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Shake Table Tests of Reinforced Concrete Bridge Columns Under Long Duration Ground Motions

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ABSTRACT
The recent occurrence of highly damaging, long duration subduction earthquakes in Chile (Maule, 2010) and Japan (Tohoku, 2011), has highlighted the importance of studying the effect of ground motion duration on structural performance. This paper presents the preliminary results of an experimental study to investigate the effect of ground motion duration. The results of shake table experiments of two identical large-scale reinforced concrete bridge columns that were tested under long and short duration motions are presented. This study utilizes ground motion records from both the 2011 Tohoku and 1989 Loma Prieta earthquakes. Both ground motions are modified to have a similar spectral shape. Preliminary findings show that the duration of the ground motion significantly affects the collapse capacity of the bridge columns.

KEYWORDS: *Ground motion duration, Shake table tests, Reinforced concrete bridge columns*

1. INTRODUCTION

The long duration ground motions that have occurred recently in Iquique, Chile (Mw 8.2, 2014), Tohoku, Japan (Mw 9.0, 2011) and Maule, Chile (Mw8.8, 2010) are a reminder of the importance of the effect ground motion duration on structural response. The durations of the motions in these earthquakes are long because of the size of the rupture. The 2010 Chile Earthquake ruptured over 500 km and many sites across Chile experienced ground motions lasting for 20-90 seconds. The fault size for the Tohoku earthquake was about 500 km x 210 km, and the strong part of the motions exceeded 100 seconds at many stations. Current seismic design codes do not consider duration effects and they are mainly based on the peak spectral acceleration. A difficulty in including the duration effect in the current design practice has been the lack of available long duration ground motion records, which has led researchers to conduct studies using simulated records. After recording a large number of long duration motions in Japan and Chile, extensive data is now available for studying this topic . What makes this study even more important is the possibility of the occurrence of another large magnitude long duration subduction earthquake along the Pacific Northwest coast of the United States, which lies near the Cascadia subduction zone.

The influence of duration on structural performance does not only depend on the duration definition, but is also highly dependent on the damage metric used and on the structural model [1]. Studies using peak response have generally found no correlation between ground motion duration and structural damage [2,3,4]; however, studies using cumulative damage measures [3,5] or energy measures [2,3,4] have found a correlation between duration and damage. Marsh and Gianotti [6] used artificial acceleration records representing the Cascadia subduction zone earthquakes as an input for inelastic response history analyses of single degree of freedom systems. They found that structures subjected to long duration motions accumulate damage as a result of repeated cycles. Although the displacement cycles are of low ductility demands, these structures experienced considerable inelastic action. Thompson [7] found that long duration ground motions cause extensive bridge damage due to the maximum displacement demands not due to the number of displacement cycles imposed on the bridges, this was because the ground motion records that were used had many loading cycles which were not at levels that caused the bridge components to yield. It is also worth mentioning that these records had a range of significant durations [8] of 12-32 seconds which means that they are not classified as long duration ground motions if compared to the Japan or Chile events. Raghunandan and Leil [9] studied the effect of ground motion duration on 17 reinforced concrete building models using nonlinear dynamic analysis. The durations of the ground motion records used varied between 1.1 and 271 seconds. Some of these records were simulated to represent the

Cascadia subduction zone. They found that the ground motion duration is very significant in affecting the collapse capacity of a structure. Foschaar et al. [10] investigated the effect of ground motion duration on the collapse capacity of a 3-story steel braced frame. They used two record sets, one with long duration records and the other with spectrally equivalent short duration records. This approach was useful in isolating the effect of the ground motion duration from other ground motion characteristics. They found that the duration affects the collapse capacity significantly. Boomer and Martinez-Pereira [11] reported more than 30 definitions of strong ground motion duration in the literature. The most common duration definitions are the bracketed and the significant duration. The bracketed duration is defined as the measure of the time interval between the first and last exceedance of an absolute acceleration threshold, for example 0.05g or 0.1g. The significant duration is defined as the interval over which a specific amount of Arias Intensity (I_A) is achieved [9], this amount is usually taken as 5 to 95% or 5 to 75% of the Arias Intensity.

2. TEST SPECIMENS

In 2005, Phan [12] tested a 1/3-scaled bridge column that was named NF-2 using Rinaldi ground motion until failure. Two identical specimens (LD-J and SD-L) were used in this study that have exactly the same details as NF-2. By using the same column, the maximum displacement capacity of the columns is known before testing, which is 9.8 inches. The design was based on the AASHTO 2002 Standard Specifications for Highway Bridges. The height of the columns is 72 inches; the diameter is 16 inches; the longitudinal reinforcement is 22#4 bars (2.20%); the transverse reinforcement is a 0.25-inch steel wire spiral with a pitch of 1.25 inches (1.10%); the axial load ratio is 8%; and the clear cover is 0.75 inches. The specimens detailing and dimensions are shown in Fig. 2.1.

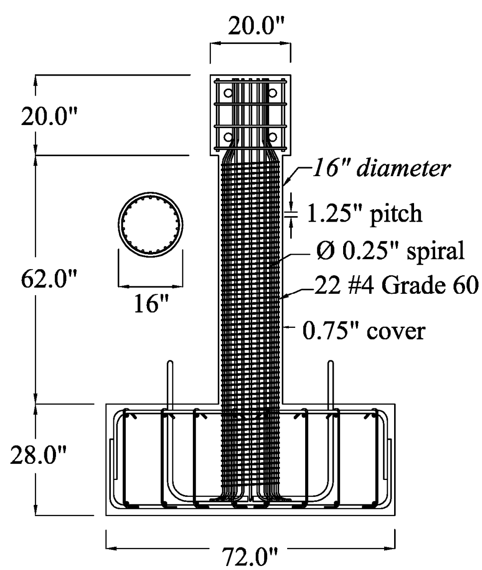


Figure 2.1 Specimen details and dimensions

3. PRE-TEST ANALYSIS AND GROUND MOTION SELECTION

As mentioned before, the maximum displacement capacity of the column (NF-2) is 9.8 inches based on Phan's test [12]. The main goal of the pre-analysis was to choose ground motions in which the displacement demands on the columns are around half of its displacement capacity. The reinforced concrete column was modeled in OpenSees [13] using a fiber cross section and a force-based beam-column element with distributed plasticity. The Concrete01 material was used to represent the stress-strain relationship of concrete, and the Steel02 material was used to represent the longitudinal reinforcement. The analytical model was calibrated using the results from Phan [12]. A simple description of the model and the calibrated results are shown in Fig. 3.1.

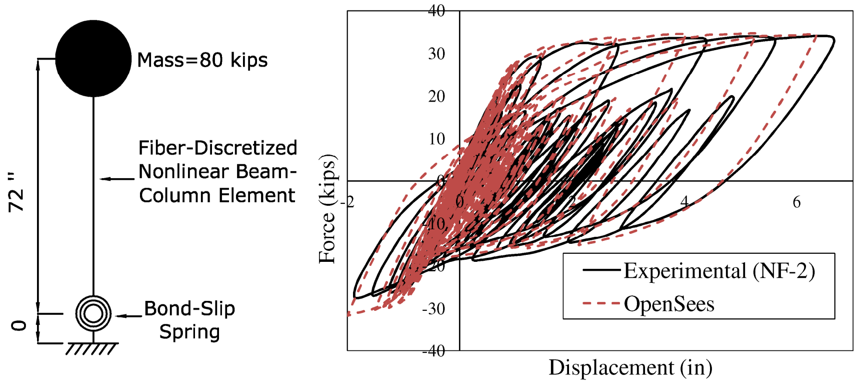


Figure 3.1 OpenSees model description and its results compared to the previous experimental test (NF-2)

Based on the calibrated OpenSees model, a long duration motion from the Tohoku 2011earthquake (FKSH20 N-S) was chosen for the first column (LD-J) with a significant duration (5-95% of A_I) of 88 seconds, and a short duration motion from the Loma Prieta 1989 earthquake (Bran 00) was chosen for the second column (SD-L), with a significant duration (5-95% of A_I) of 9.0 seconds. Fig. 3.2 shows the 2475 year design response spectra for different cities from the northwest of the United States that lie near the Cascadia subduction zone (site class D)[14]. Both the long and short duration motions were modified to match the response spectrum of Crescent City. The target was to impose maximum displacement demands on the two specimens with around half of the maximum displacement capacity which is 9.8 inches, and since the two motions have a similar spectral shape, the only difference between the two motions was their durations. The response spectra of the motions and their acceleration histories before and after the spectral matching are shown in Figs. 3.3, 3.4 and 3.5. The spectral matching was done for a period range from 0.5 to 3 seconds.

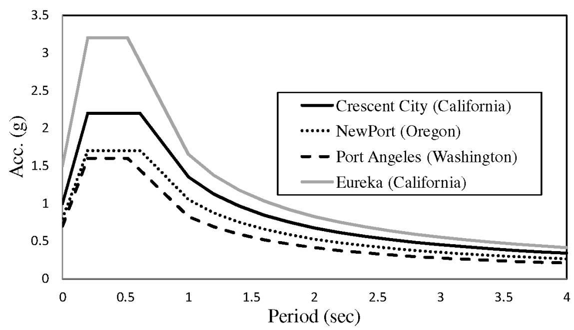


Figure 3.2 2475 year response spectra for different cities (USGS-site class D)

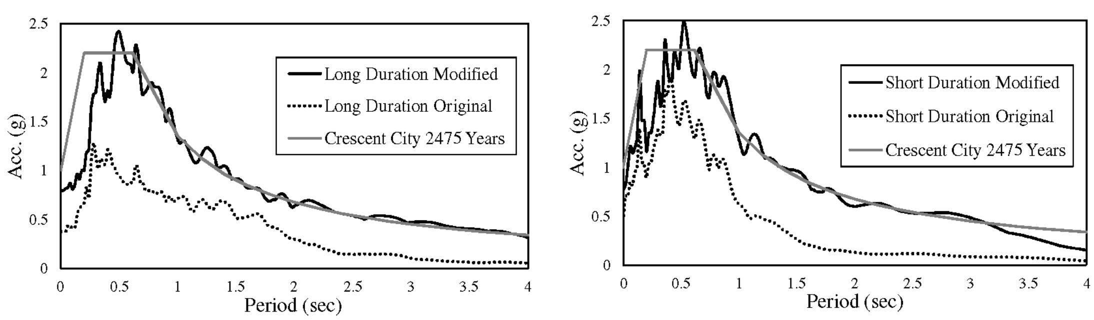


Figure 3.3 Response spectra of the long and short duration motions before and after spectral matching

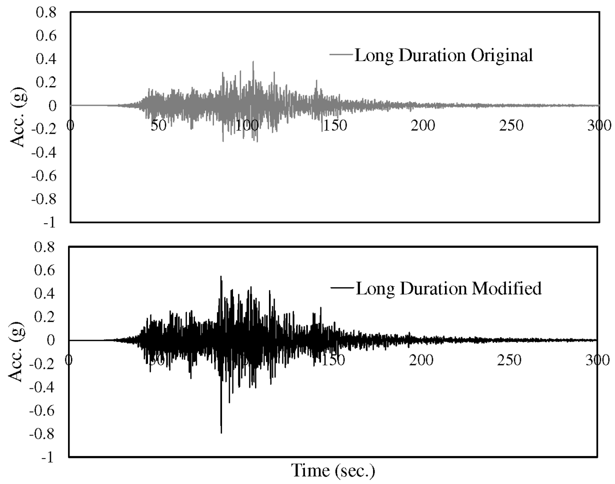


Figure 3.4 Acceleration histories for the long duration motion before and after spectral matching

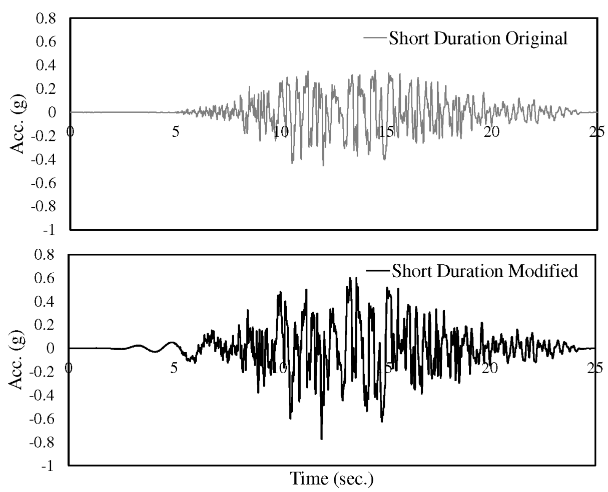


Figure 3.5 Acceleration histories for the short duration motion before and after spectral matching

The time scale of the selected ground motions was compressed by a factor of 0.577 to take into account the scaling from the prototype to the model (1/3 scale). The final motions response spectra are shown in Fig. 3.6. The Force-Displacement relationships of the calibrated OpenSees model using 100% of the selected long and short ground motions are shown in Fig. 3.7. The expected maximum displacement demand was about 4 inches.

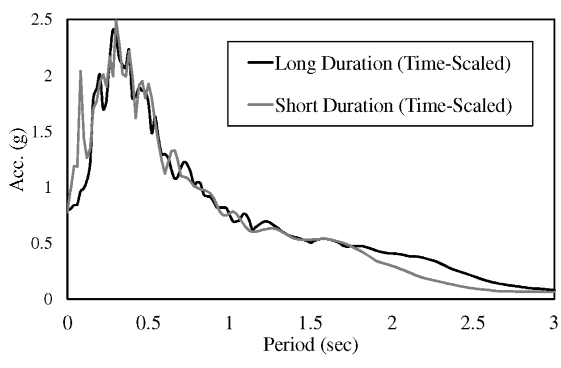


Figure 3.6 Response spectra of the modified, time-scaled long and short motions used in the test

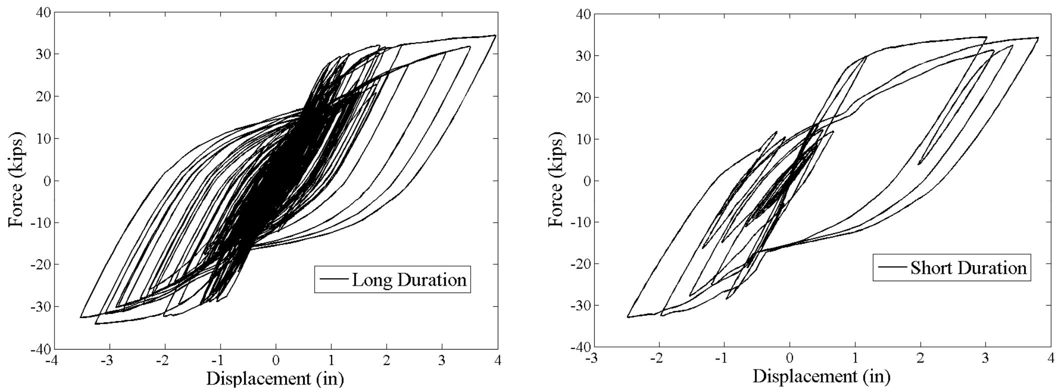


Figure 3.7 Pre-analysis results of the OpenSees model using the selected motions

4. TEST SETUP AND LOADING PROTOCOL

Both columns were tested on a shake table in the new Earthquake Engineering Laboratory at the University of Nevada, Reno. Each specimen was attached to an inertial mass of 80 kips as shown in Fig. 4.1. The ground motions were uniaxial and applied along the North-South direction of the laboratory.

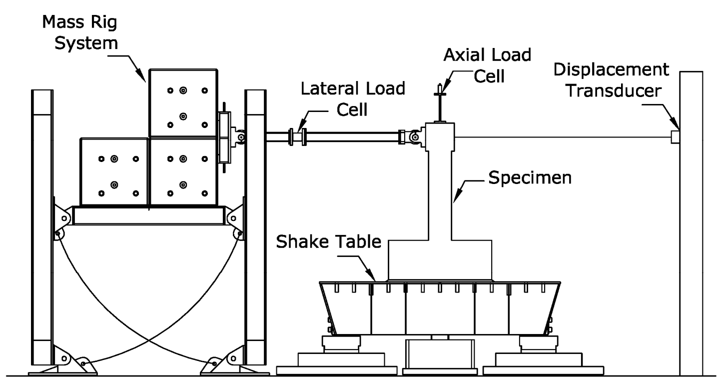


Figure 4.1 Test setup

Several instruments were used for each specimen including strain gages, LVDT's, string potentiometers, displacement transducers, accelerometers and high definition video cameras. The loading protocol for both columns was the same, and it was to begin with the 100% of the selected motions and follow up with an aftershock. Then scales of the main motions were applied until failure (125%, 150%, ..., etc.). The applied aftershock was the same for both columns and was chosen from the M_w 7.1 earthquake that occurred in Japan one month after the Tohoku earthquake.

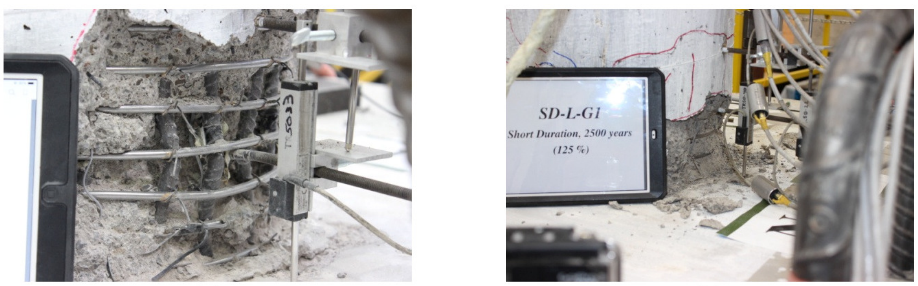
5. TEST RESULTS AND DISCUSSIONS

5.1. Damage Comparison

Table 5.1 summarizes the damage states for the two columns after each applied ground motion. The first column (LD-J) which was subjected to the long duration motion reached its final damage state after applying 125% of the main motion when four longitudinal bars fractured. The failure of the second column (SD-L), with the short duration motion, did not occur until 175% of the main motion was applied and one bar fractured. Fig. 5.1 shows the damage states for the two specimens after applying 125% of the main motion.

Table 5.1 Damage states comparison between the two columns

	Column 1 (LD-J)	Column 2 (SD-L)
100% of the main motion	-Max. Disp. =4.5 in. -South: 4.4 in. spalling and the spirals are exposed. -North: 3.0 in. spalling and the spirals are exposed.	-Max. Disp. =3.88 in. -South: cracks of max. width of 0.016 in. -North: 4.5 in. spalling and no exposed reinforcement.
Aftershock	-Same visual damage state as the previous motion.	-Same visual damage state as the previous motion.
125% of the main motion	-Max. Disp. =4.98 in. -South: 8.5 in. spalling and four longitudinal bars fractured (failure). -North: 6.4 in. spalling and the concrete core is damaged.	-Max. Disp. =4.8 in. -South: 4.5 in. spalling and the spirals are exposed. -North: 4.5 in. spalling and the spirals are exposed.
150% of the main motion	-Not applicable as bars fractured at 125% of the main motion.	-Max. Disp. =7.3 in. -South: 9.0 in. spalling and the spirals are exposed. -North: 6.0 in. spalling and the spirals are exposed.
175% of the main motion	-Not applicable as bars fractured at 125% of the main motion.	-Max. Disp. =9.2 in. -South: four longitudinal bars buckled. -North: one longitudinal bar fractured and two buckled.



(a) (b)

Figure 5.1 Damage states after applying 125% of the motion (a) Column 1 (LD-J) (b) Column 2 (SD-L)

5.2. Force-Displacement relationships

The measured force displacements hysteretic curves for the two specimens are shown in Fig. 5.2. The maximum displacement for the first column (LD-J), where the long duration motions are applied, was 4.98 inches (at 125% of the target motion). For the second column (SD-L), it was 9.2 inches (at 175% of the target motion). Although the displacements demands are not high for the first column (LD-J), it failed because of the large number of applied cycles, which demonstrates that long duration motions can be more damaging than short duration ones even if the maximum displacement demands are much less than the expected maximum displacement capacity.

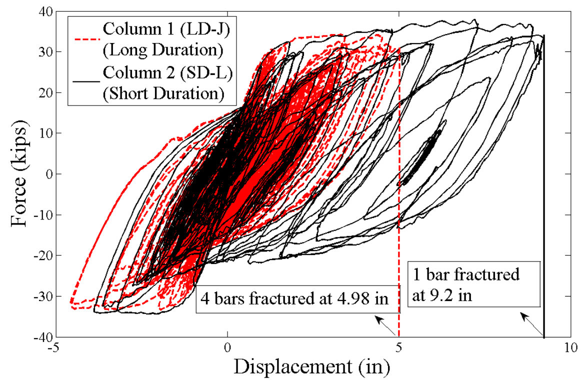


Figure 5.2 Force-Displacement hysteretic curves for the two specimens

5.3. Strain histories

Fig.5.3 shows the strain histories for both specimens when applying 100% of the main motion. The results are for strain gages placed at 4 inches above the footings. It is clear that the bars in the first column (LD-J) were subjected to a large number of high-strain cycles compared to the second one (SD-L).

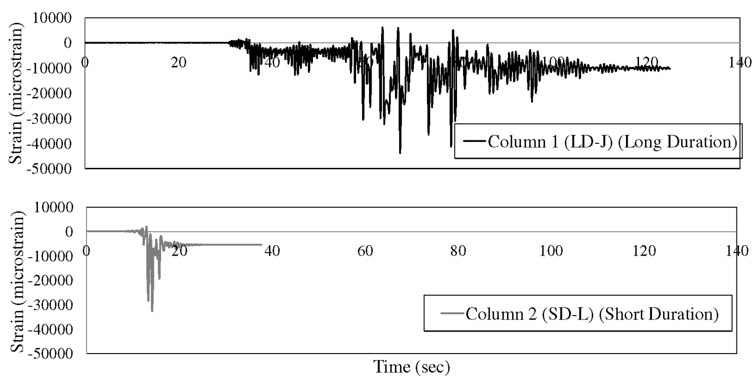


Figure 5.3 Strain histories for both columns at 4 inches above the footings

5.4. Response spectra comparison

Fig. 5.4 shows the response spectra for the specimens at the final damage state. The first column (LD-J) with the long duration motions failed at 125 % of the main motion. The second column (SD-L) failed at 175 %. The response spectrum for the long duration column is less by about 40%.

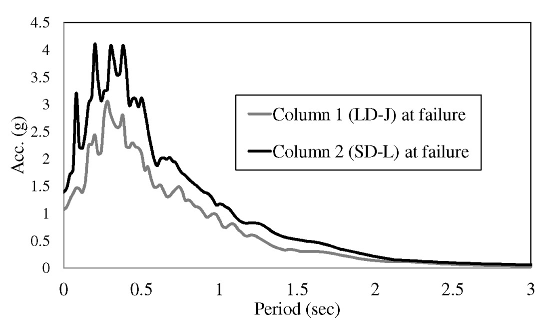


Figure 5.4 Response spectra at final damage state for both columns

6. CONCLUSIONS

This paper presented a preliminary results of a study investigating the effect of ground motion duration on structural performance. A reduction in the displacement capacity of about 45% was observed for the column that was subjected to the long duration motion compared to the one subjected to the short duration. The response spectra for the long duration motions that caused collapse were about 40% less than the response spectra of the short duration motion at collapse. The accumulated plastic strains in the reinforcing bars of the columns subjected to long motions causes the bars to fracture early even if the maximum displacement demands are low. Based on these results, ground motion duration is considered to have a significant effect on the collapse capacity of bridge columns.

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