EXPERIMENTAL STUDIES OF BRIDGE COLUMNS WITH DOUBLE INTERLOCKING SPIRALS

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Abstract

Shake table tests were conducted on six large scale concrete columns with double interlocking spirals. The primary test variables were the levels shear stress and the limits of the horizontal distance between the centers of the spirals, d_i. The tests showed that larger d_i (d_i=1.5 times the spiral radius) is satisfactory even under high shear. However, supplementary cross ties are needed to prevent premature vertical shear cracking. Design recommendation for additional horizontal cross ties were proposed based on the comparison of three methods and experimental results of the column tested in the present study.

Introduction

The Seismic Design Criteria (SDC) of the California Department of Transportation (Caltrans) [1] is the only bridge code in the United States that provides specifications to design columns with interlocking spirals. Only a limited number of experimental and theoretical studies have been conducted on interlocking spiral columns. Tanaka and Park (1993) [2], Buckingham (1993) [3], Benzoni (2000) [4] and Mizugami (2000) [5] studied the performance of columns with interlocking spirals. None of these studies included dynamic loading of the column using earthquake simulation on shake tables.

The objective of the research discussed in this article was to study the seismic performance of bridge columns with double interlocking spirals using the shake table simulations. The experimental results were used in order to determine if increasing of the 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 in function of $\sqrt{f'c}$. A further objective was to verify if the adding of horizontal cross ties connecting the hoops can improve the overall performance of the column with di of 1.5 times the radius of spirals, R.

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Column Design

Caltrans Provision

The SDC [1] denotes that a minimum element displacement ductility capacity of μ_c=3 shall be specified for columns in ductile structures.

$$\mu_c = \frac{\Delta_c}{\Delta_{y^{col}}} \tag{1}$$

The member displacement capacity, Δ_c, is determined from moment-curvature (M-ϕ) analysis with result idealized by an elasto-plastic relationship. Δ_y^{col} is the idealized effective yield displacement of the column. In the SDC [1], Δc of a cantilever member fixed at the base is defined as follows:

$$\Delta c = \Delta_y^{col} + \Delta_p \tag{2}$$

where Δ_p is the idealized plastic displacement capacity due to rotation of the plastic hinge. Δ_y^{col} and Δ_p are defined in Eq. (3) and (4), respectively.

$$\Delta_y^{col} = \frac{L^2}{3} \phi_y \tag{3}$$

$$\Delta_p = \theta_p (L - \frac{L_p}{2}) \tag{4}$$

where L = distance from the point of maximum moment to the point of contra-flexure; ϕ_y = the idealized yield curvature defined by an elasto-plastic representation of the cross section M-ϕ curve; θ_p = plastic rotation capacity ($\theta_p = L_p \phi_p$); ϕ_p = idealized plastic curvature capacity ($\phi_p = \phi_u - \phi_y$); ϕ_u = curvature capacity at the failure limit state. L_p = equivalent analytical plastic hinge length is defined as:

$$L_p = 0.08L + 0.15 f_{ye} d_{bl} \rangle 0.3 f_{ye} d_{bl} \tag{5}$$

where f_{ye}= expected yield stress for reinforcement; d_{bl} = nominal bar diameter of longitudinal column reinforcement.

Large-Scale Models

The level of shear stress was determined by the shear index. The average shear stress was calculated as the maximum measured shear force divided by 0.8 times the gross area. The shear index is found by dividing the average shear stress by 0.083 $\sqrt{f'c}$ [MPa] or $\sqrt{f'c}$ [psi]. Two 1/4 scale columns with low level of average shear stress (shear index of 3) and four 1/5 scale columns with high level of average shear stress (shear index of 7) were constructed and designed using the SDC [1]. A target displacement ductility (μ_c) of 5 was selected. The distance between the centers of adjacent spirals, di, (1.0 and 1.5 times the radius of spirals, R) was the principal variable studied in the first four specimens. The spiral spacing in these columns is the lower and upper limit in Caltrans SDC [1]. One of the remaining specimens had a di of 1.25 times R and the other one had a di of 1.5 times R with horizontal cross ties connecting the hoops. The overall dimensions of the columns are shown in Figure 1. The specified concrete compressive strength of the columns was 34.5 MPa (5000 psi) and the reinforcement was Grade 60.

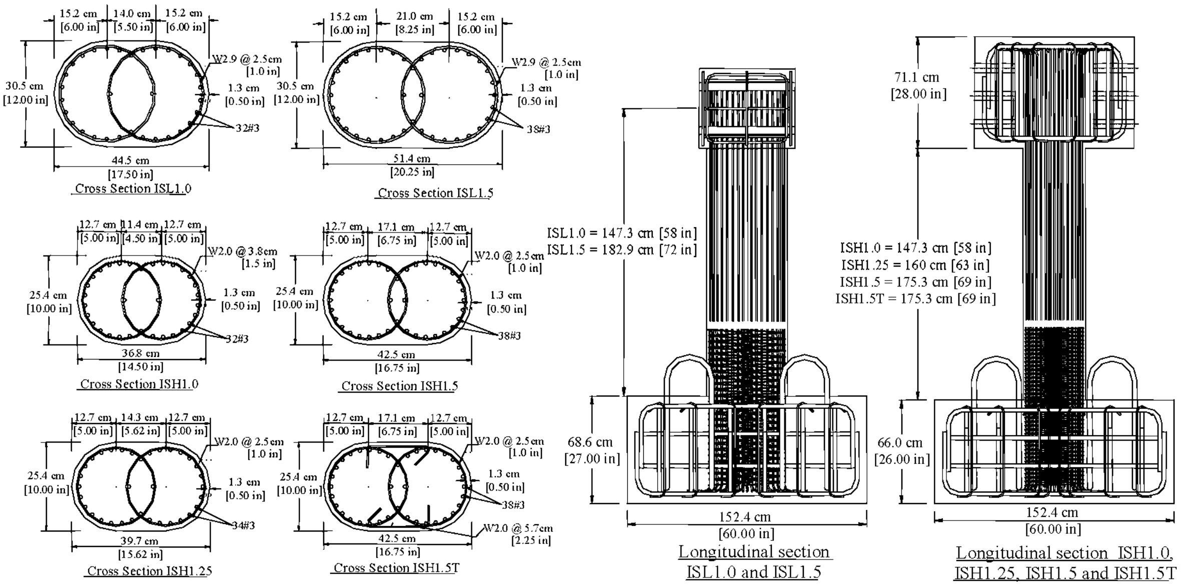

FIGURE 1. TEST SPECIMENS DIMENSIONS

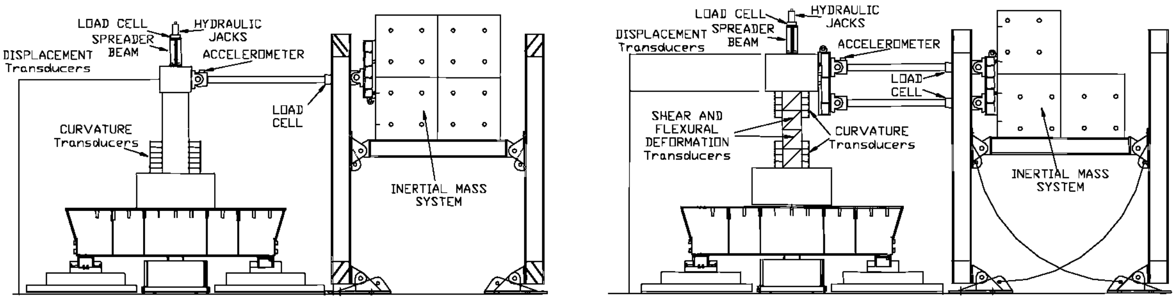

FIGURE 2. SINGLE CURVATURE AND DOUBLE CURVATURE TEST SETUP

Test Setup And Loading Procedure

The test setup for single curvature and double curvature columns is shown in Figure 2. The test setup in single curvature was used in the specimens with low average shear stress (ISL1.0, ISL1.5) whereas the test setup in double curvature was used in 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 and hydraulic jacks. The lateral 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 double curvature test, for measuring 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 capacity was calculated based on the plastic moment capacity of the columns from the M-ϕ analysis, using the program SPMC [6]. The idealized elasto-plastic force and displacement was used to perform a nonlinear response history analysis of the columns with program RCShake [7]. The Sylmar record of the 1994 Northridge, California earthquake (0.606 g PGA),, was selected as the input motion based on its high displacement ductility demand. The test motions are shown in Table I. 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.

TABLE I. LOADING MOTIONS

	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

Observed Performance

Low Average Shear Stress Columns: ISL1.0 AND ISL1.5

Flexural cracks were observed in specimen ISL1.0 during the first three runs and in specimen ISL1.5 during the first six runs. First spalling and shear cracks were formed in specimen ISL1.0 at 0.5xSylmar and specimen ISL1.5 at 1.25xSylmar. Shear cracks were located in the interlocking region near to the lower portion of the column. Considerable spalling, as well as propagation of flexural and shear cracks was observed after 1.25xSylmar in specimen ISL1.0. At 1.5xSylmar and 1.75xSlymar spirals were visible in specimens ISL1.0 and ISL1.5, respectively. There was no visible core damage. Longitudinal bars were exposed after 1.75xSylmar in specimen ISL1.0. Specimens ISL1.0 and ISL1.5 (Figure 3) failed during 2.0xSylmar (1.21g PGA) and 2.125xSylmar (1.29g PGA), respectively. The failure in both columns was due to fracturing of the spirals and buckling of the longitudinal bars.

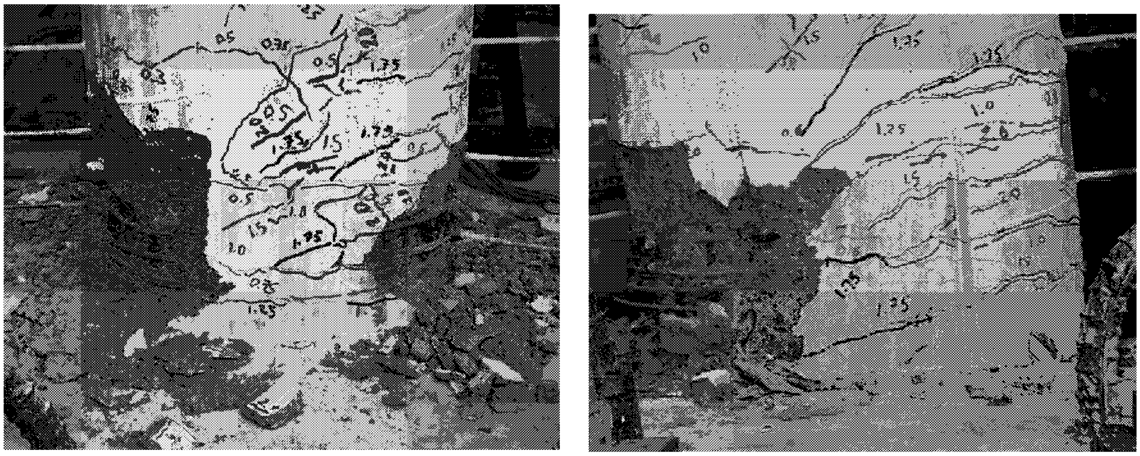

FIGURE 3. SPECIMENS ISL1.0 AND ISL1.5 AFTER COLLAPSE.

High Average Shear Stress Columns: ISH1.0, ISH1.25, ISH1.5 and ISH1.5T

During the first three runs, flexural cracks were observed in all specimens. A vertical crack located in the interlocking region along the height of the columns was visible at 0.4xSlymar (0.24g PGA) in specimen ISH1.5. First shear cracks, located in the interlocking region, were formed in the specimens ISH1.0 and ISH1.5 at 0.5xSylmar and 0.6xSylmar, respectively. For specimens ISH1.25 and ISH1.5T shear cracks appeared at 0.75xSylmar. Localized small vertical cracks were observed in specimen ISH1.5T at 1.0xSylmar. After 1.0xSylmar, first spalling was observed in specimens ISH1.0 and ISH1.5, whereas in specimens ISH1.25 and ISH1.5T, first spalling was observed at 1.25xSylmar. The spirals were visible at 1.75xSylmar in specimen ISH.125. Exposure of the longitudinal bar was observed at 1.75xSylmar in specimen ISH1.0, at 2.25xSylmar in specimen ISH1.25, at 1.5xSylmar in specimen ISH1.5 and at 2.0xSylmar in specimen

ISH1.5T. Specimens ISH1.0 and ISH.125 (Figure 4) failed in shear during 2.0xSylmar (1.21g PGA) at the bottom and 2.375xSylmar (1.44g PGA) at the top, respectively. Damage in the core was observed in specimens ISH1.5 and ISH1.5T after 2.125xSylmar. Buckling of the longitudinal bars was visible after 2.25xSylmar for specimen ISH1.5 and after 2.375xSylmar for specimen ISH1.5T. Specimen ISH1.5 and ISH.5T (Figure 5) failed during 2.375xSylmar and 2.625xSylmar, respectively. Failure in specimen ISH1.5 was due to fracturing of the spirals and buckling of the longitudinal bars whereas in specimen ISH1.5T, it was due to fracturing of the spirals and one of the longitudinal bars.

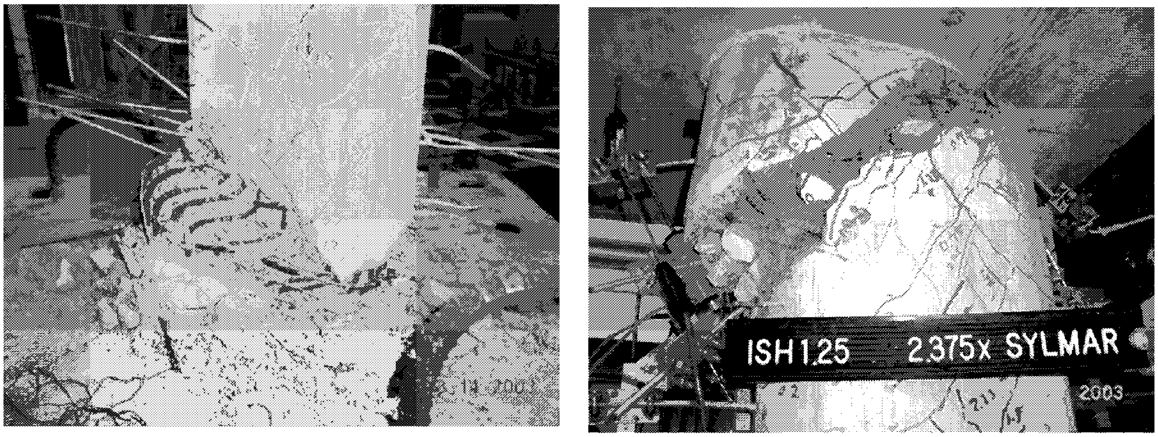

FIGURE 4. SPECIMENS ISH1.0 AND ISH1.25 AFTER COLLAPSE.

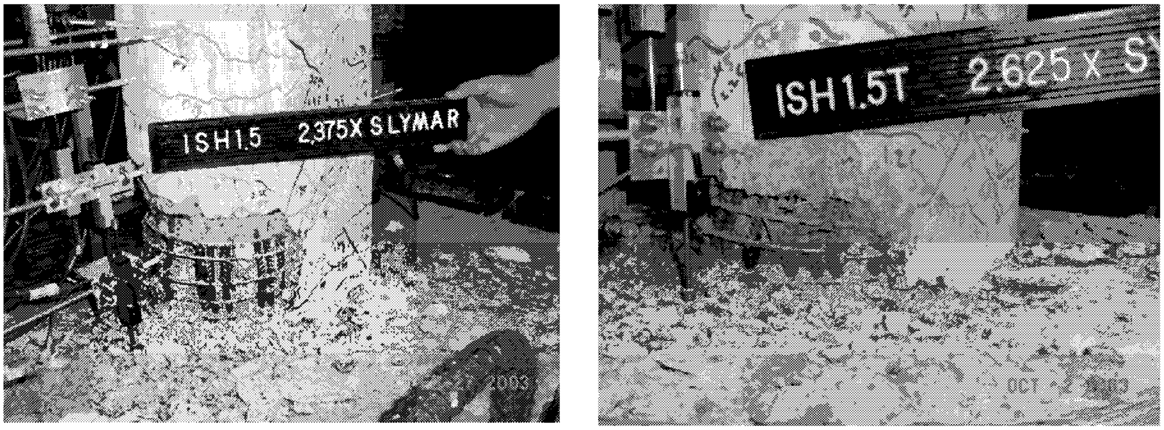

FIGURE 5. SPECIMENS ISH1.5 AND ISH1.5T AFTER COLLAPSE.

Measured Performance

Low Average Shear Stress Columns: ISL1.0 AND ISL1.5

The measured hysteretic curves, for specimens ISL1.0 and ISL1.5, are shown in Figure 4 and 5, respectively. The maximum force reached in the specimen ISL1.0 was 169 kN (38 Kips) whereas in ISL1.5 it was 180 kN (40 Kips). Specimens ISL1.0 and ISL1.5 had a maximum displacement of 161 mm (6.34 in) and 216 mm (8.52 in), respectively. The envelope curve and idealized elasto-plastic model, for the predominant direction of the motion, are plotted in Figure 4 for specimen ISL1.0 and Figure 5 for ISL1.5. The ultimate displacement of 188 mm (7.42 in) for ISL1.5 was taken as the corresponding displacement of 80% of the maximum force. Based on the elasto-plastic model ductility displacement capacity of 9.5 and 10.4 was achieved for the specimens ISL1.0 and ISL1.5, respectively. In addition, similar stiffnesses of 9634 N/mm (55 Kips/in) for ISL1.0 and 9282 N/mm (53 Kips/in) for ISL1.5 were calculated from the elasto-plastic model.

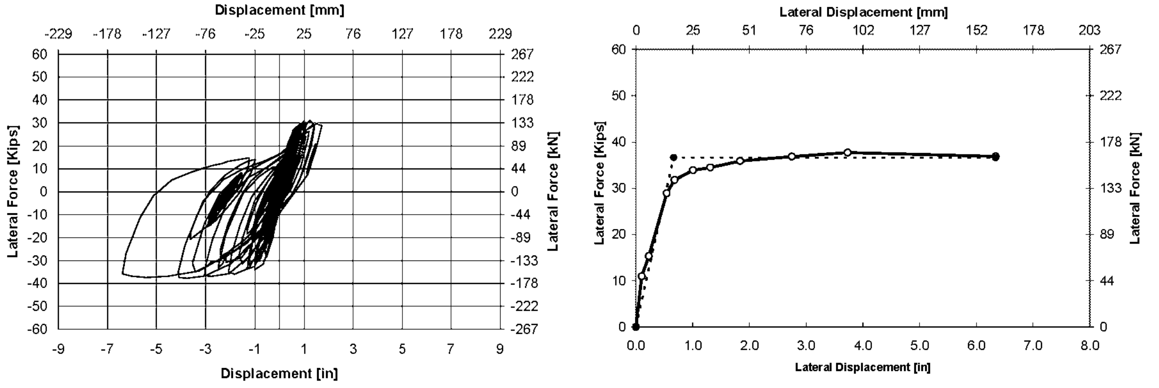

FIGURE 4. HYSTERETIC CURVE AND ENVELOPE ISL1.0

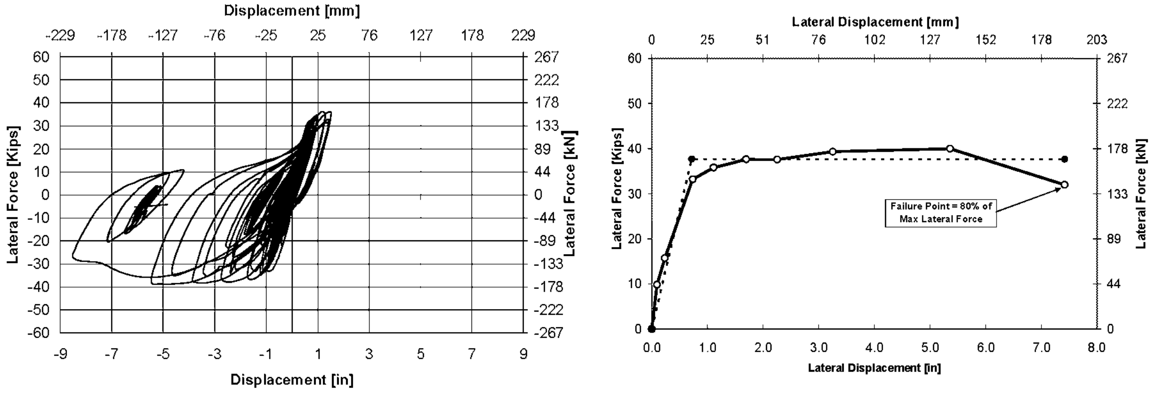

FIGURE 5. HYSTERETIC CURVE AND ENVELOPE SPECIMEN ISL1.5.

High Average Shear Stress Columns: ISH1.0, ISH1.25, ISH1.5 and ISH1.5T

Figures 6, 7, 8 and 9 show the measured hysteretic curves and the envelope curves with idealized elasto-plastic models, for specimens ISH1.0, ISH1.25, ISH1.5 and ISH1.5T, respectively. The maximum force recorded in specimen ISH1.0 was 241 kN (54.25 Kips) and the maximum force for ISH1.25 was 251 kN (56.47 Kips). For specimens ISH1.5 and ISH1.5T the maximum force was 247 kN (55.56 Kips) and 251 kN (56.48 Kips), respectively. Maximum displacements of 108 mm (4.24 in), 105 mm (4.15 in), 128 mm (5.05 in) and 101 mm (4.0 in) were achieved in specimens ISH1.0, ISH1.25, ISH1.5 and ISH1.5T, respectively. For the envelope curves, the corresponding displacement of 80% of the maximum force was taken as the ultimate displacement in specimens ISH1.0, ISH1.25 and ISH1.5. According to the elasto-plastic models, ductility displacement capacities of 4.7, 5.0, 4.0 and 3.8 were achieved for the specimens ISH1.0, ISH1.25, ISH1.5 and ISH1.5T, respectively. Furthermore, stiffnesses of 10808 N/mm (62 Kips/in), 10972 N/mm (63 Kips/in), 6949 N/mm (40 Kips/in) and 8810 N/mm (50 Kips/mm) for specimens ISH1.0, ISH1.25, ISH1.5 and ISH1.5T were calculated from the elasto-plastic model.

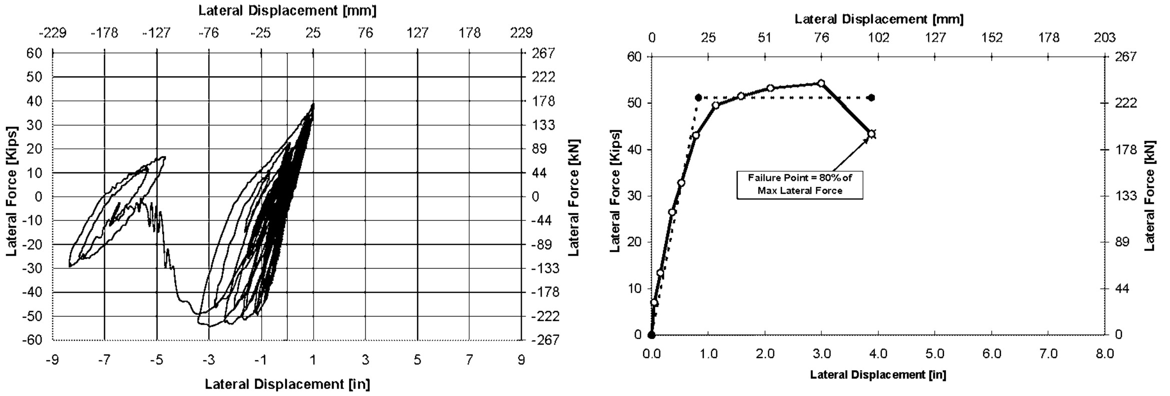

FIGURE 6. HYSTERETIC CURVE AND ENVELOPE SPECIMEN ISH1.0.

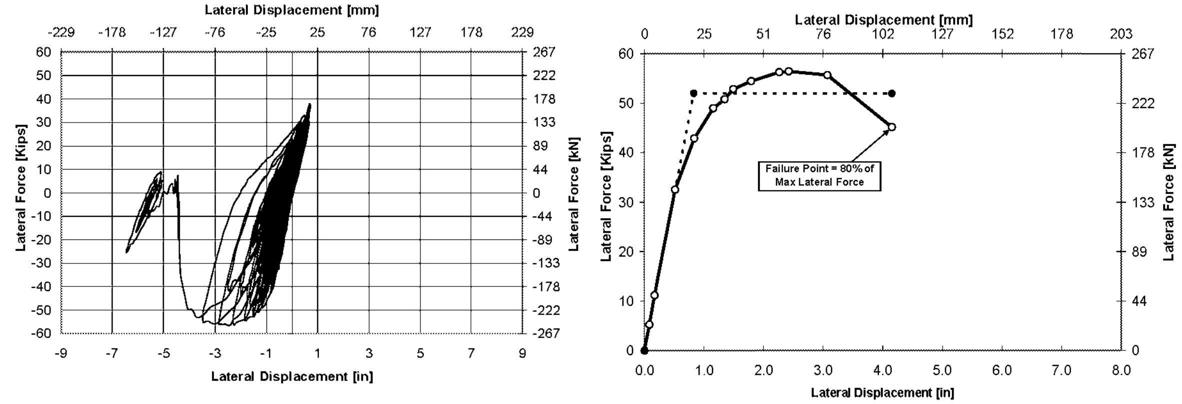

FIGURE 7. HYSTERETIC CURVE AND ENVELOPE SPECIMEN ISH1.25.

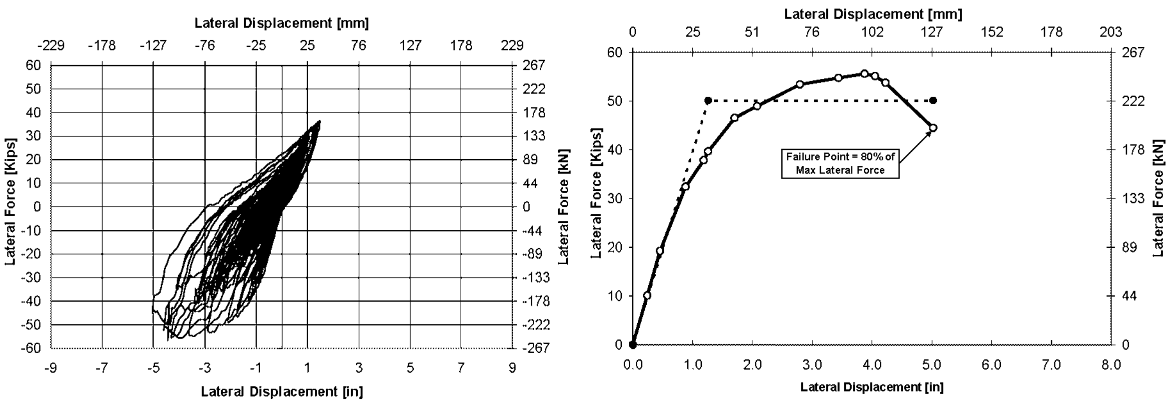

FIGURE 8. HYSTERETIC CURVE AND ENVELOPE SPECIMEN ISH1.5.

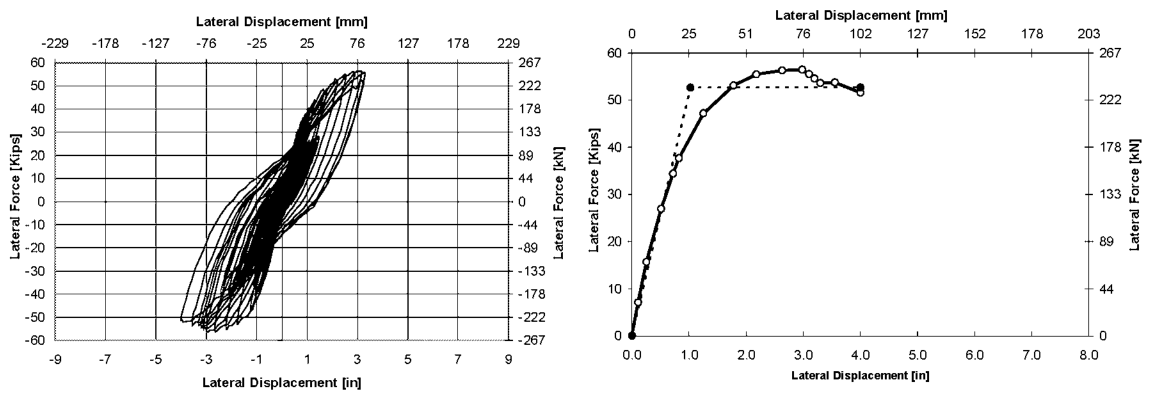

FIGURE 9. HYSTERETIC CURVE AND ENVELOPE SPECIMEN ISH1.5T.

Design Recommendation For Cross Ties

Based on the observed performance of specimens with high shear, vertical cracks located in the interlocking region were observed in the specimen with d_i of 1.5R at about 58 % of the maximum force. Three methods were studied to provide background for to the design of horizontal cross ties. The first method was based on the shear reinforcement capacity defined in SDC [1], taking into account the component of the spiral tension force at the middepth of the column section in the direction of the shear force. The second method was based on the equilibrium of the horizontal spiral force at the middepth of the column section. In these two methods a column with d_i of 1.0R was taken as the reference point for design the cross ties for columns with $d_i >$ 1.0R, based on the satisfactory seismic performance for columns with d_i of 1.0R. The shear–friction concept was the third method used to find the area of cross ties needed in the interlocking region to resist the vertical shear at middepth of the section. Based on the comparison of the three methods presented in reference [8], the individual cross tie bars should be of the same size as the spiral reinforcement with a maximum spacing of 2 times the spacing of the spirals. Horizontal ties should be detailed with 135° hook in one end and 90° hook in the other. Table II summarizes the design recommendation for cross ties based on the level of the shear stress (shear index).

TABLE II. DESIGN RECOMMENDATION FOR CROSS TIES

Shear Index	**di**	**Cross Ties**
<3	1.0R-1.5R	No
3 to 7	1.0R-1.25R	No
	>1.25R	Yes
7>	1.0R-1.5R	Yes

Conclusions

Based on the interpretation of the experimental results presented in this article the following conclusions were made for bridge columns with double interlocking spirals:

1. The seismic performance of two columns (ISL1.0 and ISL1.5) subjected to low average shear stress was similar and satisfactory. The measured displacement ductility capacity of 9.5 and 10.4 in columns ISL1.0 and ISL1.5 exceeded the target ductility of 5.

2. The larger distance between the centers of the spirals in ISL1.5 did not lead to excessive shear cracking or a reduction of the shear capacity, when the column is 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.

3. The seismic performance of columns ISH1.0 and ISH1.25 subjected to high average shear stress was similar. The measured displacement ductility capacities for both specimens were in good agreement to the target ductility of 5.

4. Specimens ISH1.5 and ISH1.5T did not achieve the target displacement ductility capacities of 5 but exceeded the minimum specified displacement ductility capacity of 3, according to SDC [1].

5. Considerable reduction of displacement ductility capacities was obtained in the columns subjected to high average shear stress, compared to columns subjected to low average shear stress.

6. Vertical cracks were observed in the specimen ISH1.5 with high average shear stress at about 58 % of the maximum force. Horizontal cross ties connecting the hoops (ISH1.5T) reduced vertical cracks in the interlocking region.

Acknowledgement

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