Executive Summary

Seismic Performance of RC Bridge Columns with Interlocking Spirals

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APPENDIX B

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1. INTRODUCTION

Double or triple interlocking spirals as transverse reinforcement in bridge columns are being used especially in large rectangular cross sections not only because they provide more effective confinement than rectangular hoops but also because interlocking spirals make the column fabrication process easier. The behavior of columns with interlocking spirals has been studied only to a limited extent. In order to revise or possibly refine the current Caltrans design provisions, Caltrans funded a study at the University of Nevada, Reno, on the seismic behavior of interlocking spirals columns. Based on past research and Caltrans seismic design engineers' input, the most critical design parameters of RC columns with interlocking spirals were: the level of average shear stress and the horizontal distance between center to center of the spirals. In addition, effect of horizontal crossties connecting the spirals was studied.

2. OBJECTIVES

The primary objective of this research was to study the seismic performance of bridge columns with double interlocking spirals using shake table simulations. The experimental results were used in order to determine if increasing of the horizontal distance between the centers of the spirals, di, affect the overall performance of the columns when they are subjected to different levels of average shear stress. A further objective was to verify if the addition of horizontal crossties connecting the hoops can improves the overall performance of columns with interlocking spirals.

3. SUMMARY OF RESEARCH

Six large-scale column specimens were tested. The first two were of 1/4-scale with a low level of average shear stress ($3\sqrt{f'c}$, psi unit) and the other four were of 1/5-scale with high level of shear stress ($7\sqrt{f'c}$, psi unit). The models were designed using Caltrans Seismic Design Criteria (SDC-99). A target displacement ductility (μ_c) of 5 was chosen for all the columns. The average shear stress is defined as the maximum plastic shear demand divide by 0.8 times the gross area and expressed as a function of $\sqrt{f'c}$. The overall dimensions of the columns are shown in Figure B-1. The specified concrete compressive strength of the columns was 34.5 Mpa (5000 psi) and the reinforcement was of Grade 60. Table B-I summaries the relevant design parameters for all the columns.

The test setups for single curvature and double curvature columns are shown in Figure B-2. The setup in single curvature was used for the specimens with low average shear stress (ISL1.0, ISL1.5) whereas the setup in double curvature was used for the specimen with high average shear stress (ISH1.0, ISH1.25, ISH1.5 and ISH1.5T). The axial load of $0.1f'_cA_g$ was imposed through a steel spreader beam by prestressed bars to hydraulic jacks. The lateral dynamic load was applied through the inertial mass system off the table for better stability. Strain gages were used to measure the strains in the longitudinal and transverse steel. A series of curvature measurement instruments were installed in the plastic hinge zone. Displacement transducers forming panels were placed along the height of the column in the high-shear models to measure shear deformations. Load cells were used to measure both the axial and lateral forces. An additional measurement of the lateral force was taken by an accelerometer. Displacement transducers measured the lateral displacements of the columns.

Force and displacement capacities were calculated based on the plastic moment capacity of the columns from the M-ϕ analysis, using the program SPMC. The idealized elasto-plastic force and displacements were used to perform a nonlinear response history analysis of the columns with program RCShake. The Sylmar record of the Northridge (0.606 g PGA), California 1994 earthquake, was selected as the input motion based on its high displacement ductility demand. The test motions are shown in Table B-II. A time compression factor was applied to the original Sylmar record (30 seconds) in order to account for the scale factor of the models and adjustment due to inertia mass in specimens. Intermittent free vibration tests were conducted to measure the changes in frequency and damping ratio of the columns.

4. SUMMARY OF RESULTS

The seismic performance of two columns (di=1.0R and di=1.5R) subjected to low average shear stress was similar and satisfactory. The measured displacement ductility capacity in both columns exceeded the target ductility of 5. The larger horizontal distance between the centers of the spirals (di=1.5R) did not lead to excessive shear cracking or a reduction of the shear capacity when the columns are subjected to low level of shear forces. The Caltrans provision of allowing the distance to reach 1.5R is satisfactory at that low level of average shear forces.

The seismic performance of columns with di=1.0R and di=1.25R subjected to high average shear stress was similar. The measured displacement ductility capacities for both specimens were in good agreement with the target ductility of 5. Columns subjected to high average shear stress and di=1.5R did not achieve the target displacement ductility capacities of 5 but exceeded the minimum displacement ductility capacity of 3 specified in SDC. In addition, vertical cracks were observed in this column under small earthquakes. Another specimen, ISH1.5T, was built with horizontal crossties added (Fig. B-1). The crossties connecting the hoops reduced vertical cracks in the interlocking region in columns subjected to high average shear stress with di=1.5R. The spacing of the additional crossties can be taken as twice the spacing of the spirals. This spacing was calculated based on the difference between tension forces in the spirals at the middepth of the column section for column with di=1.0R and di>1.0R, assuming that the crossties and the spirals have the same bar size.

The force and displacement capacities were calculated based on the plastic moment capacity of the columns obtained from the M-ϕ curves, according to SDC-99. A comparison of the predicted lateral force-displacement and the elasto-plastic idealization of the experimental results are made in Table B-III. The prediction of the lateral force was in good agreement with the experiential results. The analytical model underestimated the yield and ultimate displacements. The addition of bond-slip and shear deformation improved the correlation with the test results.

5. TENTATIVE DESIGN RECOMMENDATIONS

The following design recommendations are for columns reinforced with interlocking spirals and they are based on the experimental results presented above.

- The average shear index should be used be used as a control design parameter to choose the horizontal distance between the centers of the spirals, d_i, and the addition of cross ties in columns reinforced with interlocking spirals.

- The shear index is calculated by dividing the average shear stress by $0.083\sqrt{f'c}$ [MPa] or $\sqrt{f'c}$ [psi]. The average shear stress is found as the ratio between the lateral force capacity and the effective shear area which is defined as the gross area multiplied by 0.8.

- The current Caltrans lower and upper limits on the horizontal distance between the centers of the spirals, d_i, of 1.0R and 1.5R, respectively, are valid subject to the requirements for additional crossties listed below.

- Where needed, horizontal crossties similar to those in ISH1.5T in Fig. B-1, should be used. The crosstie bar should be of the same size as the spiral reinforcement. A maximum spacing of 2 times the spacing of the spirals should be used for the additional horizontal ties. The ties should be detailed with a 135-deg hook in one end and a 90-deg hook at the other end. The 135-deg and 90-deg hooks should alternate in adjacent crossties.

- No cross ties are necessary in columns with shear index equal or less than 3.

- In columns with shear index between 3 and 7, crossties are recommended when d_i exceeds 1.25R.

- In columns with shear index greater than 7, crossties are recommended regardless of d_i.

- Bond slip and shear deformation should be included in the calculation of the idealized yield displacement.

- The ultimate shear deformation needs to be included in the calculation of ultimate displacement for column with aspect ratio of less than 3.0.

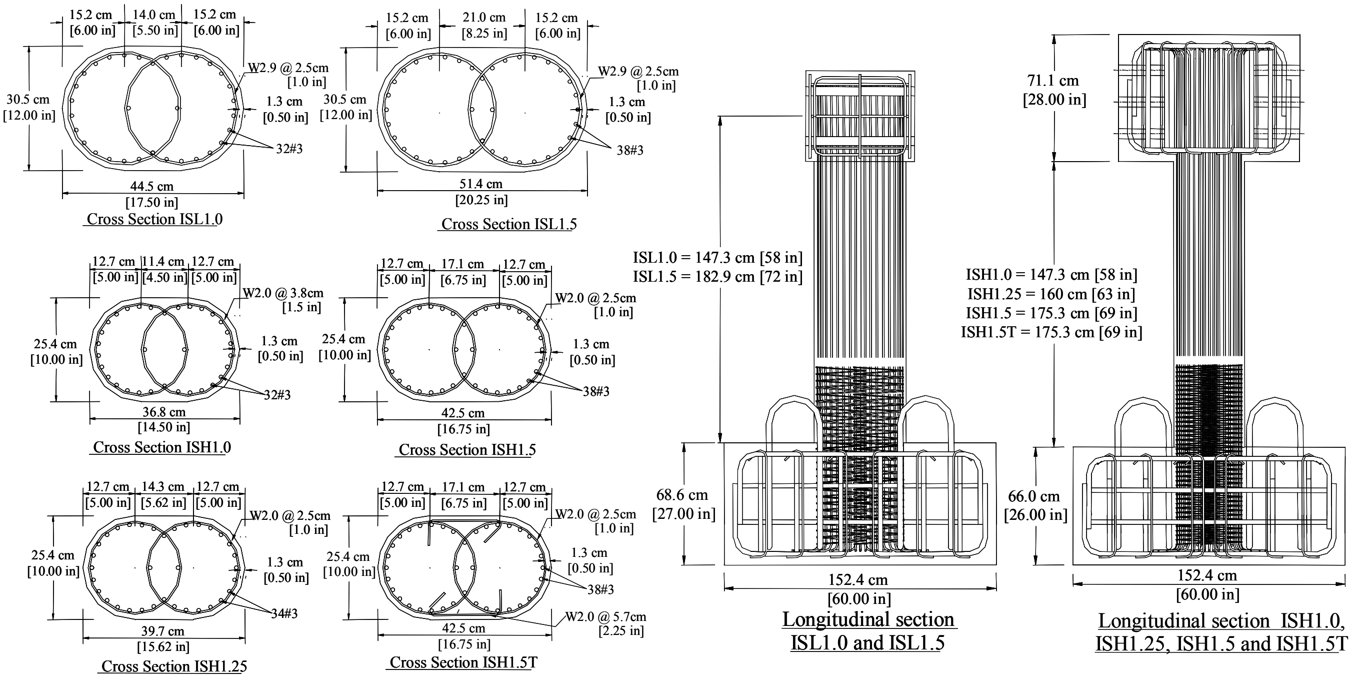

Figure B-1. Test specimens dimensions

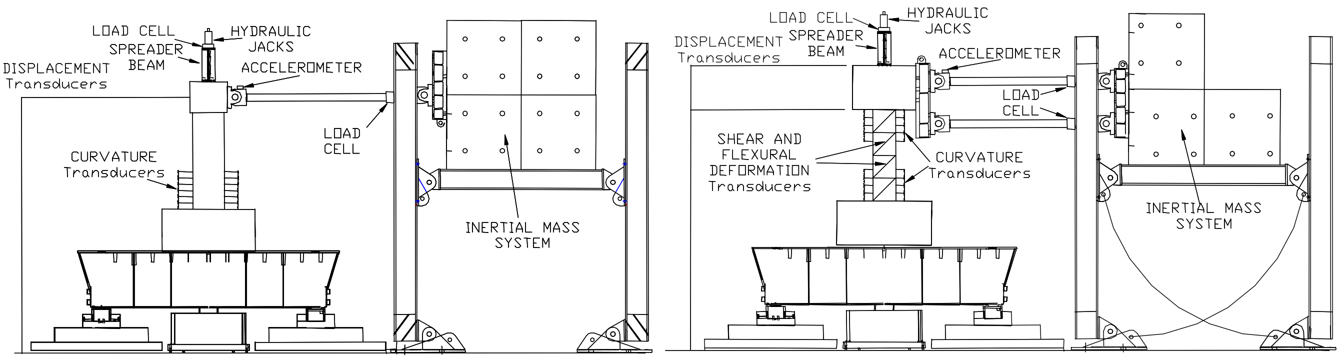

Figure B-2. Single curvature and double curvature test setup

Table B-I Design Parameter for Column Specimens

Specimen No	Aspect Ratio	di	Average shear stress as funtion of √f'c		Steel reinforcement	
					ρl	ρs
		(x R)	[MPa]	[psi]	[%]	[%]
ISL1.0	3.3	1.0	0.25	3.0	1.97	1.05
ISL1.5	3.6	1.5	0.25	3.0	1.98	1.05
ISH1.0	2.0	1.0	0.58	7.0	2.86	0.58
ISH1.25	2.0	1.25	0.58	7.0	2.79	0.87
ISH1.5	2.1	1.5	0.58	7.0	2.87	0.87
ISH1.5T*	2.1	1.5	0.58	7.0	2.87	0.87**

Note: ρl = ratio of longitudinal reinforcement
ρs = ratio of transversal reinforcement to concrete core
* = column with additional cross ties
** = steel ratio from additional cross ties is not included

Table B-II Shake Table Loading Program

	ISL1.0		**ISL1.5**		**ISH1.0**		**ISH1.25**		**ISH1.5**		**ISH1.5T**	
	Time compression factor											
	0.51		0.50		0.49		0.46		0.5		0.45	
Run No	**[g]**	**[x slymar]**	**[g]**	**[x slymar]**	**[g]**	**[x slymar]**	**[g]**	**[x slymar]**	**[g]**	**[x slymar]**	**[g]**	**[x slymar]**
1	0.06	0.1	0.06	0.1	0.06	0.1	0.06	0.1	0.06	0.1	0.06	0.1
2	0.12	0.2	0.12	0.2	0.12	0.2	0.12	0.2	0.12	0.2	0.12	0.2
3	0.18	0.3	0.24	0.4	0.24	0.4	0.30	0.5	0.24	0.4	0.24	0.4
4	0.30	0.5	0.36	0.6	0.30	0.5	0.45	0.75	0.36	0.6	0.36	0.6
5	0.45	0.75	0.48	0.8	0.45	0.75	0.61	1	0.45	0.75	0.45	0.75
6	0.61	1	0.61	1	0.61	1	0.76	1.25	0.61	1	0.61	1
7	0.76	1.25	0.76	1.25	0.76	1.25	0.91	1.5	0.76	1.25	0.76	1.25
8	0.91	1.5	0.91	1.5	0.91	1.5	1.06	1.75	0.91	1.5	0.91	1.5
9	1.06	1.75	1.06	1.75	1.06	1.75	1.21	2	1.06	1.75	1.06	1.75
10	1.21	2	1.21	2	1.21	2	1.29	2.125	1.21	2	1.21	2
11			1.29	2.125			1.36	2.25	1.29	2.125	1.29	2.125
12							1.44	2.375	1.36	2.25	1.36	2.25
13									1.44	2.375	1.44	2.375
14											1.52	2.5
15											1.59	2.625

Table B-III Comparison of SDC-Caltrans and Experimental Data

Average Shear Stress/√f'c MPa [psi]	**di [R]**	**Force Kips kN [Kips]**		**Δy mm [in]**		**Δu [in]**		**μ**	
		SDC-99 Caltrans	**Exp. Results**	**SDC-99 Caltrans**	**Exp. Results**	**SDC-99 Caltrans**	**Exp. Results**	**SDC-99 Caltrans**	**Exp. Results**
0.25 [3]	1.0	153 [34]	163 [37]	10 [0.40]	17 [0.67]	43 [1.67]	161 [6.34]	4.2	9.5
	1.5	171 [38]	168 [38]	13 [0.49]	18 [0.72]	56 [2.19]	188 [7.42]	4.4	10.4
0.58 [7]	1.0	202 [45]	228 [51]	6 [0.25]	21 [0.83]	27 [1.06]	99 [3.88]	4.2	4.7
	1.25	217 [49]	231 [52]	6 [0.22]	21 [0.83]	29 [1.16]	106 [4.15]	5.3	5.0
	1.5	199 [45]	223 [50]	10 [0.38]	32 [1.26]	38 [1.48]	128 [5.02]	3.9	4.0
	1.5T	210 [47]	235 [53]	9 [0.35]	27 [1.05]	32 [1.25]	102 [4.00]	3.6	3.8