Bridge Seismic Analysis Procedure to Address Near-Fault Effects

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INTRODUCTION

Seismic records obtained in several of the recent earthquakes, such as Northridge (1994), Hyogo-ken Nanbu (1995), Duzce (1999), and Chi-Chi (1999), have revealed peculiarities of ground motions near active faults. Measured records and analytical studies have shown that the direction of fault rupture in addition to proximity to the fault line can have considerable influence on the ground velocities. In sites located in front of the rupture direction, strong and short-duration velocity pulses associated with large ground displacements can potentially cause substantial damage [10-13]. The effect of high velocity earthquake pulse loading on structures close to active fault lines has only recently been realized to be potentially important. Since the fact that more than 50% of bridges in California are close to active faults, reliable and practical procedures for near-fault earthquake analysis and design of bridges are critically needed.

The purpose of this study is to investigate near-fault ground motion effects on typical Caltrans bridge columns. The ultimate objective is to develop practical and proven bridge design guidelines that incorporate the effects of near-fault ground motions. One task of this research is to test and analyze the performance of four large-scale bridge columns under forward directivity conditions. In addition, a large-scale two-span bridge model supported on three piers, one on each of the UNR shake tables, will be tested under a near-fault ground motion with incoherent motions that includes the fault rupture effect.

In this paper, the effects of near-fault earthquake involving velocity pulse on a flexure-dominated, single spiral circular column were investigated through shake table tests for two large scale bridge columns, which were designed according to the current Caltrans Seismic Design Criteria (SDC). The most unique response seen from both column tests was the relatively large residual displacements.

CARACTERISTICS OF NEAR-FAULT GROUND MOTION

Near-fault ground motions, which have caused much of the damage in recent major earthquakes, typically contain a strong and short-duration velocity pulse. These impulsive characteristics of the near-fault ground motions are the results of a forward directivity phenomenon. Forward rupture directivity effects occur when the rupture front propagates toward the site and the

direction of slip on the fault is aligned with the site. Measured records and analytical studies have shown that forward directivity leads to high velocity impulsive loads on structures with relatively long period (T> 0.5 sec) because of the superposition of s-waves emanating from different parts of the fault as it ruptures. In the rear of the rupture direction, however, the arrival times for the waves from different parts of the ruptured fault are different and hence a more distributed velocity history with smaller amplitudes and longer duration is measured [11].

Near-fault ground motions often contain permanent ground displacements. These ground displacements are caused by the relative movement of the two sides of the fault in which the earthquake occurs. These displacements are discontinuous across a fault having surface rupture, and can subject a bridge crossing a fault to significant differential displacements. These static ground displacements occur at about the same time as the large dynamic motions, indicating that the static and dynamic displacements need to be treated as coincident loads [11].

The 2004 Caltrans SDC does have specific provisions for sites near an active fault. For critical bridges, Caltrans SDC requires site-specific analysis of potential earthquakes when the bridge is located near active faults. For other bridges, it recommends the amplification of up to 20% of the standard SDC ARS curve as a function of the initial column period. The standard ARS curves were developed based on far-field ground motions and are amplified to take into account the higher forces that are believed to be inherent in a near field ground motion. This, however, does not clear if such approach adequately accounts for the potential adverse effects of the high velocity impulse experienced due to the forward directivity phenomenon.

Experimental Test

Two 30% scale columns underwent shake table tests at the UNR Large Scale Structures Laboratory. The two specimens were named MN and ETN. Both columns were designed to behave as cantilever members and are representative of typical single column bridge piers.

Design of the Specimens

The designs of both, MN and ETN, columns were based on the 2004 Caltrans SDC version 1.3, to satisfy the current Caltrans near fault provisions. The difference between the two specimens is that MN had 0.66 seconds prototype period, but ETN had 1.50 seconds prototype period. Soil type, seismicity of the site, and material properties used in the design of MN are also utilized in the design of ETN. The purpose of the shake table test is to further enhance our understanding of near fault ground motion effects on reinforced concrete bridge columns and to analyze how various period columns designed to Caltrans near-fault provisions stand up to near fault ground motions.

MN was nearly comparable to a column, named NF-1, tested in the UNR Large Scale Structures Laboratory during a previous research project funded by FHWA. [10]. The design of NF-1 was based on the current Caltrans SDC, but did not incorporate any of the near fault provisions. The efforts were made to ensure that MN, and NF-1 were all designed to the same criteria. Both MN and NF-1 were subjected to a near fault ground motion. The goal was to compare the responses of the two different columns under same near-fault ground motion, and to investigate the efficiency of current Caltrans approach for near-fault earthquakes. Table 1 presents information for all three columns examined in this study.

Table 1. Specimen Details

Specimen	Column Height (in)	Column Diameter (in)	Longitudinal Steel Ratio (%)	Transverse Steel Ratio (%)	Aspect Ratio	Scale (%)
MN	63	14	2.90	1.37	4.5	30
ETN	108.5	14	2.90	1.54	7.75	30
NF-1	72	16	2.00	0.92	4.5	33

Shake Table Testing

For both test specimens, the January 17, 1994 Northridge earthquake as measured at the Rinaldi Receiving Station was chosen for input motion to drive the shake table. This record was selected due to it being representative of a typical near-fault earthquake. Furthermore, preliminary analysis showed it generated large ductility demands compared to other near fault ground motions. Both columns were loaded with the fault normal component of Rinaldi ground motion. The fault normal component of the Rinaldi ground motion velocity history is shown in Figure. 1.

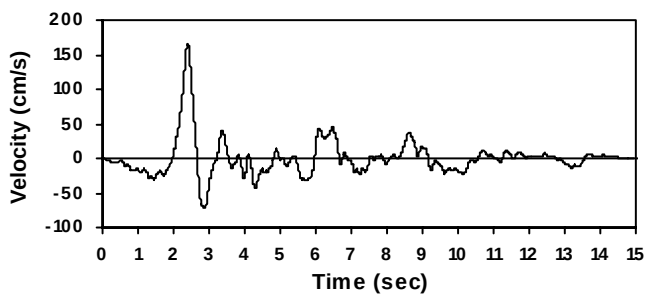

Figure 1. Velocity History of Renaldi Ground Motion

Various forms of instrumentations were used to observe the internal strains, curvatures, displacements, accelerations, and forces for each model during the excitation. Most of instrumentations were located in the lower one-third of the column to study the column responses at the plastic hinge zone. Figure 2 shows the shake table test setup for ETN.

Figure 2. ETN Shake Table Test Setup

Both specimens were subjected to a series of Rinaldi ground motions in which the acceleration amplitude was scaled by an increasing factor in subsequent runs. The series started at a low amplitude motion, which then gradually increased after each run until failure occurred. A total of 11 runs were performed for MN and 13 runs for ETN. Rupture in the spirals occurred at 135% of the original Rinaldi magnitude in MN specimen. For ETN, test was stopped at 165% of the original Rinaldi magnitude due to the specimen met the displacement limit of mass rig system. Even though the column did not collapse, were left with huge residual displacement at the top (12.3% drift). Figure 3 show the test specimens at the completion of testing when failure occurred. Significant amounts of residual displacement can be seen in both specimens.

Figure 3. MN and ETN after Shake Table Tests

Residual Displacements

The most distinctive issue seen from both test data was the magnitude of the residual displacements in the responses of MN and ETN. Figure 4 presents a plot of residual drift ratio versus the target peak ground acceleration (PGA). Residual drift ratio is defined as residual displacement divided by the length of the column. The data show that residual displacements of MN and ETN were alarmingly high. As peak ground acceleration increased, the residual displacements of MN also increased. By comparison, the residual displacement seen in ETN was practically nonexistent until a PGA of approximately 1.0g, and suddenly increased in an almost exponential manner.

The higher residual displacements seen in MN and ETN are recognized to the unique characteristics of a near fault ground motion. The one-sided tendency of a near fault pulse can cause large displacements in one direction, particularly when the pulse is asymmetrical as with

the Rinaldi ground motion. Since near fault ground motions tend to also have higher peak ground accelerations due to their proximity to the fault, the pulse can be strong enough to push a column far past the elastic range and not allow the column to return to its original position. The biased nature of the near fault Rinaldi ground motion exacerbated the residual displacement with each subsequent run [10].

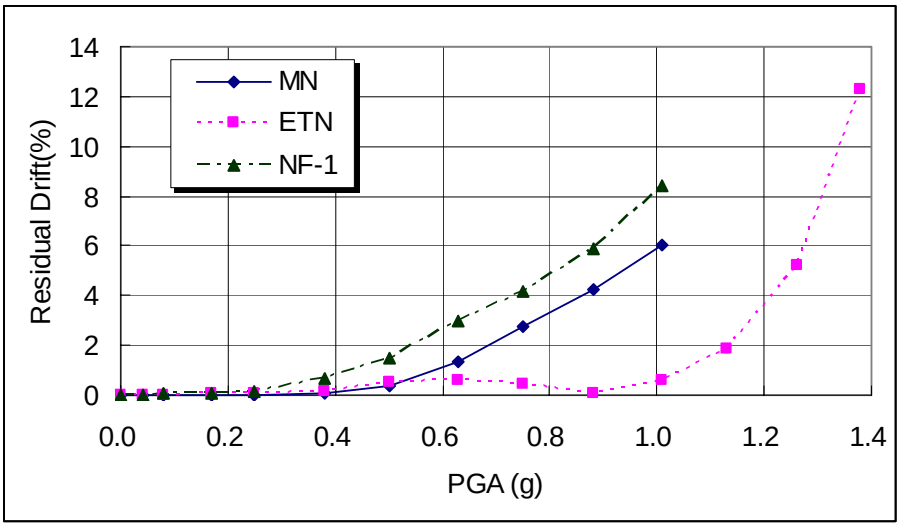

Figure 4. Residual Drift Comparison

This high residual displacement is undesirable because it presents several problems for the bridge serviceability after earthquakes. The high residual displacement in a bridge column could indicate that the bridge is unsafe and possibly be closed down to traffic even though the column does not fail at the plastic hinge zone. In Japan, reinforced concrete bridge columns with residual drift ratios of more than 1.75% were replaced after the Hyogo-ken Nanbu earthquake [9]. Both MN and ETN were easily met this criteria during the test.

MN contained 0.9% more longitudinal bars than NF-1. Due to the additional stiffness of MN, average 36% reduction in residual displacement was seen for runs with a PGA of 0.60g and higher. This shows that the columns designed for current Caltrans near-fault provision can reduce some residual displacement compare to the columns without any design consideration for near-fault effects, but the magnitude of residual displacement might be still undesirable.

Currently there are no written guidelines for the design of reinforced concrete bridge columns with respect to control of residual displacement in the Caltrans SDC.

SETN and SVTN

The seismological part of the study includes refinement of existing broadband near-fault spectra to provide a realistic level of demand incorporating forward rupture directivity effects. Dr. Somerville provided a modified spectrum comparable to current Caltrans ARS curve which was used to design specimen MN and ETN. The modified spectrum was developed from the median of the Abrahamson and Silva relation, and then adjusted for forward directivity effects [1]. Figure 5 shows the modified spectrum for magnitude 7.5 and 0.6g PGA.

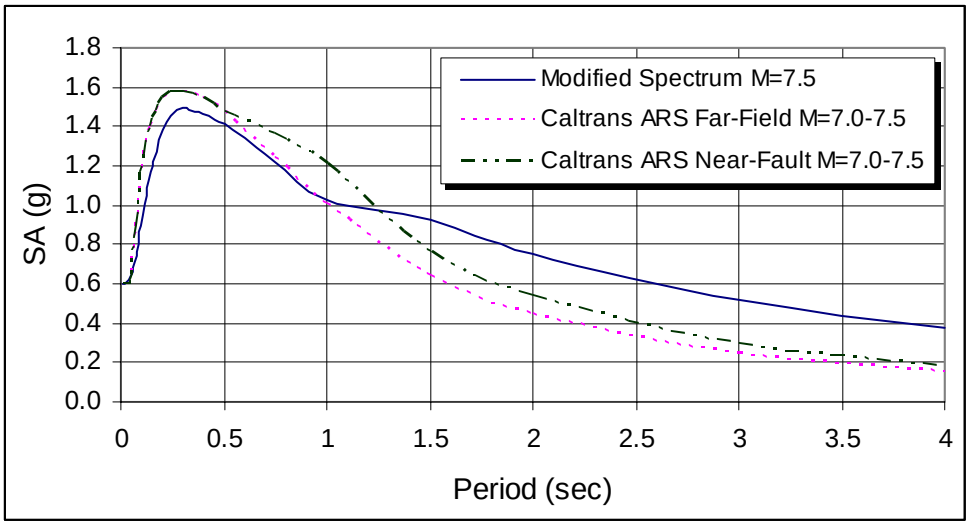

Figure 5. Response Spectra Comparison

The new modified spectrum shows considerably more higher Spectral Acceleration (SA) than Caltrans near-fault spectrum at periods exceeding 1.25 seconds, but Caltrans spectra have higher values at short periods.

To evaluate the efficiency of new spectrum, two new columns, SETN and SVTN, one with a prototype period of about 1.5seconds (SETN) and another with a prototype period of about 2 seconds (SVTN), were designed and are under construction for shake table test. Table 2 presents information for both columns.

Table 2. SETN and SVTN Details

Specimen	Column Height (in)	Column Diameter (in)	Longitudinal Steel Ratio (%)	Transverse Steel Ratio (%)	Aspect Ratio	Scale (%)
SETN	108.5	14	3.60	2.05	7.75	30
SVTN	98.5	12	3.00	1.82	8.20	20

The validity of new spectrum will be evaluated by data comparisons from SETN shake table test and its sister column, ETN. The purpose of the SVTN shake table test is to investigate how a longer period column designed to new spectrum stand up to near fault ground motions.

CONCLUSIONS

The effects of near-fault earthquake involving velocity pulse on a flexure-dominated, single spiral circular column were investigated through shake table tests for two large scale bridge columns. The measured data showed that both MN and ETN columns experienced large residual displacement under near-fault ground motion.

Asymmetrical, high amplitude velocity pulse generates large displacements in one direction. This displacement is only partially recovered leading to a significant residual displacement.

Shake table tests performed at the University of Nevada, Reno pointed out the necessity of the control of residual displacement for the design and inspection of reinforced concrete bridge columns, especially when dealing with impulsive loading conditions.

Two new designed columns will be tested on a shake table to evaluate the validity of new spectrum developed by Dr. Somerville.

ACKNOWLEDGEMENTS

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