer.berkeley.edu/peer_ground_motion_database>.

2.3 Metrics Used to Characterize Strong Ground Motion Duration

Bommer and Martínez-Pereira (2000) report over 30 definitions of duration in the literature. Whereas many of these metrics have been developed while considering the ground motion record only, this study places an emphasis on evaluating duration metrics that show correlation with structural response. For the purposes of this study, the ideal duration metric is one which is both uncorrelated from spectral intensities and insensitive to peculiarities in spectral shape or record characteristics. Based on preliminary research into ground motion duration effects, several metrics have been chosen for consideration in this study.

Arias Intensity (Arias, 1970) and Cumulative Absolute Velocity (Reed and Kassawara, 1990) are included as both metrics explicitly incorporate duration and are measures of the energy content of a ground motion. Arias Intensity is defined as the integral over the record duration of the square of the acceleration time history and is thought to be a good indicator of the damaging earthquake energy. CAV is similar to the Arias Intensity, defined as the integral over the record duration of the absolute value of the acceleration time history, and is included as it is thought to be well correlated with damage.

Two variations of Arias Intensity, I_D (Cosenza and Manfredi, 1997) and the significant duration (Trifunac and Brady, 1975) have also been chosen. I_D is defined as the Arias Intensity normalized by PGA and PGV, and is included as it is thought to be a good indicator of structural inelastic deformation demands. The significant duration is defined as the time interval over which a specific portion of the Arias Intensity is attained. Three portions are considered, the 5%-95%, 5%-75% and 2.5%-97.5% interval. Significant duration is included here as it accounts for seismic energy and is an explicit definition of duration.

Finally, the bracketed duration (Page et al., 1972) is considered as it is a simple, explicit definition of duration. The bracketed duration is defined as the time between the first and last instance when the accelerogram exceeds some threshold. Three thresholds are included: the commonly used 0.05g and two larger values, 0.1g and 0.2g, as they may be more predictive of the duration causing inelastic response.

2.4 Comparison of Preliminary Long Duration Ground Motion Record Sets

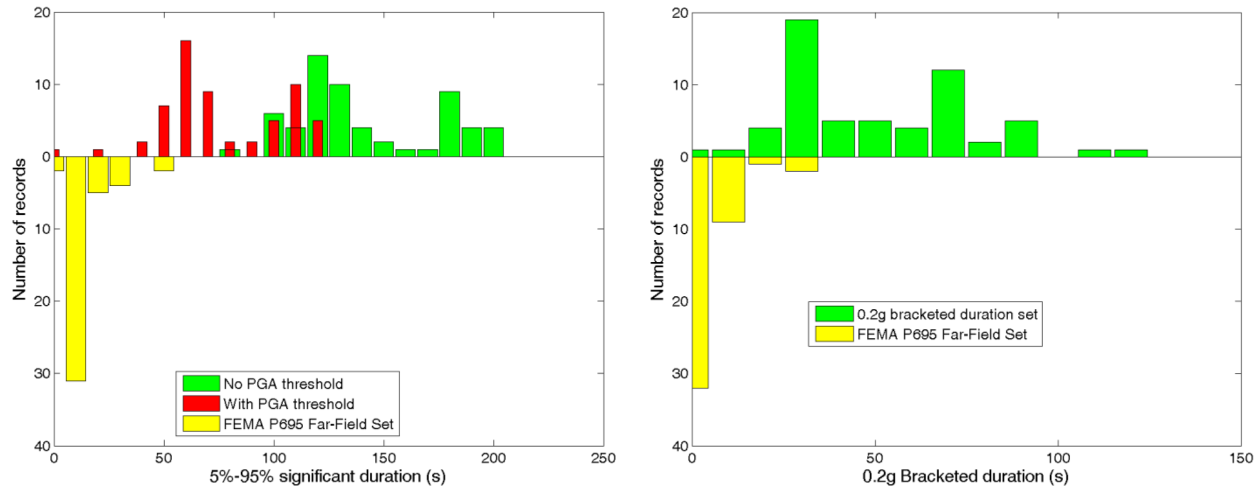
Several long duration record sets have been identified, with a set developed for each duration metric. Sets consist of both horizontal components of (30) records with the highest duration values from the events listed. To avoid event-bias, a maximum of (10) record pairs from each earthquake are used in each set.

As the significant duration and I_D are "normalized" metrics, some records can have long durations and small accelerations. These records may not be suitable for assessing structural response to long duration, large magnitude subduction motions, therefore sets were assembled for these metrics with and without a PGA threshold to capture structural damage. No threshold is necessary for the other duration metrics, as those metrics explicitly account for intensity and larger intensity records tend to dominate the sets.

Several figures are provided to highlight key characteristics of the long duration record sets. The figures show only the 0.2g bracketed duration set and the 5%-95% significant duration sets with and without a PGA threshold. The characteristics of the 0.2g bracketed duration set are similar to those of the other bracketed duration sets, the CAV set and the Arias Intensity set. The characteristics of the 5%-95% significant duration sets are similar to those of the other significant duration sets.

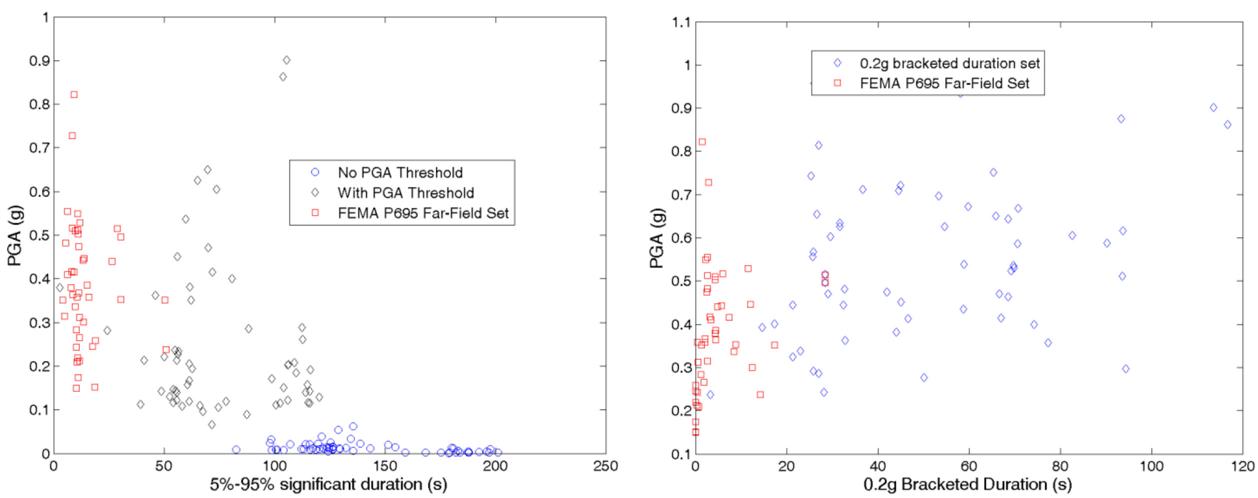
The histograms in Figure 2.1 provide a comparison between the duration values of the proposed long duration sets and the FEMA P695 set. It appears that the long duration sets have many records with duration values significantly larger than the FEMA P695 set, suggesting that the long duration sets can be used to assess duration effects. Figure 2.1a also shows how enforcement of a PGA threshold significantly reduces the 5%-95% significant duration of many records in the set, though even with this threshold, the majority of the records in this long duration set still have duration values larger than the FEMA P695 set.

The scatter plots of Figure 2.2 are used to examine possible correlations between PGA and duration for several record sets. Knowledge of this correlation will be important for interpretation of results to distinguish the influence of ground motion intensity from duration. From the figures, it appears that there does not seem to be a strong correlation between PGA and 5%-95% significant duration, but there is some correlation between PGA and the 0.2g bracketed duration. Figure 2.2a also shows how the PGA threshold affects the ground motion intensities of the records contained in the 5%-95% significant duration set. Clearly, the 5%-95% significant duration set is dominated by small amplitude acceleration records, while the 5%-95% significant duration set with a PGA threshold includes records with varying intensities.



(a) 5%-95% significant duration sets (b) 0.2g bracketed duration set

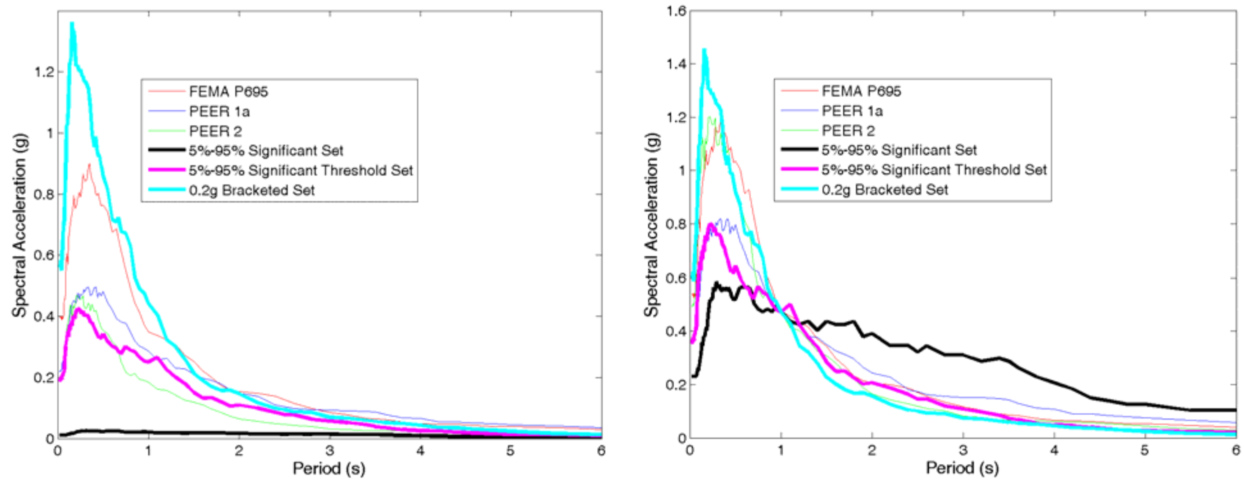
Figure 2.1. Histograms comparing the durations of the records in the long duration sets and the FEMA P695 set



(a) 5%-95% significant duration sets (b) 0.2g bracketed duration set

Figure 2.2. Scatter plots comparing the records in the long duration sets and the FEMA P695 set

Figure 2.3 compares the median response spectra for several record sets, where the spectra in Figure 2.3b have been scaled to a common spectral acceleration at a period of 1 second to illustrate differences in the shape of the median spectra. The duration metric used to screen each set appears to have a strong effect on the spectral shapes of the selected record sets, indicating that spectral shape should be considered when evaluating structural response. The correlation between the record sets and spectral shape is important since prior research (e.g., Baker and Cornell 2008 and Haselton et al. 2011) has established how spectral shape can significantly influence building performance, particularly structural collapse. Therefore, in order to differentiate the effects of ground motion duration from other ground motion characteristics, it is important to account for the influence of spectral shape variations between the various record sets.

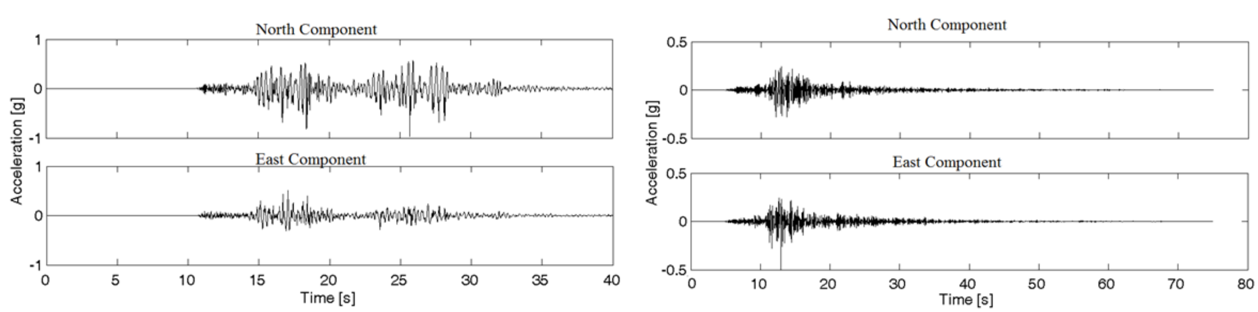


(a) Unscaled median response spectra

(b) Median response spectra scaled to common Sa(1s)

Figure 2.3. Median response spectra of ground motion record sets

In addition to peculiarities in spectral shape, it is necessary to consider peculiarities in the accelerograms. As can be seen in Figure 2.1, a few records in the long duration sets have small duration values relative to the other records. This is because both components of each record pair are included and components may be sensitive to different characteristics of the acceleration record, depending on the duration metric considered. For instance, it has been found that while the CAV and Arias Intensity sets may be sensitive to components with different acceleration amplitudes, the significant duration sets may be sensitive to the amplitude and timing of pulses. Likewise, while the bracketed duration sets may be sensitive to the thresholds chosen, I_D record sets may be sensitive to the PGA and PGV of the components. Figure 2.4a shows an example of the sensitivities for Arias Intensity, where the north and east components have Arias Intensity values of $0.65g^2{\cdot}s$ and $0.13g^2{\cdot}s$, respectively. Figure 2.4b shows an example of the sensitivities for I_D, where both components have approximately the same Arias Intensity value but different PGA and PGV values, resulting in I_D values of 27 and 10 for the north and east components, respectively.



(a) 1999 Duzce Lamont Station 375 record

(b) 1999 Chi-Chi Taiwan #5 TCU129 record

Figure 2.4. Sensitivities for (a) Arias Intensity and (b) I_D records

Finally, it should be noted that just as the significant duration sets may be sensitive to ground motion records with negligible accelerations, the CAV and Arias Intensity sets may be sensitive to short duration, pulse-like records. These records, such as the 1995 Kobe Takatori and the 1994 Northridge Tarzana records, are not long duration motions, although they exhibit large CAV and Arias Intensity values.

3. PILOT STUDY OF DURATION EFFECTS ON STRUCTURAL PERFORMANCE

The authors performed a "pilot" study to investigate any effect that duration has on the collapse capacity of a 3-story steel SCBF. It should be noted that the choice to use this model was primarily one of convenience rather than of the notion that this structure has any particular significance to duration effects over other structural systems. Furthermore, the authors wish to point out that the conclusions of this study are based on a "limited" number of long duration records from two events and on one structural system and period only. These results should not be taken as any definitive conclusions on the effects of duration.

3.1 Model Description

The 3-story frame described in chapter 5 of ATC 76, shown in Figure 3.1, was used in this study. The reader is referred to that document for frame properties and design criteria. A Giuffré-Menegotto-Pinto steel model with isotropic strain hardening and fatigue effects (Uriz and Mahin, 2004) was used to capture nonlinearity in the braces. The Modified Ibarra-Krawinkler Deterioration Model (Ibarra and Krawinkler, 2005) was used to model nonlinearity at beam-column connections, in accordance with ATC 72 (PEER/ATC, 2010). P-delta effects were modeled using a leaning column. Nonlinear dynamic analyses were performed using Open Systems for Earthquake Engineering Simulation (OpenSees, 2011).

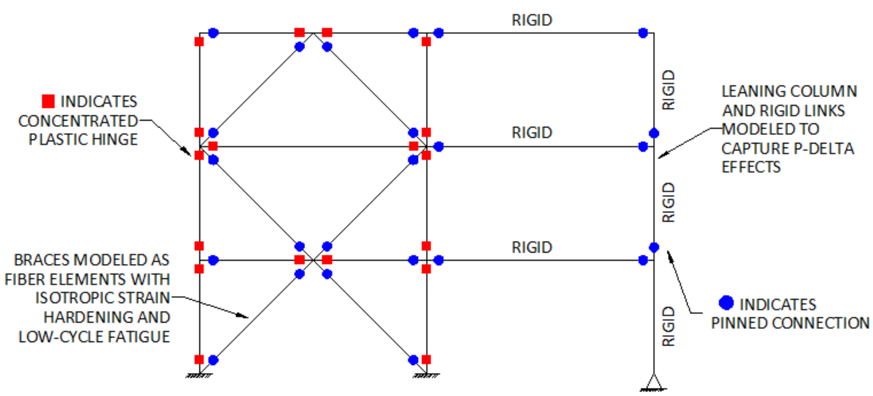


Figure 3.1. OpenSees model for nonlinear time history analysis

3.2 Record Sets

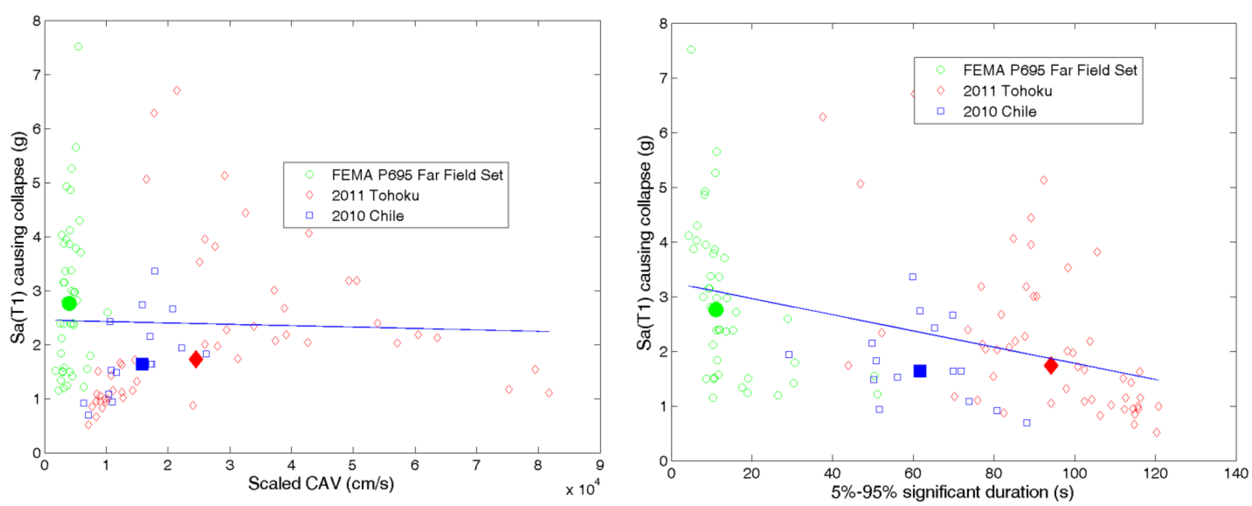
Incremental dynamic analyses (Vamvatsikos and Cornell, 2002) were used to evaluate the collapse capacity of the structure for two sets of ground motions. The unscaled records contained in the FEMA P695 far-field set were selected to represent "moderate" duration events and several unscaled records from the 2011 Tohoku and the 2010 Chile earthquakes were selected to represent "long" duration events. For each duration metric listed in section 2.3, a group of records was assembled that included the (10) highest records from the 2011 Tohoku earthquake and the (10) highest records from the 2010 Chile earthquake. As many records had the highest values of several duration metrics, there was some overlap between the groups of records. The final "long" duration record set consists of (51) records from the 2011 Tohoku earthquake and (15) records from the 2010 Chile earthquake, though each group of metrics consists of (10) records from each event. For the reasons stated previously, a threshold was placed on the spectral acceleration at the fundamental period of the structure (T_1 = 0.55s) of 0.2g to ensure the use of records with the highest significant duration and I_D values that represent large magnitude subduction events.

3.3 Discussion of Results

Table 3.1 shows how the median collapse capacity, defined as the spectral acceleration at the fundamental period of the structure that causes collapse, compares for the two ground motion sets. Results are also shown for the individual groups of records described above in order to evaluate the effects of the different duration metrics considered. As the "long" duration groups consist of (10) records from the 2011 Tohoku earthquake and (10) records from the 2010 Chile earthquake, the FEMA P695 groups consist of the (20) records with the highest respective duration values. Table 3.1 also shows the percent change between the median collapse capacities of the groups of the highest duration "long" duration records and the entire benchmark FEMA P695 record set. The median collapse capacity tends to decrease with increasing duration for all of the groups. It is interesting to note that the degree to which the median collapse capacity differs between the FEMA P695 set and the "long" duration sets depends on the duration metric used. For instance, it appears that the median collapse capacity is least affected when the 0.2g bracketed duration is considered, but is most affected when the 5%-95% significant duration is considered.

Table 3.1. Median Spectral Acceleration at Fundamental Period Causing Structural Collapse

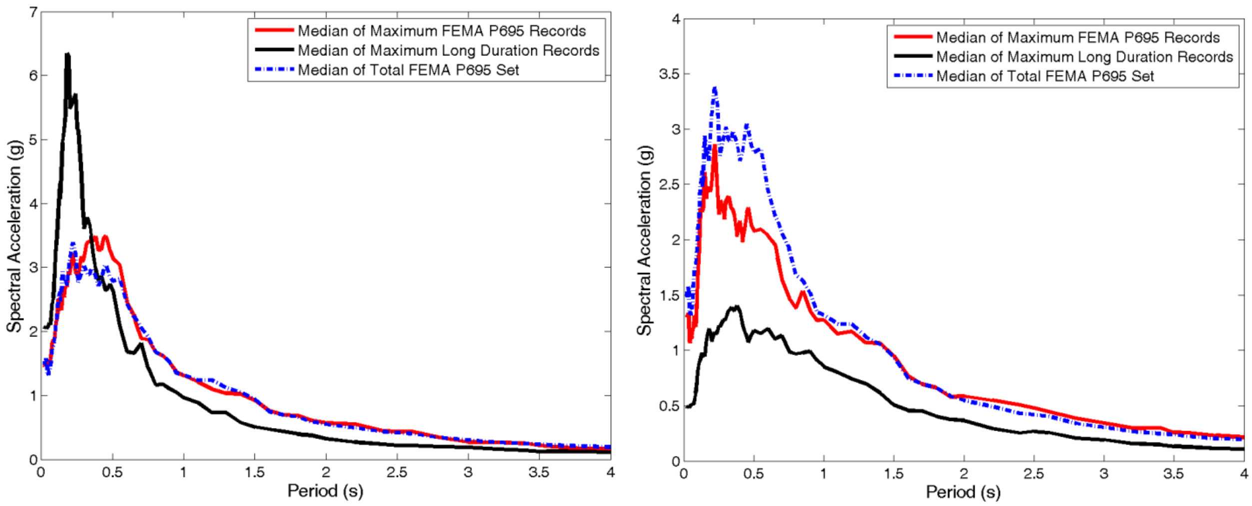
Group Considered	FEMA P695 (g)	Long Duration (g)	Percent Change
All records	2.77	1.72	-38%
(20) records with the maximum I_D values	2.71	2.06	-26%
(20) records with the maximum 5%-95% significant durations	2.10	1.12	-60%
(20) records with the maximum 5%-75% significant durations	2.38	1.51	-45%
(20) records with the maximum 2.5%-97.5% significant durations	2.10	1.33	-52%
(20) records with the maximum original CAV values	2.89	1.99	-28%
(20) records with the maximum original Arias Intensity values	3.06	1.99	-28%
(20) records with the maximum original 0.05 g bracketed durations	2.50	2.11	-24%
(20) records with the maximum original 0.1 g bracketed durations	2.66	1.90	-31%
(20) records with the maximum original 0.2 g bracketed durations	2.71	2.31	-17%



(a) CAV (b) 5%-95% significant duration

Figure 3.2. Scatter plots comparing spectral acceleration causing collapse versus duration value

Figure 3.2 illustrates graphically how the collapse capacity of the structure decreases with increasing values of CAV and 5%-95% significant duration. Each dot on the scatter plots represents one ground motion record and shows how the "long" duration ground motions compare to the FEMA P695 ground motions. The solid shapes in the figures represent the median collapse capacity for each set and the solid lines represent linear regression lines fitted to all of the records. It should be noted that the collapse capacities are plotted against the CAV values of the records when scaled to collapse rather than of the unscaled records. The scaled duration values seem most appropriate here as the study is concerned with the structural response at collapse. The fact that the values of CAV, Arias Intensity and the bracketed durations change with the scaling of the records indicate that they may not be suitable metrics to use when determining a target value for differentiating between “moderate” and “long” duration ground motions. The significant duration and I_D, which are constant for a certain ground motion record, may be more appropriate for that purpose. Figure 3.2 confirms the results shown in Table 3.1 that the collapse capacity tends to decrease with duration and the degree of the decrease varies with the duration metric considered.



(a) Maximum CAV records (b) Maximum 5%-95% significant duration records

Figure 3.3. Scaled response spectra for various groups of records

Figure 3.3 shows the median response spectra for several of the duration groups described and indicates that the choice of the duration metric seems to affect the shape of the median response spectrum. The scaled response spectra of the duration groups are shown instead of the original response spectra for the reason already mentioned. It can be noted, however, that the original response spectra are similar to the scaled response spectra shown. Furthermore, the response spectra for the other significant duration groups are similar to the 5%-95% significant duration group and the response spectra for the other duration metrics are similar to those for the maximum CAV group. For all of the groups considered, the “long” duration sets have lower spectral values than the FEMA P695 sets at periods greater than 0.5s. This implies that the “long” duration records should be less damaging than the FEMA P695 records, though the results described suggest that the “long” duration records are more damaging than the FEMA P695 records. This further suggests that spectral shape needs to be considered when choosing a duration metric.

4. CONCLUSIONS AND FUTURE WORK

This paper presented preliminary results of a study investigating different duration metrics described in the literature and determining the most appropriate duration metric for evaluating the effects of strong motion duration on structural response. It is the authors’ opinion that the ideal duration metric for use in this study is one that is uncorrelated from spectral acceleration and is insensitive to peculiarities in the acceleration record that do not affect structural response. Ground motion records were collected from various large magnitude subduction, long duration events and sets of “long” duration ground motion records were assembled for several duration metrics that the authors consider to be representative of the duration metrics presented in the literature (i.e. bracketed duration, significant duration, CAV, Arias Intensity and I_D). These “long” duration ground motion sets are used through nonlinear analyses to determine the change in structural response compared to benchmark record sets.

Preliminary investigations of the assembled "long" duration record sets found that certain duration metrics, such as Arias Intensity and the bracketed duration, seem to be correlated to intensity, while other duration metrics, such as the significant duration and I_D, seem to be uncorrelated to intensity. Furthermore, the median spectral shape of the "long" duration record sets rely heavily on the choice of the duration metric, suggesting that spectral shape must be considered when assessing structural response to long duration ground motions. Finally, sensitivities of the duration metric to certain record characteristics, such as the presence of large pulses, must be taken into account when choosing the ideal duration metric.

Using the duration metrics described, a pilot study was performed to investigate the change in collapse capacity of a 3-story steel SCBF to ground motions of varying durations. Results suggested that collapse capacity of the structure tends to decrease with increasing duration for each duration metric, but that the degree to which duration affects collapse capacity depends on the duration metric. The pilot study further reinforced the findings that spectral shape must be considered when choosing a suitable duration metric and suggested that duration metrics whose values change with the scaling of a ground motion record may not be appropriate when setting a target value between "moderate" and "long" duration ground motions.

At this time, it is the authors' opinion that, of all the duration metrics considered in this study, the 5%-95% significant duration seems to be the most appropriate for evaluating structural response. This duration metric seems to be uncorrelated from spectral acceleration and relatively robust identifying long-duration motions (i.e. high energy, short duration pulse-like motions would be excluded from consideration). From the very limited results of the pilot study, this metric also seems to be the one with the largest effect on collapse capacity and may be appropriate for determining a target value for "long" duration motions. The use of this duration metric, especially if used without a PGA threshold, would require that spectral shape be explicitly considered. This statement holds true, however, for any duration metric considered.

Future work for this study will be three-fold. First, the most appropriate duration metrics for evaluating structural response using the criteria described in this paper will be identified. As stated previously, this will require an explicit consideration of spectral shape by incorporating the effects of ε and using the conditional mean spectrum (Baker, 2011) to match long duration record sets to benchmark target response spectra. Next, extensive nonlinear dynamic analyses will be performed using OpenSees on models that explicitly capture structural collapse and incorporate cumulative damage and "in-cycle" strength and stiffness degradation. Finally, if a statistical correlation continues to be found between ground motion duration and structural collapse, the authors will investigate and propose the most appropriate ways for modifying seismic design criteria to incorporate the effects of ground motion duration.

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