ANALYTICAL AND EXPERIMENTAL INVESTIGATIONS OF THE EFFECT OF VERTICAL GROUND MOTION ON RC BRIDGE PIERS

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ABSTRACT :

A research program aimed at investigating the effect of vertical earthquake motion on the behavior of reinforced concrete piers is described. For the analytical investigation, a parametric study was conducted considering various ratios of peak vertical-to-horizontal ground accelerations (V/H) and results are compared to the case of horizontal excitation on its own. The time lag between the arrival of the peak horizontal and vertical accelerations was also studied. In the experimental investigation, hybrid simulation was employed using the Multi-Axial Full-Scale Sub-Structured Testing and Simulation (MUST-SIM) facility at the University of Illinois. In the hybrid simulations, a large scale pier was tested with an analytical module of a bridge structure. It is concluded that vertical ground motion can significantly impact RC pier behavior.

KEYWORDS: vertical ground motion, bridge pier, hybrid simulation

1. INTRODUCTION

In recent years, moderate-to-large magnitude earthquakes, e.g., the Loma Prieta (1989) and Northridge earthquakes (1994) in California and the Hyogo-ken Nanbu earthquake (1995) in Kobe, Japan, have caused significant damage to RC structures. In these past earthquakes, shear failure of concrete columns was found to be one of the major causes of damage. Previous investigations (e.g., Papazoglou and Elnashai, 1996), have attributed the observed failures to the reduction of shear strength caused by vertical ground motion effects and many studies report data showing that the vertical peak acceleration may be even higher than the horizontal value (e.g. Abrahamson and Litehiser (1989), Ambraseys and Simpson (1996), Elnashai and Papazoglou (1997), Collier and Elnashai (2001), Elgamal and He (2004)). Moreover, the influence of the arrival time of peak vertical and horizontal ground motion could be an important parameter that has not been investigated.

In this study, the effect of vertical ground motion on RC bridge piers is investigated both analytically and experimentally. In the analytical investigation, the peak vertical to horizontal acceleration ratio (V/H) and the time interval between the arrivals of these peaks at the site are the primary focus. In the experimental investigation, hybrid simulation utilizing pseudo-dynamic techniques (PSD) and sub-structuring was employed using the Multi-Axial Full-Scale Sub-Structured Testing and Simulation Facility (MUST-SIM) at the University of Illinois. MUST-SIM is one of the fifteen nodes of the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES). Building upon the results obtained from the analytical investigation, two hybrid simulations were conducted in which an experimental pier specimen was tested simultaneously and interactively with an analytical bridge model. During the first simulation, the bridge and pier were subjected to only horizontal excitation while during the second the bridge and pier were subjected to combined horizontal and vertical excitation.

2. PROTOTYPE STRUCTURE AND STRUCTURAL IDEALIZATION

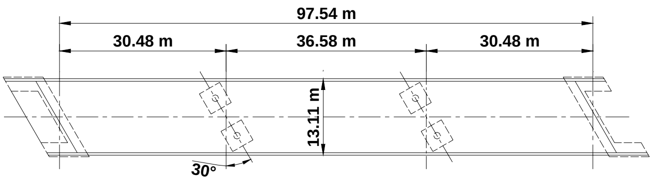
2.1 Prototype Structure

The selected prototype structure for the analytical and experimental investigations was seismic design example No. 4 prepared by the Federal Highway Administration (FHWA, 1996). This bridge structure was designed for a zone in the western United States with an acceleration coefficient of 0.3g as specified by the *Standard Specifications for Highway Bridges, Division I-A, Seismic Design* (AASHTO, 1995). This bridge is 97.5 m (320 feet) long with spans of 30.5, 36.6, and 30.5 m as illustrated in Figure 2.1. The substructure elements are oriented at a 30^o skew from a line perpendicular to the bridge deck centerline. The superstructure is a cast-in-place concrete box girder with two interior webs and the intermediate bents have a cross beam integral with the box girder and two circular columns. The connection between the pier base and the footing is designed and detailed as a pinned connection.

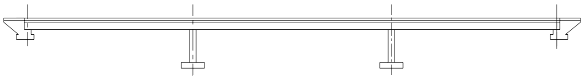
2.2 Structural Idealization and Properties of Test Specimen

To satisfy laboratory capacity limitations, half scale models of the prototype pier were constructed and tested. The diameter of prototype pier is 1219 mm with 34 #11 longitudinal bars in 2-bar bundles as illustrated in Figure 2.2 (a). The top and bottom quarter of the pier height are considered to be the plastic hinge zone. Within the design example, a #5 spiral with a spacing of 88.9 mm is used throughout the entire length, but it is noted that 152.4 mm spacing is allowed by the code in regions outside of the plastic hinge zones. As shown in Figure 2.2 (b), the diameter of test specimen is 610 mm with 16 #8 longitudinal bars. Within the plastic hinge regions, a #3 of spiral with a spacing of 63.6 mm is used while a spacing of 108.6 mm is used outside of the plastic hinge zones. The larger spacing of 108.6 corresponds to the maximum permitted by the code. The rebar configuration produces a longitudinal rebar ratio of 2.8% and spiral volumetric ratios of 0.50% and 0.84% within the central and plastic hinge zones respectively. As discussed in subsequent sections, the analytical investigation demonstrated that vertical ground motion significantly increases the variation of axial load therefore resulting in fluctuating member shear capacity and demand. However, the FHWA design is highly conservative in shear (31% overstrength in the outside of the plastic hinge zones without consideration of safety factors). Therefore, strictly following the prototype design would make it difficult to delineate the influence of vertical motion on the shear behavior. Additionally, material property uncertainties and overstrengths need to be considered. Therefore, the pinned connection at the base of prototype structure was replaced with a fixed connection therefore counteracting the overstrength in shear capacity with an increase in shear demand. Moreover, the effect of skewness on structural behavior is beyond the scope of this study and was therefore removed.

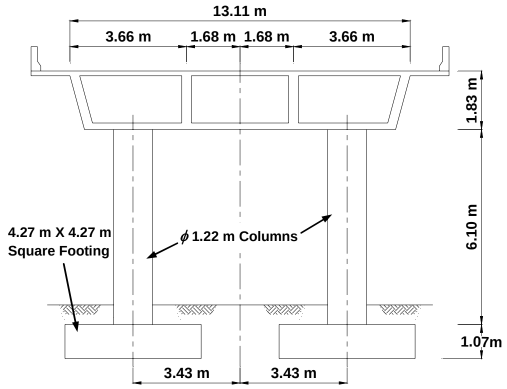
Table 2.1 summarizes the material properties of the prototype and test specimen. Although attempts were made to control the concrete overstrength, the delivered concrete obtained strength 57.6 % greater than that of the prototype. For the test specimen, ASTM A706 was used for longitudinal bars while ASTM A615 was used for spiral. The obtained strengths are shown in Table 2.1. As shown, the yield strength of longitudinal bar was close to that of prototype; however, the spiral had an overstength 25%. The overstrength in both the concrete and shear steel further justify the modifications made to the pier boundary conditions previously discussed.



(a) Plan view

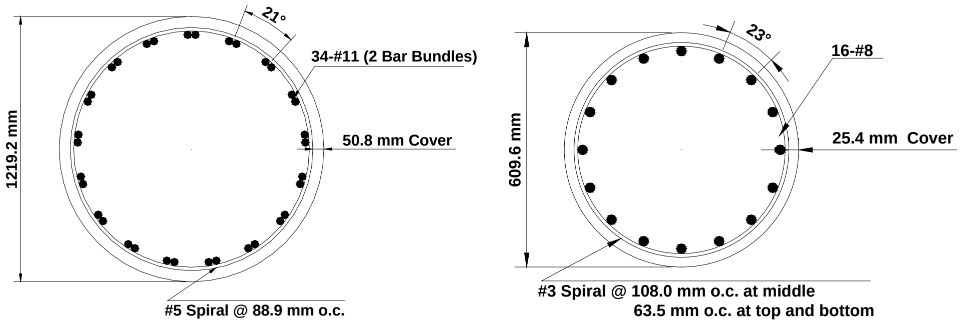


(b) Elevation



(c) Cross section

Figure 2.1 Prototype structure, FHWA No. 4 (1996)



(a) Prototype (b) Half-scaled pier

Figure 2.2 Pier section

Table 2.1 Material properties of the prototype and test specimen

	Concrete Compressive Strength (*f'c*)	Reinforcement			
		Longitudinal		Spiral	
		Fy	Fu	Fy	Fu
Prototype	27.6 MPa	414 MPa	-	414 MPa	-
Test Specimens	43.4 MPa	428 MPa	633 MPa	517 MPa	703 MPa

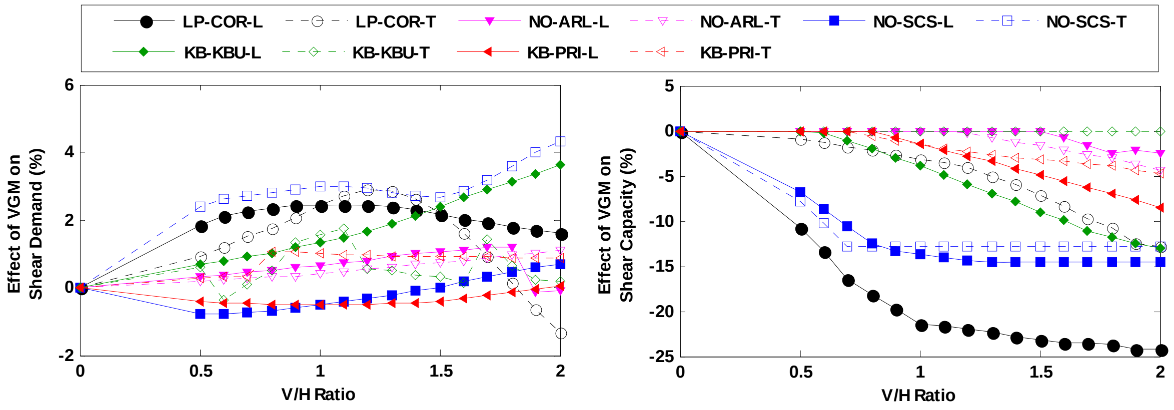
3. ANALYTICAL INVESTIGATION

To investigate the effect of vertical ground motion on RC bridges analytically, natural records from 5 stations were selected (Table 3.1) and non-linear time history analysis was conducted. The finite element program Zeus-NL (Elnashai et al, 2004) developed at the Mid-America Earthquake Center was used to perform the analyses for the selected structures. A fiber model of the pier was combined with a shear spring to model the shear deformation and behavior of the piers (Lee and Elnashai, 2001). The shear strength model of Priestley et al (1994) was employed to predict the shear capacity of the pier. The analytical investigation was undertaken to determine the influence of V/H and the time interval between vertical and horizontal peaks. The V/H ratio was considered to range from 0.5 to 2.0 in increments of 0.1 producing 16 unique analysis cases for each horizontal PGA. The results were then compared with the results from analyses with only horizontal ground motion. The influence of arrival time was investigated by varying the time lag between the vertical and horizontal acceleration peaks. For each of the records selected from 5 stations, 11 different arrival time intervals, ranging from 0.0 to 5.0 sec. in increments of 0.5 sec, were studied. This was accomplished by shifting the horizontal record along the time axis. The original recorded V/H ratios were maintained throughout the arrival time study and the results were then compared against the response with coincident horizontal and vertical peaks.

Considering the V/H ratio, it was observed that the axial force variation increases significantly as the V/H ratio increases, resulting in slight increases in shear demand and noteworthy reductions in shear capacity as shown in Figure 3.1. The shear demand, depicted in Figure 3.1 (a), increased by approximately 5% when compared to horizontal excitation only while the shear capacity, shown in Figure 3.1 (b), decreased up to 24%. Figure 3.2 illustrates the effect of time lag on both the shear demand and capacity. Although no clear correlation exists between the shear demand or capacity and the time lag, noticeable changes were noted. The change in shear demand was observed to fluctuate between 5.4% to -11.7 % when compared to coincident motion. Likewise, the change in shear capacity varied between 18.2% to -6.6%.

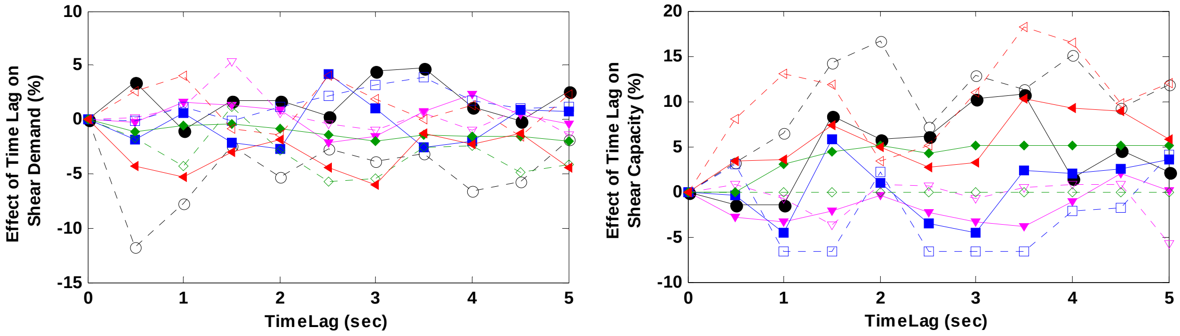
Table 3.1 Selected ground motions for analytical investigation

Earthquake	Mw	Station	Fault Distance		PGA (g)			V/H		Time Lag (sec)		Reference Name
			Epicentral	Closest	L	T	V	L	T	L	T	
Loma Prieta (10/18/1989)	7	Corralitos	7.2	3.9	0.64	0.48	0.46	0.71	0.95	0.07	1.5	LP-COR
Northridge	6.7	Arleta Fire Station	11.1	8.7	0.34	0.31	0.55	1.6	1.79	1.28	2.78	NO-ARL
(1/17/1994)		Sylmar Converter	13.1	5.4	0.61	0.9	0.58	0.96	0.65	2.03	4.32	NO-SCS
Kobe	6.9	Kobe University	25	0.9	0.29	0.31	0.38	1.31	1.22	-1.08	0.53	KB-KBU
(1/16/1995)		Port Island	20	3.3	0.31	0.28	0.56	1.79	2.02	1.89	0.77	KB-PRI



(a) Maximum shear demand (b) Minimum Shear capacity

Figure 3.1 Effect of V/H Ratio



(a) Maximum shear demand (b) Minimum shear capacity

Figure 3.2 Effect of time lag

4. EXPERIMENTAL PROGRAM

In the experimental investigation, hybrid simulations were conducted using the MUST-SIM facilities. As shown in Figure 4.1, a single bridge pier was evaluated experimentally while the rest of structure was simulated analytically using Zeus-NL. Communication and interaction was handled with UI-SIMCOR, hybrid simulation software developed at UIUC (Kwon et al., 2005). A single Load and Boundary Condition Box (LBCB) was utilized to control the top node of the pier as illustrated in Figure 4.2. An LBCB is a self-reacting assembly of actuators, swivel joints, and control software cable of imposing any combination of six actions (forces and moments) and six deformations (displacements and rotations) to test specimens connected to its loading platform. The testing procedure consisted of three stages: namely, initial stiffness estimation, static or gravity loading, and dynamic loading. During initial stiffness formulation, the stiffness matrix of test specimen was evaluated by imposing predefined displacements to both the experimental and analytical modules. During the static loading stage, initial gravity loads were imposed on the structure; while during the dynamic stage, earthquake loading was applied as determined through numerical time stepping employed within UI-SIMCOR.

For the experimental investigation, the Northridge earthquake record collected at the Sylmar Converter Station was selected. The original PGA of horizontal and vertical components was 0.612 and 0.586g respectively. Based upon the analytical investigation, the PGA of vertical component was scaled up to 0.734g resulting in a V/H ratio of 1.2. Figure 4.3 shows the plot of the original record. The first specimen (hereafter referred to as I01PSDH) was subjected to horizontal (longitudinal) ground motion only while the second specimen (hereafter referred to as I02PSDHV) was subjected to the combined horizontal (longitudinal) and vertical components. 80 steps were utilized in the static loading stage while a time step of 0.005 sec and a total 1600 steps (8 sec) were used for the dynamic loading stage.

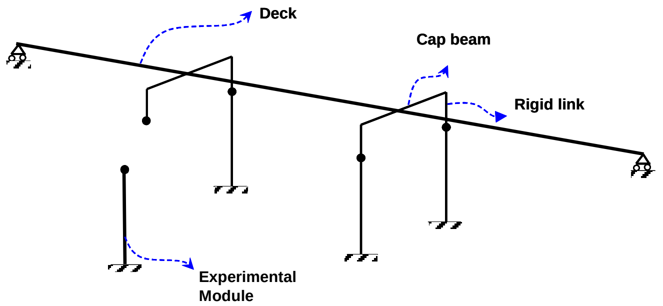


Figure 4.1 Substructure and experimental module

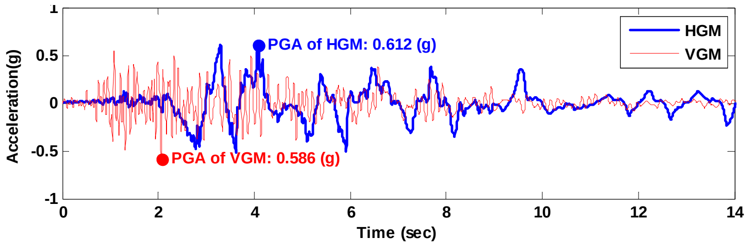


Figure 4.3 Selected ground motions for experiment

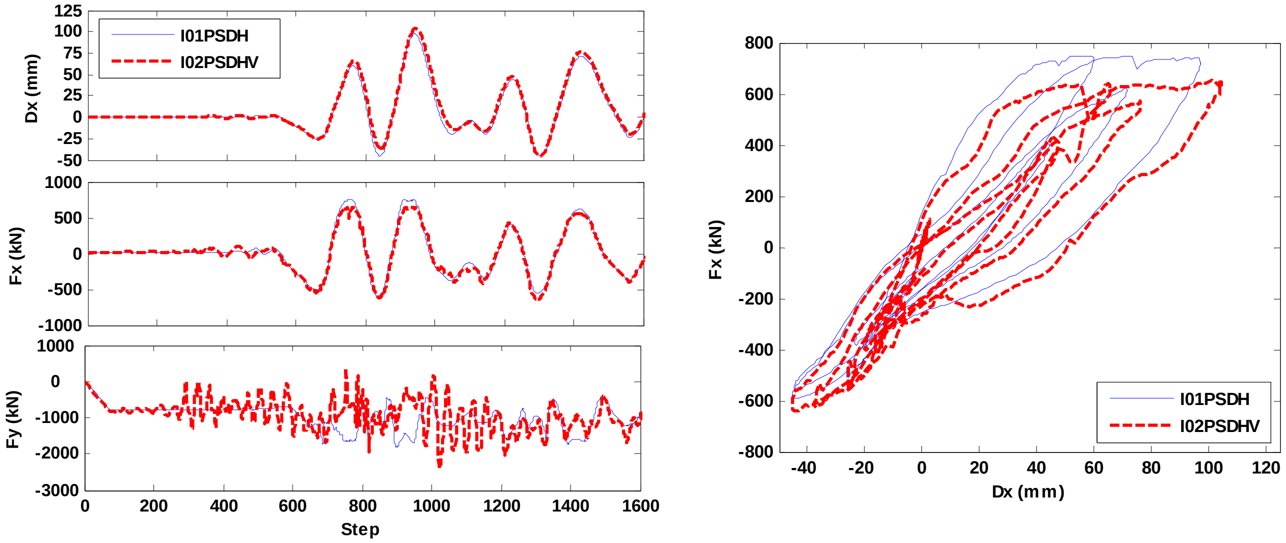
Figure 4.2 Test setup

5. EXPERIMENT RESULTS AND OBSERVATIONS

Figure 5.1 (a) and Table 5.1 compare the measured displacements and forces of specimens I01PSDH and I02PSDHV. It was observed that the vertical ground motion significantly affects the axial displacement and force resulting in corresponding changes in lateral stiffness and force. As detailed in Table 5.1, only moderate changes in the lateral displacement (increase of 6.97%) and rotation (reduction of 9.72%) were observed when vertical ground motion was included. Conversely, the effect of the vertical excitation on the axial components of response was much more notable. The maximum axial compression force increased by 31.7 % and an axial tension force, not found during testing of specimen I01PSDH, was observed. As a result, the axial force variation increased by 98.0%. The relationship between lateral force and displacement shown in Figure 5.1 (b) represents clearly the fluctuation of lateral force due to axial force. The lateral force of I01PSDH increases smoothly as displacement increases, while that of I02PSDHV shows rise and fall corresponding to fluctuations in axial force. Furthermore, it was also observed that the damage of I02PSDHV was more severe than that of I01PSDH. The observed cracking and damage shown in Figure 5.2 indicate more shear damage particularly at the mid-height of I02PSDHV.

Table 5.1 Maximum response and effect of vertical ground motion

Component	I01PSDH			I02PSDHV			Effect of VGM (%)	
	Max	Min	Variation	Max	Min	Variation	Peak response	Variation
Dx (mm)	97.7	-45.5	143.2	104.5	-45.4	149.9	6.97	4.67
Dy (mm)	7.77	-0.350	8.12	9.75	-0.600	10.36	25.4	27.5
Rz (rad)	0.00150	-0.00105	0.00256	0.00136	-0.00107	0.00243	-9.72	-5.13
Fx (kN)	749	-595	1344	653	-643	1296	-12.91	-3.60
Fy (kN)	-416	-1828	1411	388	-2410	2790	31.7	98.0
Mz (kN-m)	1067	-867	1934	970	-918	1889	-9.07	-2.37

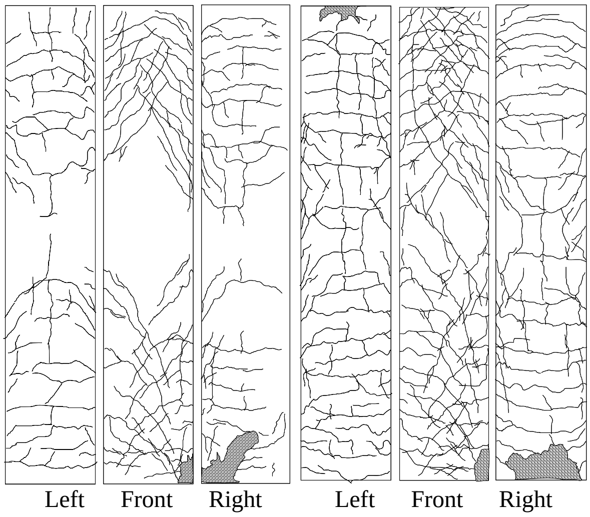


(a) Measured displacement and force history (b) Lateral displacement vs. force

Figure 5.1 Comparison of displacements and forces, I01PSDH and I02PSDHV

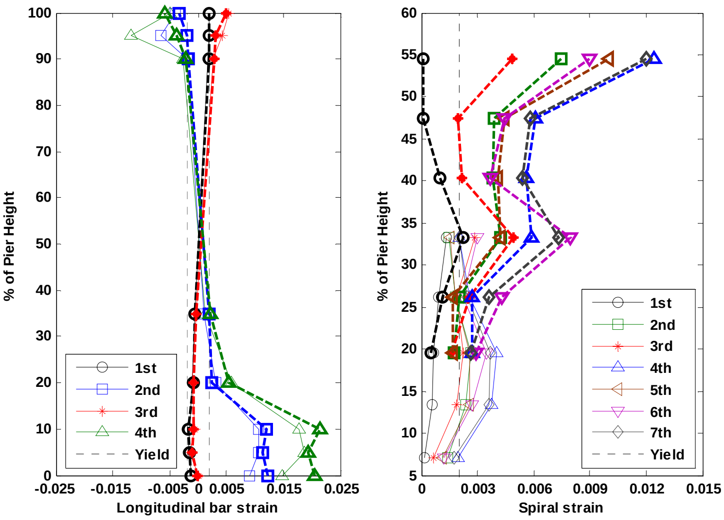
Figure 5.3 compares the longitudinal and spiral strain distribution of both piers at each lateral displacement peak. The effect of vertical ground motion on the longitudinal strain distribution shown in Figure 5.3 (a) does not appear to be significant. However, the inclusion of vertical ground motion significantly affected the spiral strain as shown in Figure 5.3 (b). The maximum spiral strains recorded from tests I01PSDH and I02PSDHV occur at the 4th horizontal peak where maximum lateral displacement for both piers was imposed. The maximum recorded strains were 0.00401 at 20% of pier height and 0.01241 at 55% of pier height for piers I01PSDH and I02PSDHV respectively. Although recorded at different locations, the maximum recorded spiral strains provide a relative measure of shear damage and, as previously reported, the maximum spiral strain increased by approximately 200% when vertical ground motion was included. Therefore, the inclusion of vertical ground motion tended to weaken the shear capacity of the pier.

Comparisons between experimental and analytical pier behavior are shown in Figure 5.4. During hybrid simulation, the analytical modules can significantly impact the imposed demands placed upon the experimental specimen. Thus, accurate and reasonable behavior in the analytical modules must be ensured. As previously noted, the analytical pier specimens were modeled using a shear spring model within Zeus-NL. Figure 5.4 shows the comparison between purely analytical predictions made prior to testing and measured data collected during hybrid simulations. For specimen I01PSDH, the errors in maximum lateral displacement and force were observed to be 1.26% and -0.23% respectively. For specimen I02PSDHV, the errors in maximum lateral displacement and force were observed to be 5.52% and -13.78% respectively. In both cases, acceptable agreement was achieved and it can be concluded that interaction between analytical and experimental modules was accurately modeled. Moreover, the agreement further validates the results from that analytical investigation previously discussed.



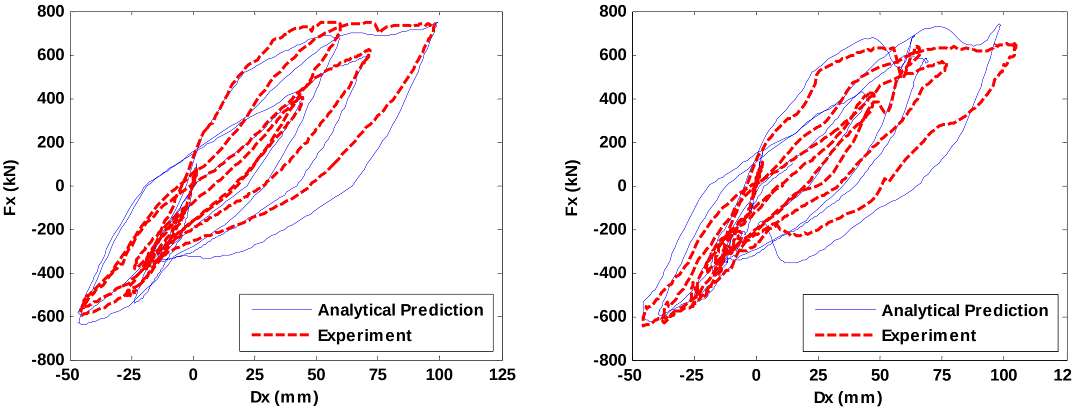
(a) I01PSDH (b) I02PSDHV

Figure 5.2 Crack comparison



(a) Longitudinal strain, left (b) Spiral strain

Figure 5.3 Strain distribution at each lateral displacement peak, Thin line: I01PSDH and thick dot line: I02PSDHV



(a) I01PSDH (b) I02PSDHV

Figure 5.4 Comparison with analytical prediction

6. CONCLUSION

The effect of vertical ground motion on RC bridge behavior was investigated analytically and experimentally. The analytical work focused on the effect of the V/H ratio and the arrival time of peak vertical and horizontal acceleration. The analysis indicates that the shear capacity of bridge piers is significantly affected by inclusion of vertical ground motion. This is especially true as the V/H ratio increases. Moreover, the arrival time is also observed to influence the shear demand and capacity. However, no clear trend between the arrival time and shear demand or capacity could be distinguished. The experimental study was conducted using hybrid simulation comprising a large scale experimental pier interacting with analytical models of the remainder of the bridge structure. The hybrid simulations results confirmed that the vertical motion can significantly affect pier behavior. The test specimen that was subjected to the combined horizontal and vertical ground motion suffered more severe damage as indicated by more extensive cracking, especially at pier mid-height, and strains in the spiral reinforcement many times higher than in the case of horizontal motion on its own.

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