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A structural assessment and qualification-testing program, coupled with a complementary material testing program, were conducted. In order to verify the performance of reinforced concrete bridge columns retrofitted with advanced composite material jackets, cyclic testing of column samples was carried out at the University of California, Irvine, Structural Test Hall. Twenty-seven half-scale, circular and rectangular columns, with and without lap splices, were built and tested under cyclic loading in both single and double bending configurations. Six different jacket systems were evaluated. All tests conformed to Caltrans guidelines for the Pre-qualification Requirements for Alternative Column Casings for Seismic Retrofit.

The behavior of the retrofitted columns was predicted by available analytical models. The accuracy of such models was assessed by direct comparison of the experimental and theoretical results. This study has demonstrated that advanced composite material jackets can significantly improve the ductility of rectangular and circular columns with insufficient shear strength, and only the ductility of circular columns with insufficient lap splice length.

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FINAL REPORT TO
THE CALIFORNIA DEPARTMENT OF TRANSPORTATION

STRUCTURAL QUALIFICATION TESTING OF COMPOSITE-JACKETED CIRCULAR AND RECTANGULAR BRIDGE COLUMNS

RTA – 59A0005

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DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

UNIVERSITY OF CALIFORNIA, IRVINE

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The damage and collapse of highway bridges during recent destructive earthquakes has demonstrated that reinforced concrete bridge columns designed and constructed using older design specifications may suffer from lack of sufficient shear reinforcement and/or sufficient lap splice length. This summary report presents an experimental and analytical study on the seismic retrofit of half-scale bridge columns using advanced composite-material (carbon or glass fiber) jackets.

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The structural testing program was funded from several sources: the Federal Highway Administration (FHWA) contract #DTFH71-95-PTP-CA-32 through the California Department of Transportation (Caltrans), the Society for Advancement of Materials and Process Engineering (SAMPE), and the manufacturers of the composite jackets: Mitsubishi Chemical, Obyashi, Tonen, Myers Technologies, Hexcel-Fyfe, Master Builders, and Hardcore Dupont.

This program was supervised by Mr. Mohsen Sultan of Caltrans, as Program Manager. Support for this testing program was attained by Mr. Roland Nimis, Regional Structural Engineer. These tests were monitored by Mr. Lihong Sheng of Caltrans. The composite materials were supplied and installed by the manufacturers of the composite jackets. The material data were provided by the Aerospace Corporation.

The construction and testing of the column samples in this study were carried out by Hussain Bhatia, Kevin Baird, Hisham Nofal, Hussein Elsanadedy, and Carla Yland, with the help of Daniel Del Carlo, David Larsen, and others from the UC Irvine Structural Test Hall. The experimental testing program was supervised by Senior Development Engineer, Robert Kazanjy.

ABSTRACT

The damage and collapse of highway bridges during recent destructive earthquakes has demonstrated that reinforced concrete bridge columns designed and constructed using older design specifications may suffer from lack of sufficient shear reinforcement and/or sufficient lap splice length. This summary report presents an experimental and analytical study on the seismic retrofit of half-scale bridge columns using advanced composite-material (carbon or glass fiber) jackets.

A structural assessment and qualification-testing program, coupled with a complementary material testing program, were conducted. In order to verify the performance of reinforced concrete bridge columns retrofitted with advanced composite material jackets, cyclic testing of column samples was carried out at the University of California, Irvine, Structural Test Hall. Twenty-seven half-scale, circular and rectangular columns, with and without lap splices, were built and tested under cyclic loading in both single and double bending configurations. Six different jacket systems were evaluated. All tests conformed to Caltrans guidelines for the Pre-qualification Requirements for Alternative Column Casings for Seismic Retrofit.

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Chapter 1

INTRODUCTION

Existing reinforced concrete bridge columns designed and constructed according to older seismic design provisions may suffer from the following potential problems:

- Insufficient Lap Splice Length: Lap Splices were often used to extend the longitudinal steel of the columns. Typically, the length of lap splices was equal to 20 times the bar diameter, and the transverse reinforcement was provided by hoops spaced at every 12 inches. The low confinement steel ratio may not provide the necessary restraint for the rebars to develop their full strength throughout the lap splice zone due to debonding and slip. Accordingly, such columns may have unreliable flexural capacity.

- Insufficient Shear Strength: Columns with continuous longitudinal steel bars may still have problems due to insufficient confinement reinforcement and shear reinforcement. Such columns may not exhibit enough ductility to dissipate the earthquake energy and may become vulnerable to failure by buckling of the longitudinal steel, concrete crushing, and shear failure.

Proven as an effective technology for alleviating these problems and for enhancing the seismic performance of old bridge columns, steel jacketing has been widely implemented for their seismic retrofit. Recently, advanced composite materials have shown great potential to becoming a viable alternative to steel jackets. The light weight, high strength, corrosion resistance, and more importantly the ease of installation make such materials most suitable for retrofitting bridge columns. Carbon fiber systems are generally applied to columns either by hand-lay operations or by using filament winding techniques. E-glass systems are prefabricated shells manufactured in the factory and bonded to the column on site. All retrofit systems are essentially passive systems in which the overwrap is not under any significant stress until an earthquake occurs. Their effectiveness in enhancing the seismic resistance of bridge columns depends upon confinement of the column concrete.

In order to examine and qualify the seismic performance of bridge columns retrofitted with composite material jackets, an experimental structural qualification study was conducted at the University of California, Irvine, on both circular and rectangular columns. Columns with lap splices were tested in flexure to evaluate the effectiveness of the composite jackets on the enhancement of lap splice clamping, while columns with continuous longitudinal steel were tested for shear enhancement in a fixed-fixed condition. In addition, environmental durability of the proposed composite casing materials were evaluated by the Aerospace Corporation.

The structural assessment program involved the testing of 27 half-scale columns. The Caltrans contract called for the testing of twelve columns divided between lap splice enhancement of circular columns and shear enhancement of rectangular columns. Additional support was also received from individual manufacturers for more column testing. Altogether, there were 27 samples tested as follows:

- Nine circular columns were tested in single bending for lap splice enhancement; two of them were as-built columns, and seven were retrofitted with different composite jacket systems.

- Five circular columns were tested for shear enhancement; two as-built columns, and three retrofitted columns with composite jacket systems.

- Six square columns were tested in single bending for lap splice enhancement; two of them were as-built columns, and four were retrofitted columns with different composite jacket systems.

- Seven rectangular columns were tested for shear enhancement; one as-built column, and six retrofitted columns with composite jacket systems. This category of tests was only supported by the Caltrans/Federal Highway project.

Table 1.1 provides a list of all tested columns. Note that the names of the manufacturers of the composite jackets are withheld. Throughout the report, reference is only made to the assigned sample identification number shown in Table 1.1, such as CF-3, RF-5,.. etc. It should be noted that the letters "C" and "R" denote circular and rectangular columns, respectively, and the letters "F" and "S" denote flexure and shear testing, respectively.

Table 1.1: Identification Codes for Tested Columns

Manufacturer	Identification Code	Support Source
Shear Testing of Circular Columns		
As-built	CS-1	Other
	CS-2	Other
	CS-3	Other
As-built	CS-4	Other
	CS-5	Other
Flexural Testing of Circular Columns		
As-built	CF-1	Caltrans/FHWA
As-built	CF-2	Other
	CF-3	Other
	CF-4	Other
	CF-5	Caltrans/FHWA
	CF-6	Caltrans/FHWA
	CF-7	Caltrans/FHWA
	CF-8	Caltrans/FHWA
	CF-9	Other
Flexural Testing of Rectangular Columns		
As-built	RF-1	Other
	RF-2	Other
	RF-3	Other
As-built	RF-4	Other
	RF-5	Other
	RF-6	Other
Shear Testing of Rectangular Columns		
As-built	RS-1	Caltrans/FHWA
	RS-2	Caltrans/FHWA
	RS-3	Caltrans/FHWA
	RS-4	Caltrans/FHWA
	RS-5	Caltrans/FHWA
	RS-6	Caltrans/FHWA
	RS-7	Caltrans/FHWA

Chapter 2

TEST SPECIMENS

2.1 Column Designs

Four different column designs were built to approximately half of the scale of those existing in the field. All columns were designed and built to conform to the Caltrans Pre-qualification Requirements for Alternative Column Casings for Seismic Retrofit (Composites) [Caltrans, 1997].

2.1.1 Shear Enhancement Circular Columns

The shear enhancement circular columns were built with a column height of 8′, and with a circular section 24″ in diameter. The longitudinal reinforcement is continuous from the footing, through the column, to the top box. The dimensions and rebar configuration are shown in Figure 2.1. Physical properties of the first three columns are given in Table 2.1 and those for the last two columns are given in Table 2.2. The as-built and retrofitted columns were constructed at the same time with identical dimensions and material properties.

Table 2.1: Physical Properties of First Three Shear Enhancement Circular Columns

Diameter of section (in)	24.0
Height (in)	96.0
Yield stress of longitudinal steel (ksi)	43.41
Number of main longitudinal bars	20
Size of main longitudinal bars	6
Clear cover to confinement steel (in)	0.75
Size of confinement steel	2
Yield stress of confinement steel (ksi)	30.5
Spacing of confinement steel (in)	5.0

Table 2.2: Physical Properties of Last Two Shear Enhancement Circular Columns

Diameter of section (in)	24.0
Height (in)	96.0
Yield stress of longitudinal steel (ksi)	64.36
Number of main longitudinal bars	20
Size of main longitudinal bars	6
Clear cover to confinement steel (in)	0.75
Size of confinement steel	2
Yield stress of confinement steel (ksi)	30.5
Spacing of confinement steel (in)	5.0

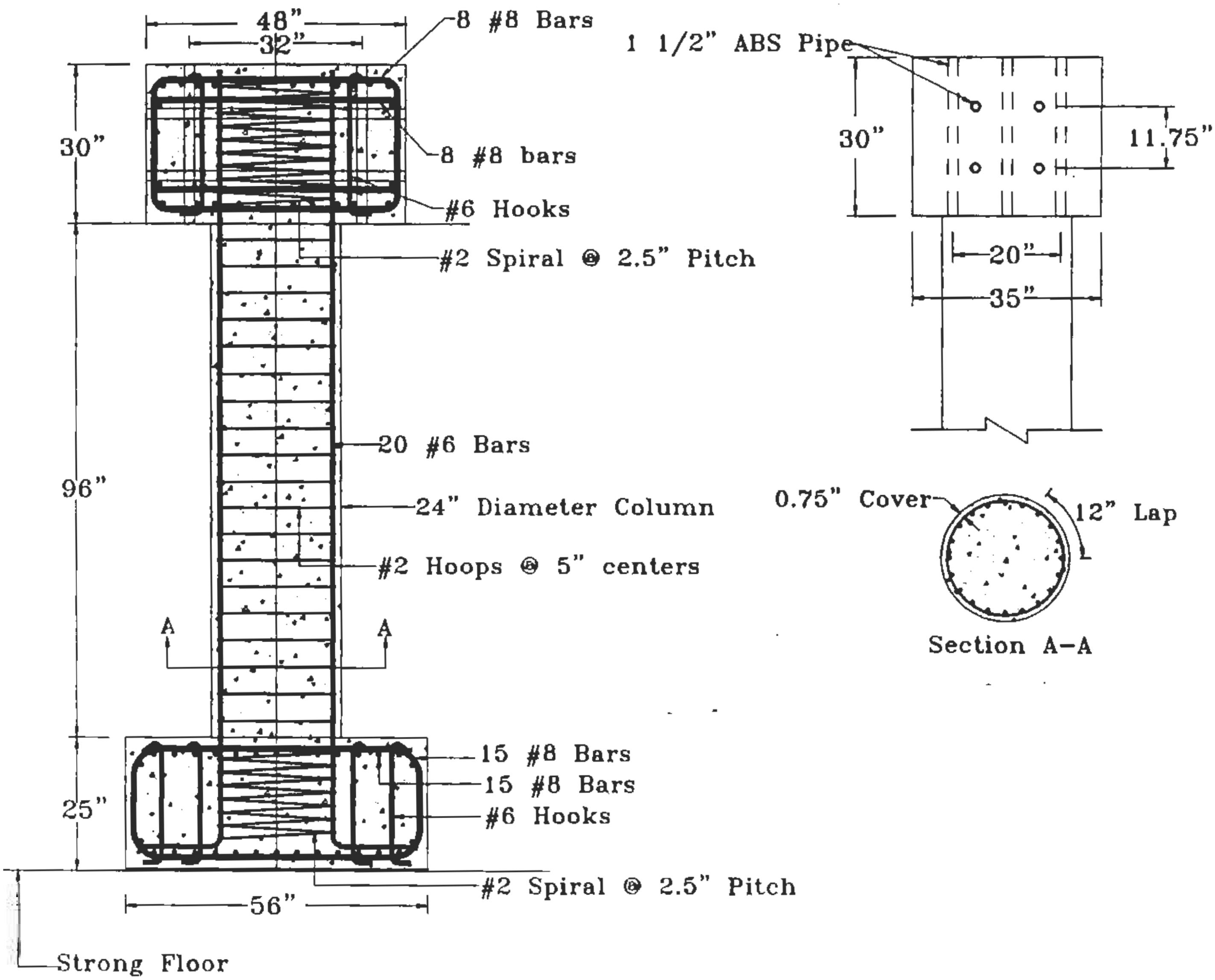

Figure 2.1: Reinforcement Details for Shear Enhancement Circular Columns

2.1.2 Lap Splice Enhancement Circular Columns

The lap splice enhancement circular columns were built with a column height of 12′ high, and with a circular cross section 24″ in diameter. The longitudinal reinforcement has 15″ lap splices at the column base. The dimensions and rebar configuration are shown in Figure 2.2. Physical properties of the columns are given in Table 2.3. The as-built and four of the five retrofitted columns were constructed at the same time with the same concrete batch. The last column was poured with a different batch of the same concrete strength. The as-built and retrofitted columns have identical dimensions and material properties.

Table 2.3: Physical Properties of Lap Splice Enhancement Circular Columns

Diameter of section (in)	24.0
Height (in)	144.0
Yield stress of longitudinal steel (ksi)	43.41
Number of main longitudinal bars	20
Size of main longitudinal bars	6
Clear cover to confinement steel (in)	0.75
Size of confinement steel	2
Yield stress of confinement steel (ksi)	30.5
Spacing of confinement steel (in)	5.0

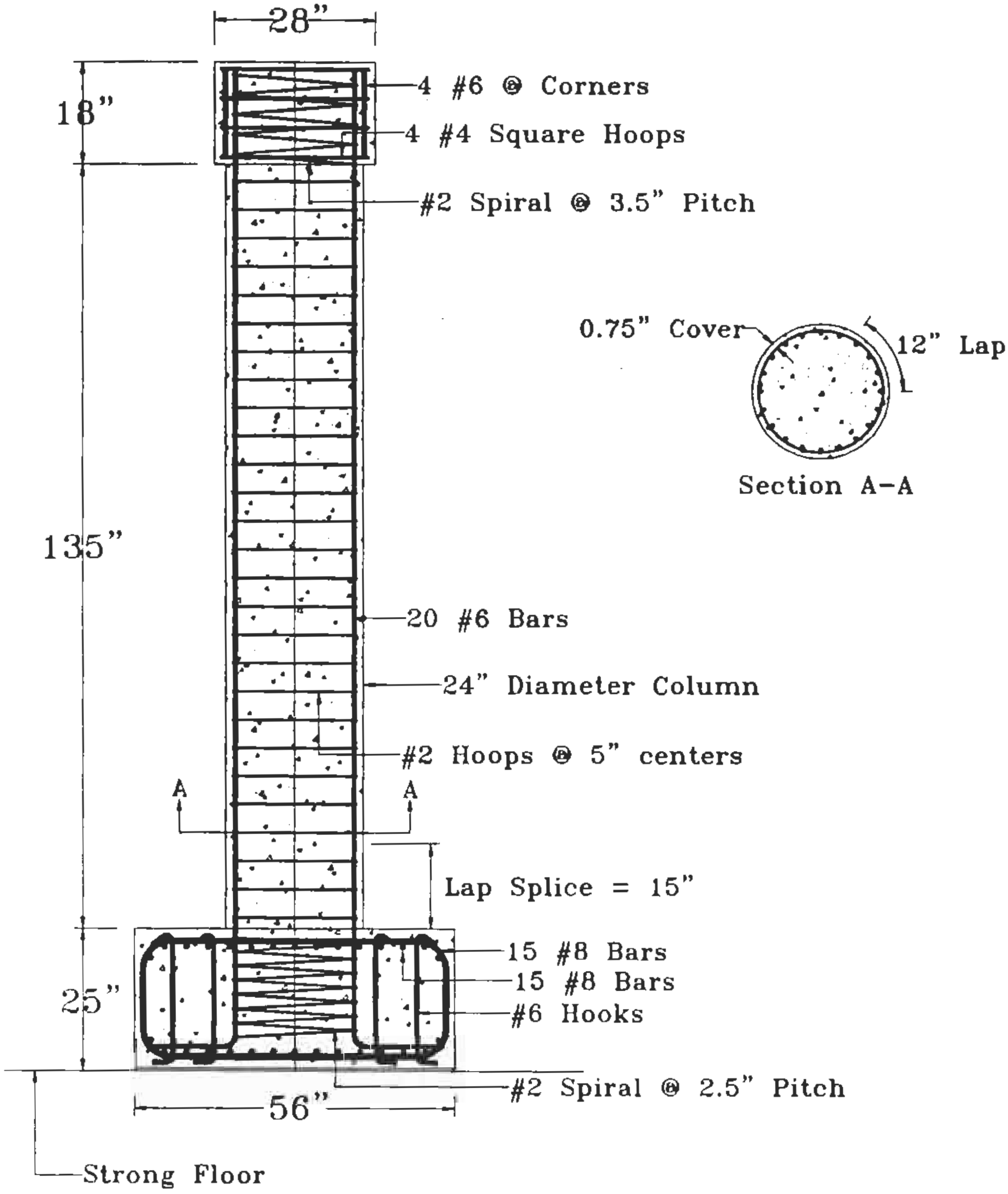

Figure 2.2: Reinforcement Details for Lap Splice Enhancement Circular Columns

2.1.3 Lap Splice Enhancement Rectangular Columns

The lap splice enhancement rectangular columns were built with a column height of 12′, and with a 24″ × 24″ square cross section. The longitudinal reinforcement has 15″ lap splices at the base of the column. The dimensions and rebar configuration are shown in Figure 2.3. Physical properties of the columns are given in Table 2.4. The as-built and retrofitted columns were constructed at the same time with identical dimensions and material properties.

Table 2.4: Physical Properties of Lap Splice Enhancement Rectangular Columns

Depth of section (in)	24.0
Width of section (in)	24.0
Height (in)	144.0
Yield stress of longitudinal steel (ksi)	64.36
Number of main longitudinal bars	28
Size of main longitudinal bars	6
Clear cover to confinement steel (in)	0.75
Size of confinement steel	2
Yield stress of confinement steel (ksi)	64.27
Spacing of confinement steel (in)	5.0

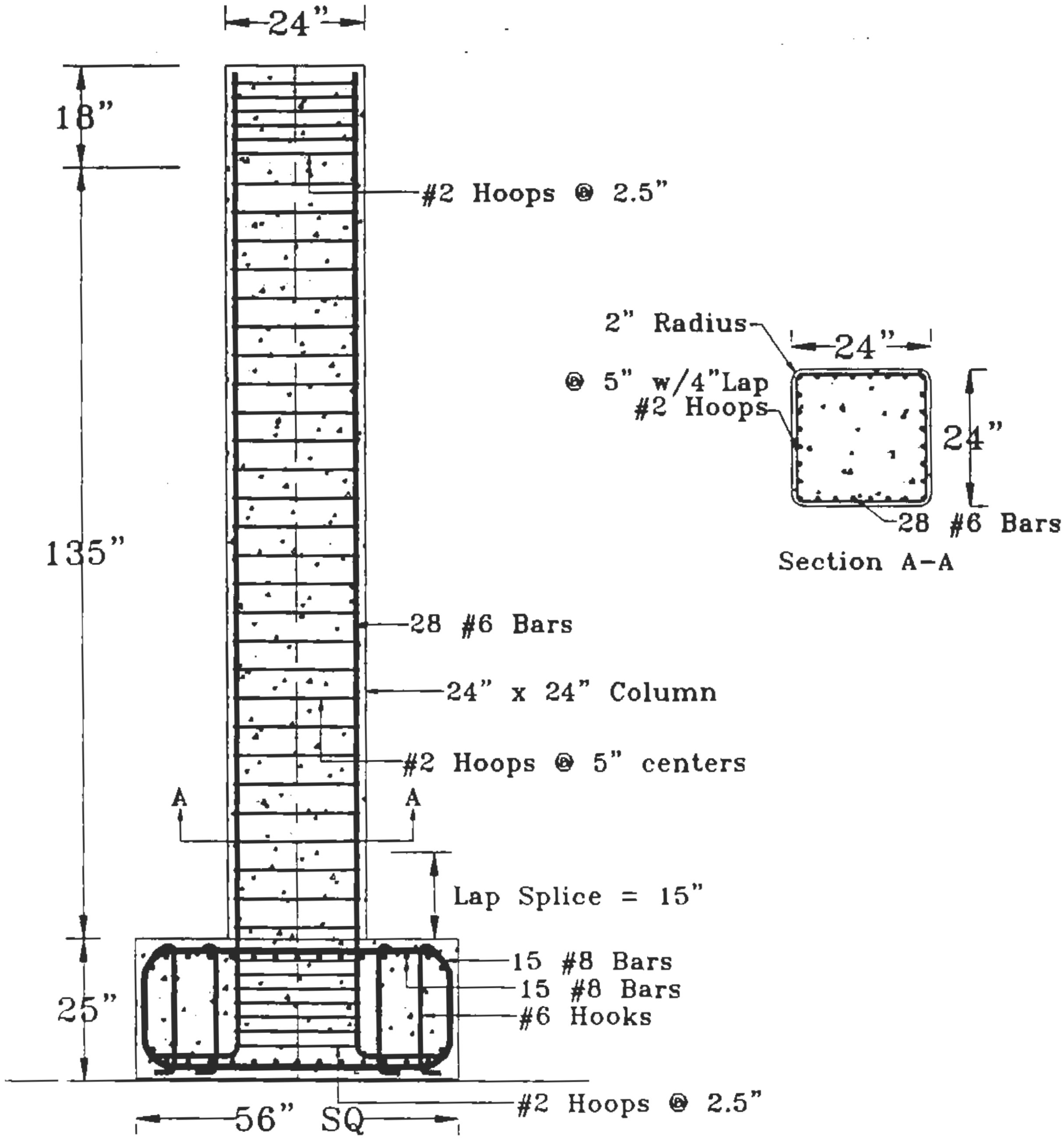

Figure 2.3: Reinforcement Details for Lap Splice Enhancement Rectangular Columns

2.1.4 Shear Enhancement Rectangular Columns

The shear enhancement rectangular columns were built with a column height of 8′, and with an 18″ × 24″ rectangular cross section. The longitudinal reinforcement is continuous from the footing, through the column, to the top box. The dimensions and rebar configuration are shown in Figure 2.4. Physical properties of the columns are given in Table 2.5. The as-built and retrofitted columns were constructed at the same time with identical dimensions and material properties.

Table 2.5: Physical Properties of Shear Enhancement Rectangular Columns

Depth of section (in)	24.0
Width of section (in)	18.0
Height (in)	96.0
Yield stress of longitudinal steel (ksi)	43.41
Number of main longitudinal bars	20
Size of main longitudinal bars	6
Clear cover to confinement steel (in)	0.75
Size of confinement steel	2
Yield stress of confinement steel (ksi)	30.5
Spacing of confinement steel (in)	5.0

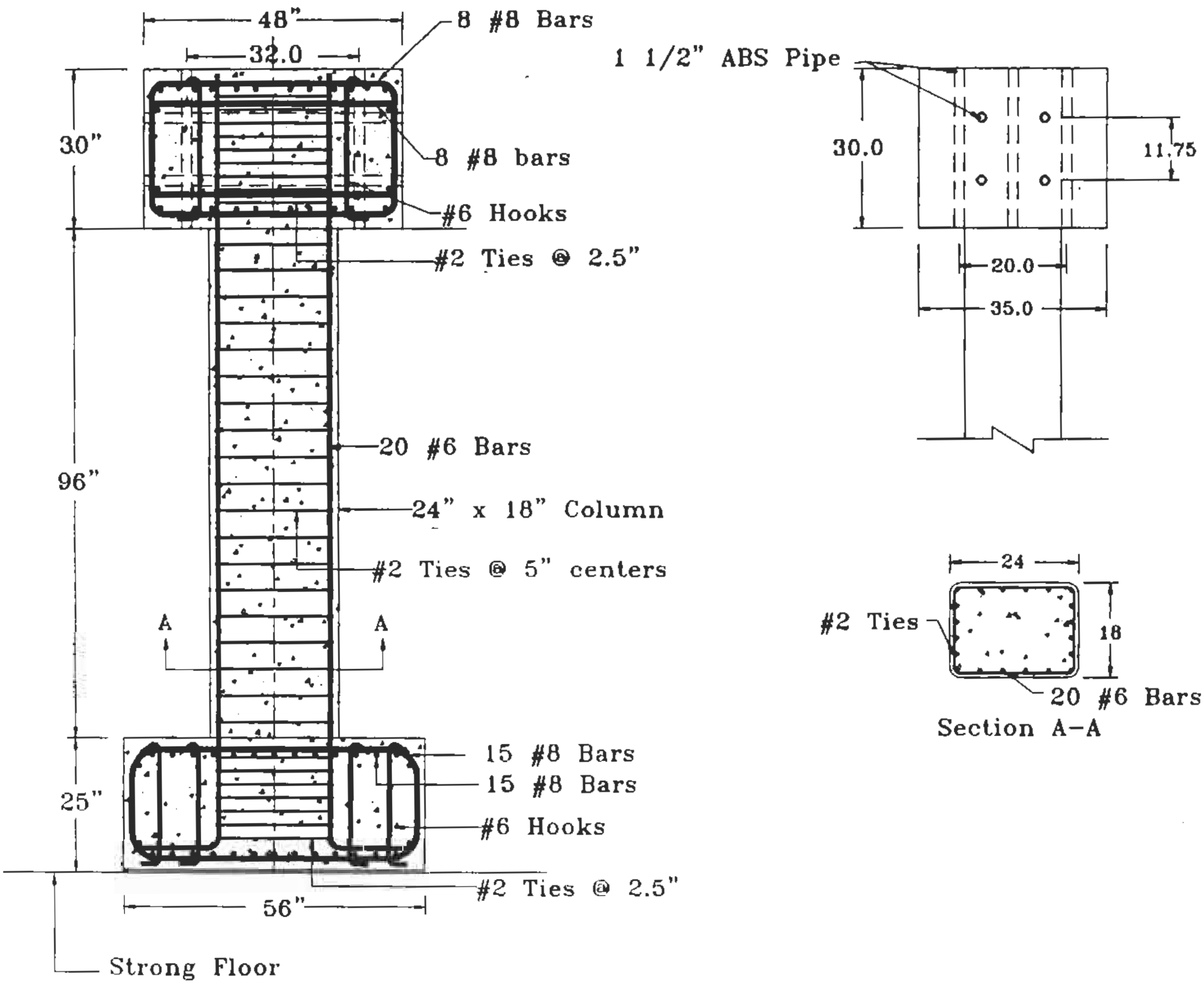

Figure 2.4: Reinforcement Details for Shear Enhancement Rectangular Columns

2.2 Material Properties

2.2.1 Steel

The rectangular lap splice columns were built with grade 60 No. 6 longitudinal steel and grade 60 No. 2 lateral steel. The last two circular shear columns were built with grade 60 No. 6 longitudinal steel and grade 40 No. 2 lateral steel. The rest of the columns were built with grade 40 No. 6 longitudinal steel and grade 40 No. 2 lateral steel.

Billet testing was performed on steel samples from each batch of steel in order to obtain the actual yield and ultimate stress of the steel. The results of these tests are shown in Tables 2.6 to 2.9. From this testing, the average yield stress of steel is shown in Tables 2.1 to 2.5. These values are representative of typical steel in each test column.

Table 2.6: Grade 40 No. 6 Longitudinal Steel (d=0.442″)

Sample #	Yield (kips)	Ultimate (kips)	Yield Stress (ksi)	Ultimate Stress (ksi)
1	19.5	27.5	44.32	62.50
2	18.7	26.8	42.50	60.91
3	19.1	26.2	43.41	59.55
		Average:	43.41	60.98

Table 2.7: Grade 40 No. 2 Transverse Steel (d=0.049″)

Sample #	Yield (kips)	Ultimate (kips)	Yield Stress (ksi)	Ultimate Stress (ksi)
1	1.625	2.35	32.50	47.00
2	1.5	2.35	30.00	47.00
3	1.45	2.375	29.00	47.50
		Average:	30.50	47.17

Table 2.8: Grade 60 No. 6 Longitudinal Steel (d=0.442″)

Sample #	Yield (kips)	Ultimate (kips)	Yield Stress (ksi)	Ultimate Stress (ksi)
1	28.4	46.6	64.28	105.48
2	28.4	46.3	64.28	104.80
3	28.5	46.5	64.51	105.25
		Average:	64.36	105.18

Table 2.9: Grade 60 No. 2 Transverse Steel (d=0.049″)

Sample #	Yield (kips)	Ultimate (kips)	Yield Stress (ksi)	Ultimate Stress (ksi)
1	3.119	X	63.52	X
2	3.161	X	64.38	X
3	3.187	X	64.91	X
4	3.182	X	64.81	X
5	3.308	X	67.37	X
		Average:	64.27	X

2.2.2 Concrete

A nominal 5000 psi concrete was used in the construction of each column type. A single batch of concrete was used to pour a set of columns of the same type. This was done to ensure that each retrofitted column possessed the same material properties as the as-built column.

Cylinder samples were poured from each batch of concrete. Tests were performed on these cylinders at different dates to determine the average concrete strengths, f'_c, as shown in Tables 2.10 to 2.13. In each test, three samples are brought to failure under compression using the Tinius-Olsen materials testing machine located at the University of California, Irvine Structural Test Hall as shown in Figure 2.5. This was done 7 and 28 days after pouring the concrete, as well as on the day of each column test. (Note: The different concrete strengths are due to concrete aging).

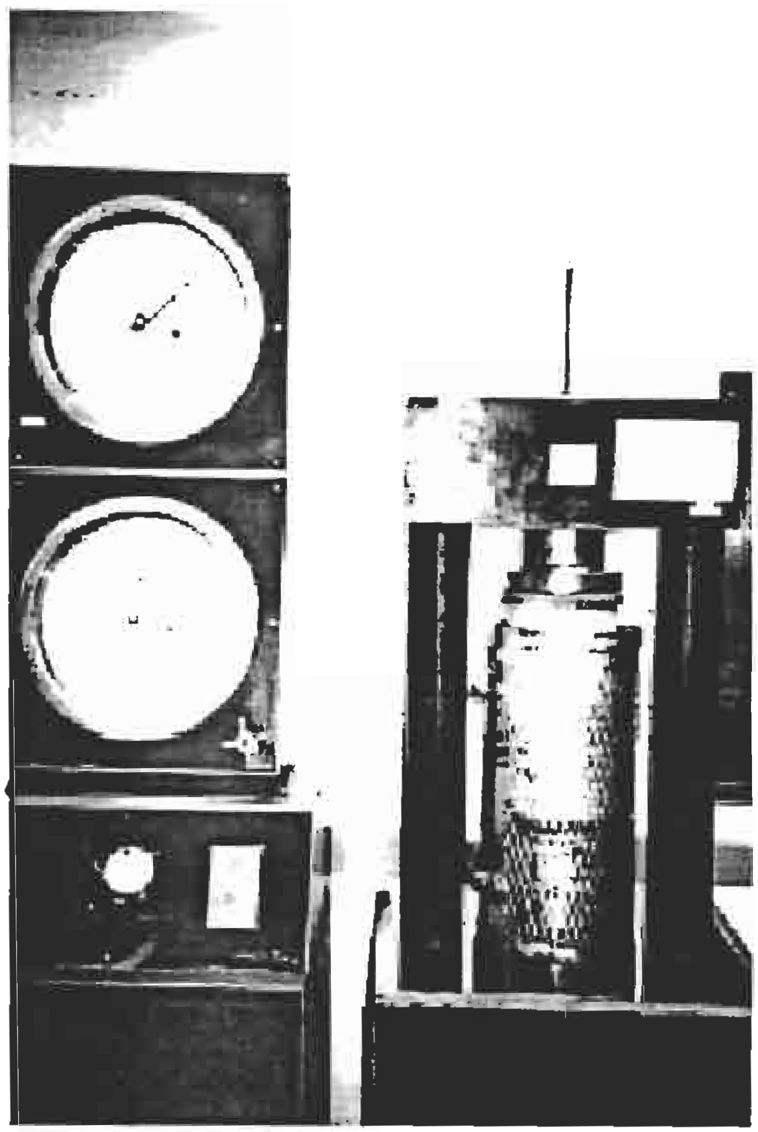

Figure 2.5: Testing of Concrete Cylinders

Table 2.10: Concrete Strength for Shear Enhancement Circular Columns

# Days	Cyl #1 (kips)	Cyl #2 (kips)	Cyl #3 (kips)	f'_c (psi)	Note:
7	118	124	108	4126	Batch #1
28	155	157	163	5600	
41	150	158	145	5341	As-built CS-1
7	109	110	113	3914	Batch #2
28	142	144	138	4999	
146	161	144	178	5694	Specimen CS-2
153	174	163	165	5918	Specimen CS-3
7	108	121	118	4091	Batch #3
28	169	160	175	5942	As-built CS-4
49	183	180	182	6425	Specimen CS-5

Table 2.11: Concrete Strength for Lap Splice Enhancement Circular Columns

# Days	Cyl #1 (kips)	Cyl #2 (kips)	Cyl #3 (kips)	f'_c (psi)	Note:
7	111	118	114	4044	Batch #1
28	142	144	138	4999	
35	⋆	146	147	5181	As-built CF-2
48	146	145	153	5234	Specimen CF-4
50	151	149	155	5364	Specimen CF-3
7	111	118	114	4044	Batch #2
28	129	145	130	4763	
53	167	159	150	5612	As-built CF-1
53	130	127	147	4763	Specimen CF-6
68	158	163	167	5753	Specimen CF-8
81	158	150	156	5470	Specimen CF-5
136	160	161	168	5765	Specimen CF-9
7	92.5	95	⋆	3316	Batch #3
28	112	119	⋆	4085	
60	142	130	⋆	4810	Specimen CF-7

⋆ Bad concrete test cylinder sample.

Table 2.12: Concrete Strength for Lap Splice Enhancement Rectangular Columns

# Days	Cyl #1 (kips)	Cyl #2 (kips)	Cyl #3 (kips)	f'_c (psi)	Note:
7	109	113.5	106.5	3879	Batch #1
28	140.5	147.5	139.5	5040	
61	154	170	186	6013	As-built RF-1
56	144	143	149	5140	Specimen RF-3
60	157	172	187	6083	Specimen RF-2
7	119	109	115	4043	Batch #2
28	177	120	178	5600	Specimen RF-4
53	175	175	174	6117	Specimen RF-5
60	175	175	174	6117	Specimen RF-6

Table 2.13: Concrete Strength for Shear Enhancement Rectangular Columns

# Days	Cyl #1 (kips)	Cyl #2 (kips)	Cyl #3 (kips)	f'_c (psi)	Note:
7	109	113.5	106.5	3879	
28	⋆	143	139	4987	
75	143	143	170	5376	As-built RS-1
81	165	145	159	5529	Specimen RS-4
94	146	167	171	5706	Specimen RS-2
101	182	183	176	6378	Specimen RS-3
101	‡	‡	‡	6378	Specimen RS-5
164	‡	‡	‡	6378	Specimen RS-6
178	175	183	166	6178	Specimen RS-7

⋆ Bad concrete test cylinder sample.

‡ No concrete cylinder samples tested. Prior sample results used for concrete strength.

Chapter 3

COMPOSITE JACKETS

3.1 Design Considerations

3.1.1 Shear Strength Enhancement

To increase shear strength in circular columns, the areas within the top and bottom 24″ of the column, regarded as the plastic hinge zones, are to be strengthened with a composite jacket with a minimum confinement of 300 psi. The rest of the column, regarded as the nonplastic hinge zone, is to be strengthened with a composite jacket with a minimum confinement of 150 psi. The jacket must provide the required confinement strength without exceeding a jacket strain of 0.004. For rectangular column sections, the required jacket thickness shall be increased by a factor of 1.5.

3.1.2 Lap Splice Enhancement

To increase lap splice strength in columns, the design requirements are identical to that previously described except that the jacket must provide the required confinement strength without exceeding a jacket strain of 0.001.

3.2 Material Description

The composite jacket retrofit systems were made of either carbon fiber or E-glass material with varying material properties. Table 3.1 shows the modulus of elasticity of the jacket, E_j, and the layer thickness, t_l.

Table 3.1: Material Properties for Composite Jackets

	E_j (Msi)	t_l (in)
Circular Shear Enhancement		
Specimen CS-3	34.1	0.0066
Specimen CS-2	34.1	0.0007
Specimen CS-5	34.1	0.0065
Circular Lap Splice Enhancement		
Specimen CF-4	34.1	0.0066
Specimen CF-3	34.1	0.0007
Specimen CF-6	5.1	0.1500
Specimen CF-8	5.5	0.1000
Specimen CF-5	34.1	0.0065
Specimen CF-9	5.5	0.1000
Specimen CF-7	8.0	0.0410
Rectangular Lap Splice Enhancement		
Specimen RF-3	34.1	0.0066
Specimen RF-2	34.1	0.0007
Specimen RF-5	34.1	0.0065
Specimen RF-6	5.1	0.4500
Rectangular Shear Enhancement		
Specimen RS-4	34.1	0.0066
Specimen RS-2	34.1	0.0007
Specimen RS-3	34.1	0.0066
Specimen RS-5	5.1	0.1500
Specimen RS-6	8.0	0.0410
Specimen RS-7	5.5	0.1000

3.3 Required Composite Jacket Thickness

The lateral confinement pressure, p, provided by the composite jacket is given by the equation

$$\begin{aligned} p &= \rho_{sj} f_j \\ &= \rho_{sj} E_j \epsilon_j \end{aligned} \tag{3.1}$$

where ϵ_j is the jacket design strain of 0.001 for lap splice enhancement columns and 0.004 for shear enhancement columns, and ρ_{sj} is the volumetric ratio of the confinement jacket given by the following equations

For circular columns

$$\rho_{sj} = 4\frac{t_j}{d} \tag{3.2}$$

For rectangular columns

$$\rho_{sj} = 2(\frac{b+d}{b \times d})t_j \tag{3.3}$$

where b is the width and d is the depth of the column cross section. Substituting 300 psi or 150 psi for p produces the required thicknesses of the jacket (t'_j) in the plastic hinge zones and nonplastic hinge zones, respectively. For rectangular column sections, the required jacket thickness is increased by a factor of 1.5.

The required number of composite jacket layers, N', is then calculated

$$N' = \frac{t'_j}{t_l} \tag{3.4}$$

where t_l is the thickness of one layer of composite jacket material. The calculations showing the minimum required jacket thicknesses are shown in Table 3.2. The number of composite jacket layers actually provided is also shown in Table 3.2.

Table 3.2: Composite Jacket Thicknesses

	Plastic Hinge Region			Nonplastic Hinge Region		
	t'_j (in)	N'	N	t'_j (in)	N'	N
Circular Shear Enhancement						
Specimen CS-3	0.0132	2	4	0.0066	1	3
Specimen CS-2	0.0132	19	37	0.0066	9	26
Specimen CS-5	0.0132	2	4	0.0066	1	4
Circular Lap Splice Enhancement						
Specimen CF-4	0.0528	8	4	0.0264	4	3
Specimen CF-3	0.0528	75	37	0.0264	37	26
Specimen CF-6	0.3529	3	3	0.1765	2	0
Specimen CF-8	0.3273	4	5	0.1636	2	4
Specimen CF-5	0.0528	9	10	0.0264	4	5
Specimen CF-9	0.3273	4	5	0.1636	2	4
Specimen CF-7	0.2250	6	8	0.1125	3	2
Rectangular Lap Splice Enhancement						
Specimen RF-3	0.1584	24	24	0.0792	12	12
Specimen RF-2	0.1584	223	223	0.0792	111	112
Specimen RF-5	0.0794	13	15	0.0397	7	7
Specimen RF-6	0.529	2	2	0.265	1	2
Rectangular Shear Enhancement						
Specimen RS-4	0.0396	6	6	0.0198	3	3
Specimen RS-2	0.0396	56	56	0.0198	28	56
Specimen RS-3	0.0396	6	6	0.0198	3	6
Specimen RS-5	0.2647	2	2	0.1324	1	2
Specimen RS-6	0.1688	5	5	0.0844	2	2
Specimen RS-7	0.2455	3	3	0.1227	1	3

Note: Most columns were reinforced with a number of layers which meet or exceed the required number of layers as shown in this table. The exceptions are columns CF-3 and CF-4 which were designed incorrectly by the manufacturer according to a jacket strain of $\epsilon_j = 0.004$.

3.4 Jacket Installation

Prior to jacket installation, the corners of the rectangular columns were ground smooth to a radius of about 1.5″ as shown in Figure 3.1.

Figure 3.1: Grinding the Edges of Rectangular Columns

The composite jacket is manually applied to the column using a number of procedures. Samples of these applications are shown in Figure 3.2. Other composite jacket installations are shown in Appendix A.

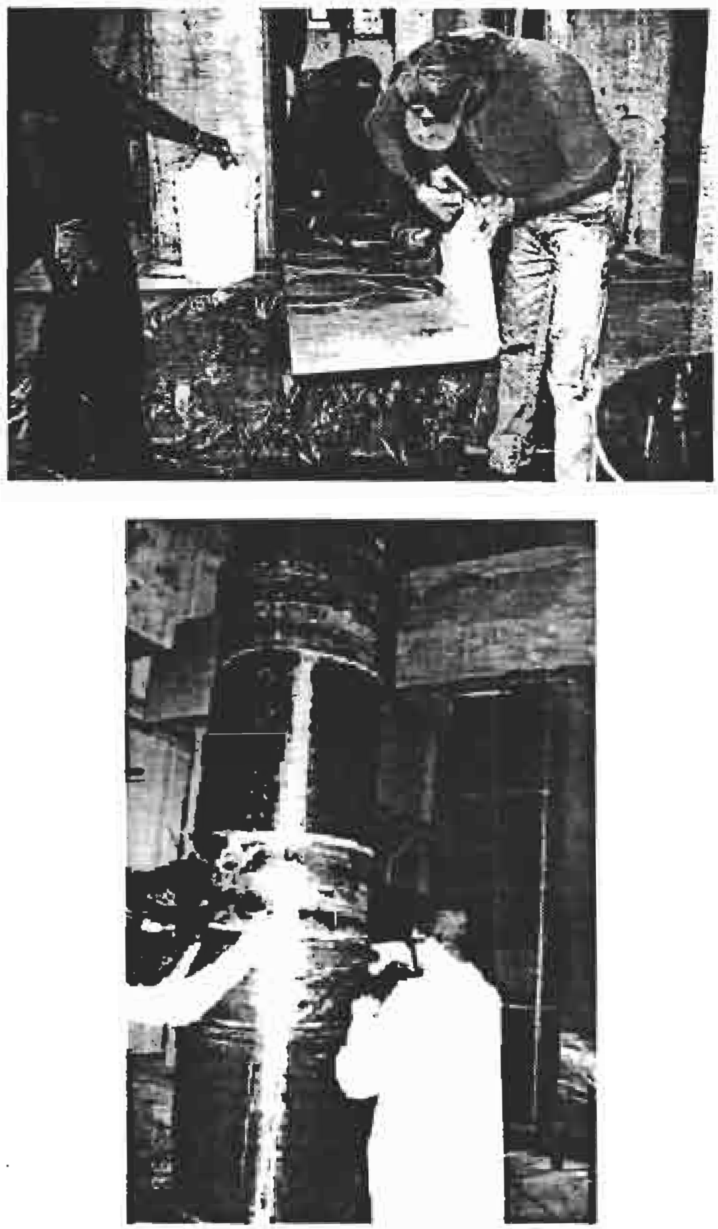

Figure 3.2: Typical Jacket Applications

Chapter 4

PERFORMANCE PREDICTION

4.1 Modeling the Jacket

The confinement effect provided by the composite jacket is modeled by considering the jacket as equivalent transverse steel reinforcement with spacing, s', calculated as follows:

Within a column section with a depth equal to the transverse reinforcement spacing, s, the equivalent transverse steel area of the jacket, A_{vj}, is

$$A_{vj} = 2t_j \times \frac{E_j K_{ej}}{E_s K_{et}} \times s \tag{4.1}$$

where E_j is the Young's Modulus of the composite jacket, K_{ej} is the confinement effectiveness coefficient for the jacket, E_s is the Young's Modulus of the transverse steel reinforcement, and K_{et} is the confinement effectiveness coefficient for the transverse steel reinforcement.

The transverse steel area, A_v, within that same section is

$$A_v = 2 \times A_{tb} \tag{4.2}$$

where A_{tb} is the cross sectional area of the transverse steel.

The equivalent transverse steel reinforcement spacing is then

$$s' = s \times \frac{A_v}{A_v + A_{vj}} \tag{4.3}$$

Values for s' are calculated as shown in Table 4.1. The equivalent transverse steel spacing due to the transverse steel and the composite jacket combined is calculated as s'_{t+j}. Assuming the jacket acts independently of the transverse steel, the value due to the jacket alone is calculated as s'_j.

Table 4.1: Equivalent Transverse Reinforcement Spacing

	t_j (in)	K_{et}	K_{ej}	A_v (in^2)	A_{vj} (in^2)	s'_{t+j} (in)	s'_j (in)
Circular Shear Enhancement							
Specimen CS-3	0.026	0.95	0.95	0.0982	0.310	1.202	1.582
Specimen CS-2	0.026	0.95	0.95	0.0982	0.310	1.202	1.583
Specimen CS-5	0.026	0.95	0.95	0.0982	0.305	1.218	1.61
Circular Lap Splice Enhancement							
Specimen CF-4	0.026	0.95	0.95	0.0982	0.310	1.202	1.582
Specimen CF-3	0.026	0.95	0.95	0.0982	0.310	1.202	1.583
Specimen CF-6	0.450	0.95	0.95	0.0982	0.791	0.552	0.620
Specimen CF-8	0.500	0.95	0.95	0.0982	0.948	0.469	0.518
Specimen CF-5	0.065	0.95	0.95	0.0982	0.764	0.569	0.642
Specimen CF-9	0.500	0.95	0.95	0.0982	0.948	0.469	0.518
Specimen CF-7	0.287	0.95	0.95	0.0982	0.792	0.552	0.620
Rectangular Lap Splice Enhancement							
Specimen RF-3	0.158	0.75	0.5	0.0982	1.242	0.366	0.395
Specimen RF-2	0.159	0.75	0.5	0.0982	1.246	0.365	0.394
Specimen RF-5	0.0975	0.75	0.5	0.0982	0.764	0.569	0.642
Specimen RF-6	0.9	0.75	0.5	0.0982	1.055	0.426	0.465
Rectangular Shear Enhancement							
Specimen RS-4	0.039	0.75	0.5	0.0982	0.306	1.216	1.606
Specimen RS-2	0.040	0.75	0.5	0.0982	0.313	1.194	1.569
Specimen RS-3	0.040	0.75	0.5	0.0982	0.310	1.202	1.582
Specimen RS-5	0.300	0.75	0.5	0.0982	0.352	1.091	1.396
Specimen RS-6	0.205	0.75	0.5	0.0982	0.377	1.033	1.302
Specimen RS-7	0.300	0.75	0.5	0.0982	0.379	1.028	1.294

4.2 Moment-Curvature Analysis

A computer program, Colduct [Caltrans & Seyed, 1993], is used for the moment-curvature analysis of the columns using the physical properties shown in Tables 2.1 to 2.4, and Table 4.1. This program analyzes the columns by incorporating a stress-strain relationship of confined concrete developed by Mander [Mander et al, 1988].

Sample results of a moment-curvature analysis of a column are shown in Table 4.2. The concrete strains (ϵ_c) and neutral axis location ($y_{N.A.}$) of the column section at various lateral load levels are shown in columns 2 and 3. The moment and the curvature are shown in columns 4 and 5.

The last column labeled "comments" describes the onset of column degradation. The ideal yield of steel corresponds to the extreme fiber concrete strain, $\epsilon_c = 0.004$ for as-built, and $\epsilon_c = 0.005$ for retrofitted columns. Failure mode predictions are based on calculations shown in Section 4.4. The moment-curvature analyses for all columns are shown in Appendix B.

Table 4.2: Output Data for As-built Lap Splice Enhancement Circular Column CF-1

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00016	-8.26	0.000008	53	
2	0.00018	-6.67	0.000009	61	
3	0.00020	-5.28	0.000011	69	
4	0.00022	-4.08	0.000013	76	
5	0.00024	-3.02	0.000016	84	
6	0.00026	-2.11	0.000019	93	
7	0.00029	-1.30	0.000022	102	
8	0.00032	-0.58	0.000026	111	
9	0.00036	0.05	0.000030	122	
10	0.00039	0.62	0.000035	133	
11	0.00044	1.10	0.000040	146	
12	0.00048	1.58	0.000046	159	
13	0.00053	1.97	0.000053	175	
14	0.00059	2.30	0.000061	192	
15	0.00065	2.59	0.000069	210	
16	0.00072	2.83	0.000079	231	
17	0.00080	3.07	0.000089	254	
18	0.00088	3.26	0.000101	279	
19	0.00097	3.46	0.000114	304	Begin Yield of Steel
20	0.00108	3.74	0.000130	323	
21	0.00119	4.08	0.000150	339	
22	0.00132	4.42	0.000173	352	
23	0.00145	4.70	0.000199	365	
24	0.00161	5.04	0.000231	373	
25	0.00178	5.33	0.000266	383	
26	0.00196	5.62	0.000308	389	
27	0.00217	5.90	0.000356	393	
28	0.00240	6.10	0.000407	397	
29	0.00265	6.24	0.000461	401	
30	0.00293	6.38	0.000522	403	
31	0.00324	6.53	0.000593	404	
32	0.00359	6.62	0.000667	406	
33	0.00396	6.72	0.000751	406	
⋆	0.00400	6.72	0.000759	406	Ideal Yield of Steel
34	0.00438	6.77	0.000838	406	
35	0.00484	6.82	0.000935	402	
36	0.00536	6.77	0.001024	403	
37	0.00592	6.77	0.001132	400	
⋆	0.00632	6.71	0.001194	401	Tranverse Steel Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

4.3 Yield Displacement

Column flexural response can be estimated based on results of the moment-curvature analysis using a bilinear approximation as shown in Figure 4.1.

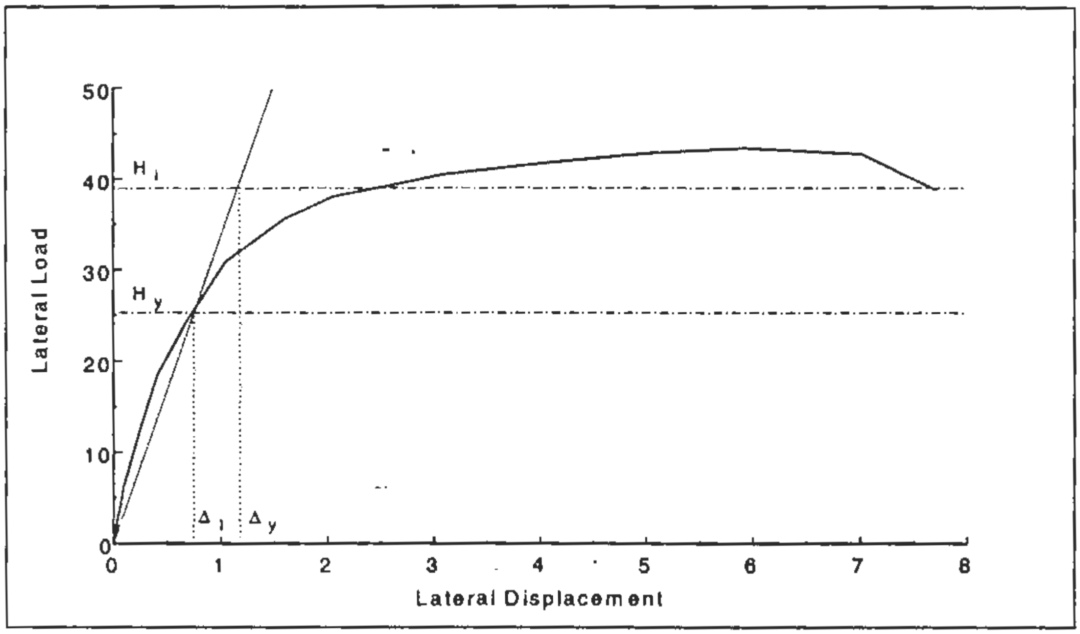

Figure 4.1: Load-Displacement Diagram - Bilinear Approximation

Allowing for strain penetration of the longitudinal reinforcement into the footing, the effective column height, h_e, of the column can be taken as

$$h_e \quad = \quad h + 0.15 d_{bl} f_{ye} \tag{4.4}$$

where h is the height of the column, d_{bl} is the nominal diameter (in) of the longitudinal steel reinforcement, and f_{ye} is the yield stress (ksi) of the longitudinal steel reinforcement.

The expected lateral displacement at first yield, Δ_1, for the column is

$$\Delta_1 = \frac{1}{3}\phi_1 h_e^2 \tag{4.5}$$

The lateral force at the yield condition for the bilinear approximation is taken as the lateral load capacity of the column, H_y. Thus, the idealized yield displacement (Δ_y) corresponding to the lateral yield force for the bilinear approximation can be found by extrapolating from the first yield displacement(Δ_1)

$$\Delta_y = \frac{H_i}{H_y}\Delta_1 \tag{4.6}$$

The calculations for yield displacement are shown in Table 4.3.

Note: Columns in double bending may be modeled as two half columns in single bending. The preceding analysis can then be performed on a column with half of the height of the actual column, and then the results are doubled.

Table 4.3: Calculations of Expected Yield Displacement

	h_e (in)	ϕ_1	H_y	H_i	Δ_1 (in)	Δ_y (in)
Circular Shear Enhancement						
As-built CS-1	52.88	0.000113	75.3	100.5	0.211	0.281
Specimen CS-3	52.88	0.000114	75.8	104.6	0.213	0.293
Specimen CS-2	52.88	0.000118	76.8	104.2	0.220	0.299
As-built CS-4	54.75	0.000163	99.3	123.5	0.326	0.405
Specimen CS-5	54.75	0.000144	94.5	136.1	0.288	0.414
Circular Lap Splice Enhancement						
As-built CF-2	148.88	0.000112	24.8	33.6	0.828	1.119
Specimen CF-4	148.88	0.000120	25.6	34.3	0.887	1.190
Specimen CF-3	148.88	0.000116	25.2	34.3	0.857	1.167
As-built CF-1	148.88	0.000114	25.3	33.8	0.842	1.125
Specimen CF-6	148.88	0.000122	25.3	34.5	0.901	1.227
Specimen CF-8	148.88	0.000115	25.3	35.1	0.850	1.183
Specimen CF-5	148.88	0.000116	25.3	35.0	0.857	1.188
Specimen CF-9	148.88	0.000115	25.3	35.2	0.850	1.183
Specimen CF-7	148.88	0.000122	25.4	34.5	0.901	1.224
Rectangular Lap Splice Enhancement						
As-built RF-1	151.25	0.000171	59.7	79.0	1.304	1.726
Specimen RF-3	151.25	0.000157	57.4	84.7	1.197	1.767
Specimen RF-2	151.25	0.000171	59.4	86.6	1.304	1.901
Specimen RF-5	151.25	0.000151	57.3	86.1	1.151	1.729
Specimen RF-6	151.25	0.000151	57.3	86.7	1.151	1.742
Rectangular Shear Enhancement						
As-built RS-1	52.88	0.000106	91.3	118.0	0.198	0.256
Specimen RS-4	52.88	0.000118	93.5	128.2	0.220	0.302
Specimen RS-2	52.88	0.000116	93.5	128.8	0.216	0.298
Specimen RS-3	52.88	0.000117	94.5	131.6	0.218	0.304
Specimen RS-5	52.88	0.000117	94.8	132.4	0.218	0.305
Specimen RS-6	52.88	0.000114	93.8	132.1	0.213	0.299
Specimen RS-7	52.88	0.000114	93.8	132.6	0.213	0.301

4.4 Failure Modes

Under quasi-static lateral loading, the column is expected to exhibit a number of potential failure modes. These include shear failure, lap splice failure (where applicable), confinement failure, and longitudinal steel failure. These failure modes may be quantified as follows:

4.4.1 Shear Failure

The lateral shear strength, V', of the column is provided by four major components: the concrete (V_c), the lateral steel (V_s), the axial load (V_p), and the composite jacket (V_{cj}). The shear strength may be estimated using the following equation [Priestley & Seible, 1996; McDaniel, 1997]

$$V' = V_c + V_s + V_p + V_{cj} \tag{4.7}$$

For circular columns:

$$V' = \alpha\beta k\sqrt{f_c'}A_e + \frac{\pi}{2}\frac{A_h f_{yh} d'}{s} \times \cot\theta^\circ + \frac{d-c}{h}P + 2t_j f_j d \times \cot\theta^\circ \tag{4.8}$$

For rectangular columns:

$$V' = \alpha\beta k\sqrt{f_c'}A_e + \frac{A_v f_{yt} d'}{s} \times \cot\theta^\circ + \frac{d-c}{h}P + 2t_j f_j d \times \cot\theta^\circ \tag{4.9}$$

where

f'_c = actual concrete strength measured on the day of testing;
A_e = effective area in shear equal to $0.8A_{gross}$;
A_v = $2A_{tb}$, the total area of tranverse reinforcement in a layer in the direction of the shear force;
f_{yt} = yield stress of transverse steel;
d' = center to center depth of transverse reinforcement;
s = spacing of hoops;
$\theta°$ = 30°, the angle of expected shear crack with respect to the vertical axis;
d = depth of the column cross section;
h = half the height of the column;
c = depth of the compression block;
P = applied axial force;
f_j = the stress in the jacket corresponding to a jacket strain $\epsilon = 0.004$
α = factor modifies the equation according to aspect ratio, and is given by

$$1 \leq \alpha = 3 - \frac{M}{VD} \leq 1.5$$

β = factor accounts for the longitudinal steel ratio, ρ_l, and is estimated by

$$\beta = (0.5 + 20\rho_l) \leq 1.0$$

k = 0.6 to 3.5 depending on the displacement ductility, μ_Δ, quantified by the set of equations as shown:

$$k = \begin{cases} 3.5 & : \quad 0 \leq \mu_\Delta < 2 \\ 3.5 - 1.15(\mu_\Delta - 2) & : \quad 2 \leq \mu_\Delta < 4 \\ 1.2 - 0.15(\mu_\Delta - 4) & : \quad 4 \leq \mu_\Delta < 8 \\ 0.6 & : \quad \mu_\Delta \geq 8 \end{cases}$$

Shear strength, V', is calculated for brittle and flexural failure modes as shown in Tables 4.4 and 4.5. Note that the effect of the composite jacket is negligible for brittle shear failure, but is significant for flexural failure mode.

Shear strength is also calculated for each step of the moment curvature analysis from brittle failure mode to flexural failure mode as shown in the example in Table 4.6. Note that the shear strength degrades as the displacement ductility, μ_Δ, increases. Shear strength calculations for all columns are shown in Appendix C.

Table 4.4: Shear Strength Calculations - Brittle Failure Mode

	V_c (kips)	V_s (kips)	V_p (kips)	V_j (kips)	V' (kips)
Circular Shear Enhancement Columns					
As-built CS-1	92.6	18.3	10.1		121.0
Specimen CS-3	97.4	18.3	10.1		125.8
Specimen CS-2	95.6	18.3	10.1		124.0
As-built CS-4	97.6	18.3	10.1		126.0
Specimen CS-5	101.5	18.3	10.1		129.9
Circular Lap Splice Enhancement Columns					
As-built CF-2	91.2	18.3	10.1		119.6
Specimen CF-4	91.6	18.3	10.1		120.0
Specimen CF-3	92.8	18.3	10.1		121.2
As-built CF-1	94.9	18.3	10.1		123.3
Specimen CF-6	87.4	18.3	10.1		115.8
Specimen CF-8	96.1	18.3	10.1		124.5
Specimen CF-5	93.7	18.3	10.1		122.1
Specimen CF-9	96.2	18.3	10.1		124.6
Specimen CF-7	87.9	18.3	10.1		116.3
Rectangular Lap Splice Enhancement Columns					
As-built RF-1	125.1	49.8	13.0		187.8
Specimen RF-3	115.6	49.8	13.0		178.4
Specimen RF-2	125.8	49.8	13.0		188.5
Specimen RF-5	126.1	49.8	13.0		188.9
Specimen RF-6	126.1	49.8	13.0		188.9
Rectangular Shear Enhancement Columns					
As-built RS-1	88.7	36.0	31.7		156.3
Specimen RS-4	89.9	36.0	31.7		157.6
Specimen RS-2	91.4	36.0	31.7		159.0
Specimen RS-3	96.6	36.0	31.7		164.2
Specimen RS-5	96.6	36.0	31.7		164.2
Specimen RS-6	96.6	36.0	31.7		164.2
Specimen RS-7	96.8	36.0	31.7		164.4

Table 4.5: Shear Strength Calculations - Flexural Failure Mode

	V_c (kips)	V_s (kips)	V_p (kips)	V_j (kips)	V' (kips)
Circular Shear Enhancement Columns					
As-built CS-1	15.9	18.3	8.1		42.3
Specimen CS-3	16.7	18.3	8.1	96.9	140.0
Specimen CS-2	16.4	18.3	8.1	96.9	139.6
As-built CS-4	16.7	18.3	8.1	0.0	43.1
Specimen CS-5	17.4	18.3	8.1	95.5	139.3
Circular Lap Splice Enhancement Columns					
As-built CF-2	15.6	18.3	8.1		42.0
Specimen CF-4	15.7	18.3	8.1	48.5	90.6
Specimen CF-3	15.9	18.3	8.1	48.4	90.7
As-built CF-1	16.3	18.3	8.1		42.7
Specimen CF-6	15.0	18.3	8.1	123.6	164.9
Specimen CF-8	16.5	18.3	8.1	148.1	190.9
Specimen CF-5	16.1	18.3	8.1	119.3	161.8
Specimen CF-9	16.5	18.3	8.1	148.1	190.9
Specimen CF-7	15.1	18.3	8.1	123.6	165.1
Rectangular Lap Splice Enhancement Columns					
As-built RF-1	21.4	49.8	10.4		81.6
Specimen RF-3	19.8	49.8	10.4	449.1	529.0
Specimen RF-2	21.6	49.8	10.4	450.8	532.5
Specimen RF-5	21.6	49.8	10.4	276.4	358.2
Specimen RF-6	21.6	49.8	10.4	381.6	463.4
Rectangular Shear Enhancement Columns					
As-built RS-1	15.2	36.0	25.3		76.5
Specimen RS-4	15.4	36.0	25.3	442.3	519.0
Specimen RS-2	15.7	36.0	25.3	452.8	529.8
Specimen RS-3	16.6	36.0	25.3	449.1	526.9
Specimen RS-5	16.6	36.0	25.3	508.8	586.7
Specimen RS-6	16.6	36.0	25.3	545.4	623.3
Specimen RS-7	16.6	36.0	25.3	548.7	626.6

Table 4.6: Ductility and Shear Strength Calculations for As-built Lap Splice Enhancement Circular Column CF-1

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	4.4	0.059	0.1	3.50	123.4	
2	5.1	0.066	0.1	3.50	122.6	
3	5.8	0.081	0.1	3.50	121.9	
4	6.3	0.096	0.1	3.50	121.3	
5	7.0	0.118	0.1	3.50	120.8	
6	7.8	0.140	0.1	3.50	120.3	
7	8.5	0.163	0.1	3.50	119.9	
8	9.3	0.192	0.2	3.50	119.6	
9	10.2	0.222	0.2	3.50	119.2	
10	11.1	0.259	0.2	3.50	119.0	
11	12.2	0.296	0.3	3.50	118.7	
12	13.3	0.340	0.3	3.50	118.5	
13	14.6	0.392	0.3	3.50	118.3	
14	16.0	0.451	0.4	3.50	118.1	
15	17.5	0.510	0.5	3.50	118.0	
16	19.3	0.584	0.5	3.50	117.8	
17	21.2	0.658	0.6	3.50	117.7	
18	23.3	0.746	0.7	3.50	117.6	
19	25.3	0.842	0.7	3.50	117.5	Begin Yield of Steel
20	26.9	0.895	0.8	3.50	117.4	
21	28.3	0.939	0.8	3.50	117.2	
22	29.3	0.975	0.9	3.50	117.0	
23	30.4	1.011	0.9	3.50	116.9	
24	31.1	1.034	0.9	3.50	116.7	
25	31.9	1.061	0.9	3.50	116.6	
26	32.4	1.078	1.0	3.50	116.4	
27	32.8	1.089	1.0	3.50	116.3	
28	33.1	1.100	1.0	3.50	116.2	
29	33.4	1.111	1.0	3.50	116.1	
30	33.6	1.117	1.0	3.50	116.1	
31	33.7	1.119	1.0	3.50	116.0	
32	33.8	1.125	1.0	3.50	115.9	
33	33.8	1.125	1.0	3.50	115.9	
⋆	33.8	1.125	1.0	3.50	115.9	Ideal Yield of Steel
34	33.8	1.307	1.2	3.50	115.9	
35	33.5	1.521	1.4	3.50	115.8	
36	33.6	1.728	1.5	3.50	115.9	
37	33.3	1.970	1.8	3.50	115.9	
⋆	33.4	2.115	1.9	3.50	115.9	Tranverse Steel Failure

4.4.2 Lap Splice Failure

Lap splice failure is known to occur in unconfined columns when the extreme fiber concrete strain reaches $\epsilon_c = 0.0015$ [Priestley & Seible, 1996]. This will translate into a lateral strain of $\epsilon = 0.0015$ in the transverse steel and the composite jacket.

Provided Confinement

Lateral strains develop in the transverse reinforcement and the composite jacket as the critical column section deforms under a flexural load. These lateral strains dilate the transverse steel and the composite jacket causing a confinement effect. This confinement acts to inhibit lap splice failure.

The overall lateral confinement provided by the combined effect of the lateral steel and composite jacket is

$$f_l' = f_{lt} + f_{lj} \tag{4.10}$$

The confining stress, f_{lt}, provided by the transverse steel reinforcement is

For circular column sections:

$$f_{lt} = K_e \frac{2A_{tb}f_{yt}}{d'\,s} \tag{4.11}$$

For rectangular column sections:

$$\begin{aligned} f_{lt} &= \frac{f_{lt_x} + f_{lt_y}}{2} \\ &= \frac{K_e}{2s}\left(\frac{A_{v_x} f_{t_x} b' + A_{v_y} f_{t_y} d'}{b'd'}\right) \end{aligned} \tag{4.12}$$

where K_e is the confinement effectiveness coefficient equal to 0.95 for the circular transverse reinforcement and 0.75 for rectangular transverse reinforcement, and b' is the center to center width of the transverse reinforcement.

The confining stress, f_{lj}, provided by the composite jacket is

For circular column sections:

$$f_{lj} = K_e \frac{4t_j}{d} f_j \qquad (4.13)$$

For rectangular column sections:

$$\begin{aligned} f_{lj} &= \frac{f_{lj_x} + f_{lj_y}}{2} \\ &= K_e t_j \left(\frac{f_{j_x} d + f_{j_y} b}{bd}\right) \end{aligned} \qquad (4.14)$$

where K_e is the confinement effectiveness coefficient equal to 1.0 for the circular composite jacket, and 0.5 for the rectangular composite jacket.

Required Confinement

The confinement stress required to inhibit lap splice failure, f_l', is computed using the following procedure:

The perimeter, p, of the characteristic block is calculated from

For circular sections:

$$p = \frac{\pi d'}{2n} + 2(d_{bl} + c) \leq 2\sqrt{2}(c + d_{bl}) \qquad (4.15)$$

For rectangular sections:

$$p = \frac{s}{2} + 2(d_{bl} + c) \leq 2\sqrt{2}(c + d_{bl}) \qquad (4.16)$$

where n is the number of pairs of column bars of diameter d_{bl} being lap spliced, d' is the diameter of the core column section, s is the spacing between each pair of lapped bars in the critical column face, and c is the clear cover to the longitudinal reinforcement.

Therefore, the confining strength required to inhibit lap splice failure is

$$f'_l = \frac{A_{bl} f_s}{p \mu l_s} \tag{4.17}$$

where A_{bl} is the cross sectional area of the lapped bar, f_s is the stress in the longitudinal reinforcement, μ is the coefficient of friction taken as 1.4, and l_s is the length of the lap splice.

By substituting f_s with the yield and ultimate strengths of the longitudinal steel, f_{yl} and f_{ul}, the required confining stresses to inhibit lap splice failure beyond longitudinal steel yield and failure, f'_{ly} and f'_{lu}, may be found.

If the provided confining stress, f'_l, is larger than the required confining stress, f'_{ly}, it may be inferred that a brittle failure will occur as shown in Table 4.7.

Similarly, f_{yl} may be replaced with the longitudinal bar stress, f_s, to find the lateral confinement required to inhibit lap splice failure at various load levels. Example of these calculations is shown in Table 4.8. These calculations are shown in Appendix D.

Table 4.7: Calculations of Lap Splice Strength

	f_l' (psi)	f_{l_y}' (psi)	f_{l_u}' (psi)	μ_Δ
Circular Lap Splice Enhancement				
As-built CF-2	25	215	387	< 1
Specimen CF-4	250	215	387	> 1
Specimen CF-3	250	215	387	> 1
As-built CF-1	25	215	387	< 1
Specimen CF-6	599	215	387	> 1
Specimen CF-8	713	215	387	> 1
Specimen CF-5	579	215	387	> 1
Specimen CF-9	713	215	387	> 1
Specimen CF-7	599	215	387	> 1
Rectangular Lap Splice Enhancement				
As-built RF-1	42	319	574	< 1
Specimen RF-3	380	319	574	> 1
Specimen RF-2	381	319	574	> 1
Specimen RF-5	250	319	574	< 1
Specimen RF-6	329	319	574	$= 1$

Table 4.8: Lap Splice Strength Calculations for As-built Column (CF-1)

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00002	0.68	3.42	
2	0.00004	1.28	6.39	
3	0.00007	2.00	10.00	
4	0.00010	2.84	14.19	
5	0.00013	3.81	19.03	
6	0.00017	4.88	24.37	
7	0.00022	6.29	31.39	
8	0.00027	7.87	39.27	
9	0.00034	9.87	49.25	
10	0.00041	11.80	58.86	
11	0.00050	14.46	72.13	
12	0.00059	17.14	85.51	
13	0.00070	20.26	101.07	
14	0.00082	23.90	119.25	
15	0.00096	27.72	138.32	
16	0.00111	32.06	159.95	
17	0.00128	37.20	185.61	
18	0.00146	42.37	211.38	
19	0.00167	43.41	216.58	Begin Yield of Steel
20	0.00196	43.41	216.58	
21	0.00230	43.41	216.58	
22	0.00273	43.41	216.58	
23	0.00317	43.41	216.58	
24	0.00377	43.41	216.58	
25	0.00442	43.41	216.58	
26	0.00518	43.41	216.58	
27	0.00610	43.41	216.58	
28	0.00706	43.41	216.58	
29	0.00805	43.42	216.62	
30	0.00919	43.64	217.73	
31	0.01053	43.90	219.03	
32	0.01192	44.17	220.37	
33	0.01348	44.47	221.88	
⋆	0.01363	44.50	222.02	Ideal Yield of Steel
34	0.01509	44.78	223.44	
35	0.01688	45.13	225.17	
36	0.01847	45.44	226.70	
37	0.02040	45.81	228.57	
⋆	0.02144	46.01	229.57	Tranverse Steel Failure

4.4.3 Confinement Failure

As the jacket or transverse reinforcement dilates, it may reach a stress beyond its ultimate strength, f_u, causing failure. The extreme fiber concrete ultimate strain at confinement failure, ϵ_{cu}, may be found as follows [Mander et al, 1988]:

The provided lateral confining pressure, f_l', is calculated as shown in Section 4.4.2.

The confined concrete compressive strength is

$$f_{cc}' = f_c'(2.254\sqrt{1+\frac{7.94f_l'}{f_c}} - \frac{2f_l'}{f_c} - 1.254) \tag{4.18}$$

Circular Column Sections

The volumetric ratio of confinement steel, ρ_{st}, is

$$\rho_{st} = \frac{2A_v}{D's} \tag{4.19}$$

The transverse steel will fail when extreme fiber concrete ultimate strain, ϵ_{cut}, is

$$\epsilon_{cut} = 0.004 + \frac{1.4\rho_{st}f_{yt}\epsilon_{su}}{f_{cc}'} \times 1.5 \tag{4.20}$$

where ϵ_{su} is the ultimate strain of the longitudinal column steel taken as 0.12.

The volumetric ratio of the confinement jacket, ρ_{sj}, is

$$\rho_{sj} = \frac{4t_j}{d} \tag{4.21}$$

Assuming the bonding between layers is adequate, the confinement jacket will fail when the extreme fiber concrete ultimate strain, ϵ_{cuj}, is

$$\epsilon_{cuj} = 0.004 + \frac{2.5\rho_{sj}f_{uj}\epsilon_{sj}}{f_{cc}'} \tag{4.22}$$

where f_{uj} is the ultimate strength of the jacket, and ϵ_{sj} is the expected maximum strain in the composite jacket.

Rectangular Column Sections

The volumetric ratio of confinement steel, ρ_{st}, is

$$\begin{aligned}\rho_{st} &= \rho_x + \rho_y \\ &= \frac{A_v}{b' s} + \frac{A_v}{d' s}\end{aligned} \tag{4.23}$$

where ρ_x and ρ_y are the confinement steel ratios in the strong and weak directions, respectively.

The transverse steel will fail when the extreme fiber concrete ultimate strain, ϵ_{cut}, is

$$\epsilon_{cut} = 0.004 + \frac{1.4\rho_{st} f_{yt} \epsilon_{su}}{f'_{cc}} \times 1.5 \tag{4.24}$$

where ϵ_{su} is the ultimate strain of the longitudinal column steel taken as 0.12.

The volumetric ratio of the confinement jacket, ρ_{sj}, is

$$\rho_{sj} = \frac{2t_j}{b} + \frac{2t_c}{d} \tag{4.25}$$

Assuming the bonding between layers is adequate, the confinement jacket will fail when the extreme fiber concrete ultimate strain, ϵ_{cuj}, is

$$\epsilon_{cuj} = 0.004 + \frac{1.25\rho_{sj} f_{uj} \epsilon_{sj}}{f'_{cc}} \tag{4.26}$$

where f_{uj} is the ultimate strength of the jacket, and ϵ_{sj} is the expected maximum strain in the composite jacket.

These strain calculations are shown in Table 4.9. By linear interpolation these values may be used to obtain moment and curvature for transverse steel and jacket failure from the moment-curvature analysis shown in Tables B.4 and B.26 in the appendix.

4.4.4 Longitudinal Steel Failure

Failure may occur in the longitudinal steel due to the steel being stressed beyond its ultimate strength, f_{lu}. This failure mode is mainly dependent on the ultimate strength of the longitudinal reinforcing steel. "Colduct", the computer program used for the moment-curvature analysis, indicates at what level this failure mode may occur as shown in Appendix B.

Table 4.9: Confinement Calculations

	f_l (psi)	ρ_{st}	ϵ_{cut}	ρ_{sj}	ϵ_{cuj}
Circular Shear Enhancement					
As-built CS-1	25	0.00175	0.00643		
Specimen CS-3	625	0.00175	0.00542	0.00440	0.01633
Specimen CS-2	625	0.00175	0.00546	0.00440	0.01666
As-built CS-4	25	0.00175	0.00619		
Specimen CS-5	616	0.00175	0.00535	0.00433	0.01552
Circular Lap Splice Enhancement					
As-built CF-2	25	0.00175	0.00651		
Specimen CF-4	175	0.00175	0.00648	0.00440	0.02548
Specimen CF-3	175	0.00175	0.00642	0.00440	0.02496
As-built CF-1	25	0.00175	0.00632		
Specimen CF-6	408	0.00175	0.00672	0.07500	0.05167
Specimen CF-8	484	0.00175	0.00626	0.08333	0.04490
Specimen CF-5	395	0.00175	0.00638	0.01083	0.05466
Specimen CF-9	484	0.00175	0.00626	0.08333	0.04482
Specimen CF-7	408	0.00175	0.00669	0.04783	0.03164
Rectangular Lap Splice Enhancement					
As-built RF-1	42	0.001746	0.00849		
Specimen RF-3	380	0.001637	0.00759	0.026400	0.05116
Specimen RF-2	381	0.001637	0.00716	0.026500	0.04570
Specimen RF-5	250	0.001637	0.00744	0.016250	0.03186
Specimen RF-6	329	0.001637	0.00726	0.150000	0.03290
Rectangular Shear Enhancement					
As-built RS-1	36	0.002063	0.00834		
Specimen RS-4	295	0.001909	0.00708	0.007583	0.01762
Specimen RS-2	301	0.001909	0.00699	0.007764	0.01755
Specimen RS-3	299	0.001909	0.00674	0.007700	0.01633
Specimen RS-5	334	0.001909	0.00668	0.058333	0.01484
Specimen RS-6	355	0.001909	0.00664	0.039861	0.01448
Specimen RS-7	357	0.001909	0.00663	0.058333	0.00956

4.5 Expected Plastic Displacements

The equivalent plastic hinge length, L_p, appropriate for a bilinear approximation of the response is [Priestley & Seible, 1996]

$$L_p = 0.08h + 0.15d_{bl}f_{ye} \leq 0.3d_{bl}f_{ye} \quad (4.27)$$

The plastic rotation, θ_p, can then be estimated as

$$\theta_p = L_p(\phi_u - \phi_y) \quad (4.28)$$

The plastic displacement, Δ_p, is given by

$$\Delta_p = (\frac{M_u}{M_i} - 1)\Delta_y + L_p(\phi_u - \phi_y)(h_e - 0.5L_p) \quad (4.29)$$

The ultimate displacement, Δ_u, is then

$$\Delta_u = \Delta_y + \Delta_p \quad (4.30)$$

Thus, the displacement ductility, μ_Δ, is given by

$$\mu_\Delta = \frac{\Delta_u}{\Delta_y} \quad (4.31)$$

Using this same procedure, substituting M_u and ϕ_u with all values within the plastic region for moment and curvature, displacement ductility may be calculated for multiple steps of the moment-curvature analysis as shown in Appendix C.

4.6 Summary of Predictions

From the calculations based on the moment curvature analysis, Appendix B, the progression of column degradation may be seen. By reviewing these tables as well as those in Appendices C and D, the ultimate failure modes for each column may be obtained.

4.6.1 Shear Enhancement Circular Columns

The as-built column is predicted to exhibit a brittle shear failure, while the retrofitted columns will fail in flexure at about ductility 6 as shown in Table 4.10.

4.6.2 Lap Splice Enhancement Circular Columns

The as-built columns are predicted to exhibit a brittle lap splice failure. Two of the retrofitted columns are also expected to exhibit lap splice failure at about ductility 4. The remainder of the retrofitted columns will fail in flexure at about ductility 8 as shown in Table 4.10.

4.6.3 Lap Splice Enhancement Rectangular Columns

The as-built column is predicted to exhibit a brittle lap splice failure. The retrofitted columns will also exhibit lap splice failure, but not until about ductility 4 as shown in Table 4.10.

4.6.4 Shear Enhancement Rectangular Columns

The as-built column is predicted to exhibit a brittle shear failure, while the retrofitted columns will exhibit composite jacket failure from ductility 6 to ductility 8 as shown in Table 4.10.

Table 4.10: Summary of Predictions of Column Behavior

	$H_u(kips)$	Δ_y (in)	Δ_u (in)	μ_Δ	Failure Mode
Circular Shear Enhancement					
As-built CS-1	99.9	0.281	0.651	2.3	Brittle Shear Failure
Specimen CS-3	118.5	0.293	1.833	6.2	Flexural Failure
Specimen CS-2	118.0	0.299	1.891	6.3	Flexural Failure
As-built CS-4	122.0	0.405	0.61	1.5	Brittle shear failure
Specimen CS-5	149.0	0.414	2.06	4.97	Flexural Failure
Circular Lap Slice Enhancement					
As-built CF-2	30.2	1.119	1.008	0.9	Lap Splice Failure
Specimen CF-4	38.5	1.190	4.409	3.7	Lap Splice Failure
Specimen CF-3	38.3	1.167	4.499	3.9	Lap Splice Failure
As-built CF-1	30.6	1.125	1.018	0.9	Lap Splice Failure
Specimen CF-6	44.4	1.227	9.648	7.9	Flexural Failure
Specimen CF-8	44.3	1.183	9.673	8.2	Flexural Failure
Specimen CF-5	43.3	1.188	9.145	7.7	Flexural Failure
Specimen CF-9	44.4	1.183	9.648	8.2	Flexural Failure
Specimen CF-7	42.6	1.224	8.871	7.2	Flexural Failure
Rectangular Lap Slice Enhancement					
As-built RF-1	64.1	1.726	1.357	0.8	Lap Splice Failure
Specimen RF-3	93.3	1.767	8.465	4.8	Lap Splice Failure
Specimen RF-2	92.7	1.901	7.751	4.1	Lap Splice Failure
Specimen RF-5	97.6	1.7291	12.70	7.3	Lap Splice Failure
Specimen RF-6	97.9	1.7420	11.93	6.9	Lap Splice Failure
Rectangular Shear Enhancement					
As-built RS-1	125.0	0.256	0.786	3.1	Brittle Shear Failure
Specimen RS-4	150.2	0.302	2.465	8.2	Jacket Failure
Specimen RS-2	151.2	0.298	2.515	8.4	Jacket Failure
Specimen RS-3	151.6	0.304	2.495	8.2	Jacket Failure
Specimen RS-5	152.0	0.305	2.411	7.9	Jacket Failure
Specimen RS-6	152.0	0.299	2.357	7.9	Jacket Failure
Specimen RS-7	147.3	0.301	1.686	5.6	Jacket Failure

Chapter 5

COLUMN TESTING

5.1 Test Setup

5.1.1 Set-up for Double Bending Column Testing

Shear enhancement columns are tested in double bending using the shear column testing apparatus, Figures 5.1 and 5.2, located in the UCI Structural Test Hall. A hydraulic actuator connected to a strong wall is fastened to the rigid steel shear arm. This arm is fastened to the top box of the column. The column footing is fastened to the strong floor.

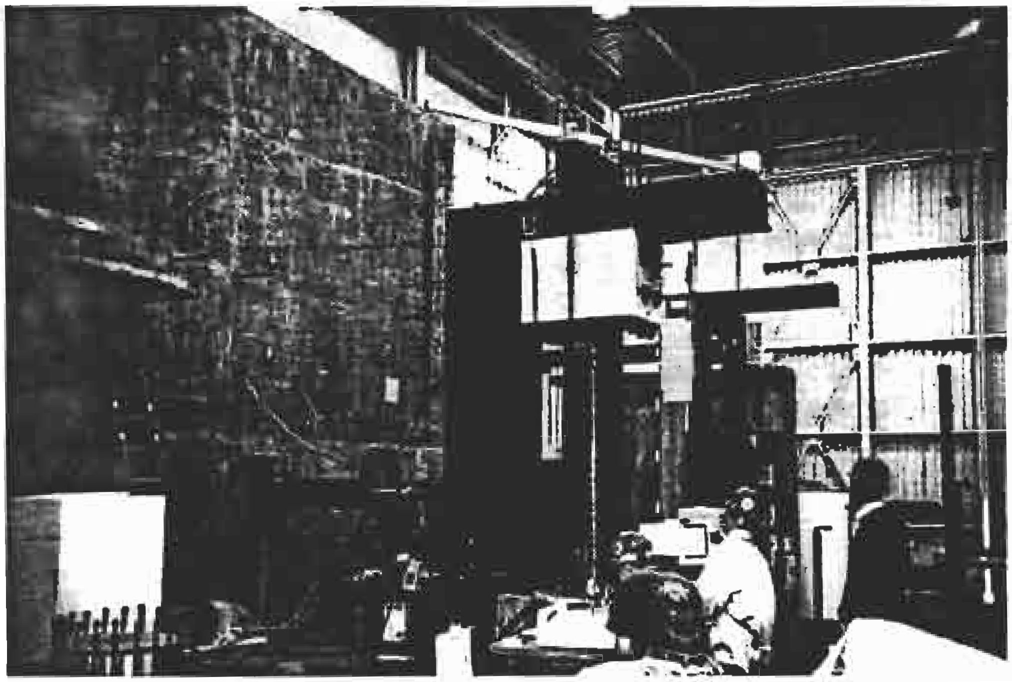

Figure 5.1: Double Bending Column Testing

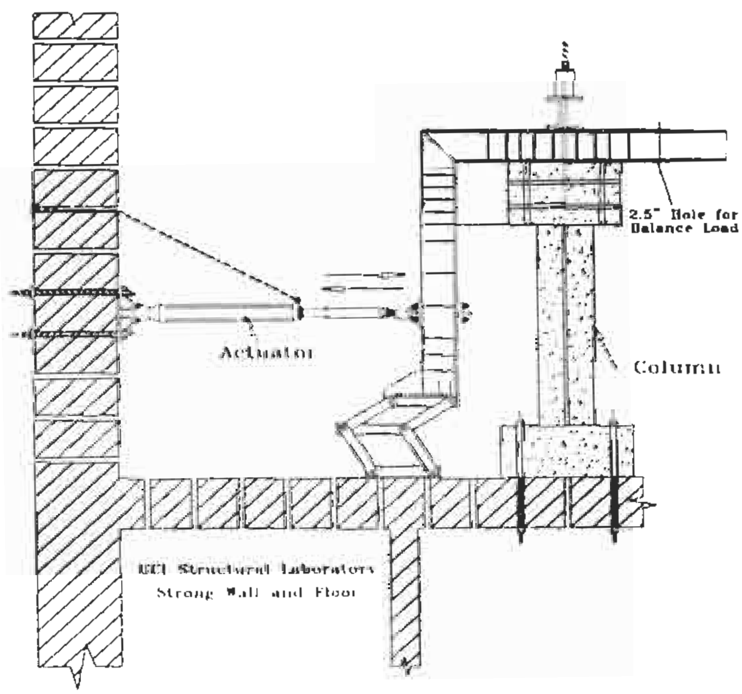

Figure 5.2: Set-up for Double Bending Column Testing

5.1.2 Set-up for Single Bending Column Testing

Lap splice enhancement columns are tested in single bending using the testing apparatus, Figures 5.3 and 5.4, located in the UCI Structural Test Hall. A hydraulic actuator fastened to the strong wall is also fastened to the top of the bending column. The footing is fastened to the strong floor.

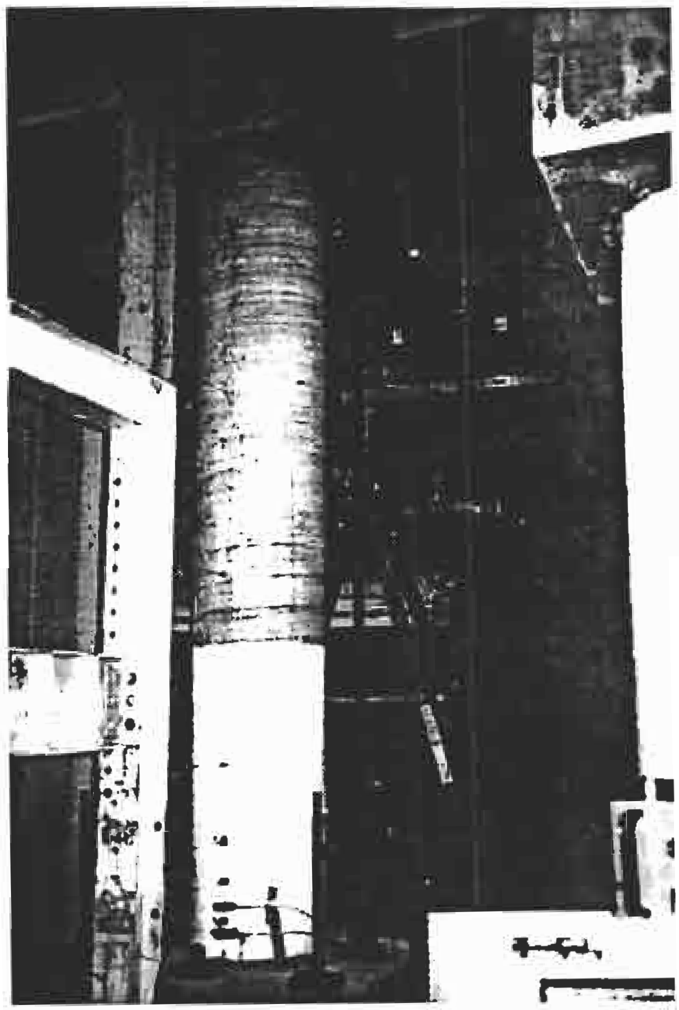

Figure 5.3: Single Bending Column Testing

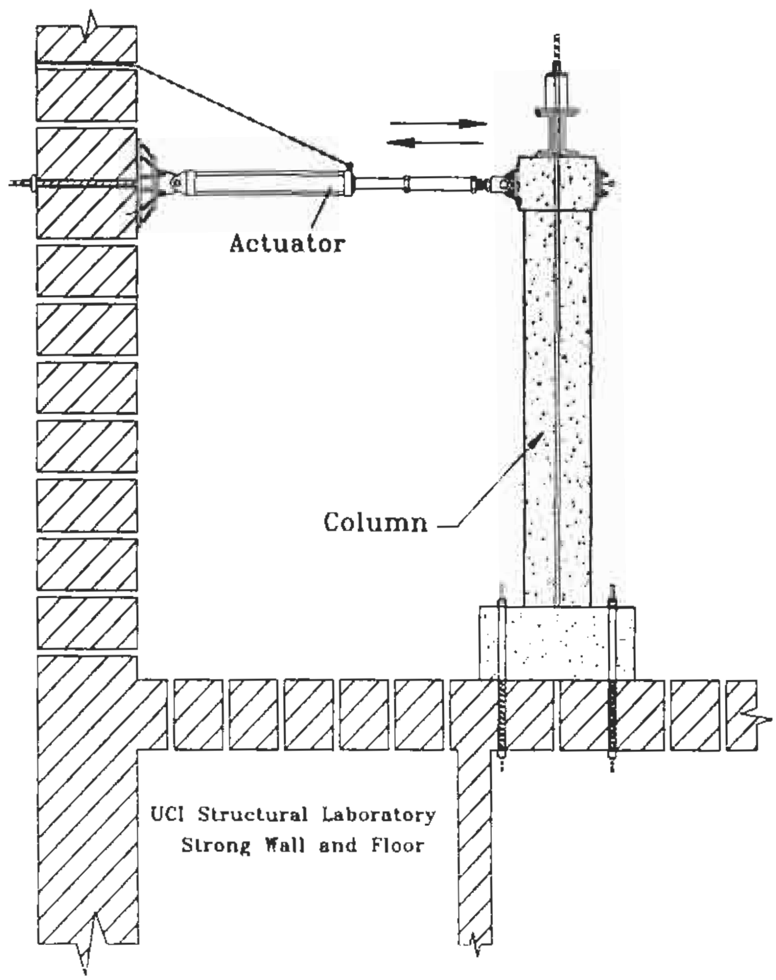

Figure 5.4: Set-up for Single Bending Column Testing

5.2 Column Preparation

5.2.1 Post Tensioning

Shear Columns

The shear column footing is tensioned with 6 vertical steel rods of diameter $d_b = 1.25''$ and yield stress $f_y = 150$ ksi. Each rod is tensioned to 95 kips, well below the rod's yield capacity of 187.5 kips. Through statics, it is determined that this tensioning produces the force necessary to resist 192 kips of lateral load.

The column top box is also tensioned with 4 lateral and 6 vertical steel rods of diameter $d_b = 1.0''$ and yield stress $f_y = 150$ ksi. Each rod is tensioned to 95 kips, below the rod's yield capacity of 150 kips. Through statics, it is determined that this tensioning produces the force necessary to resist 213.7 kips of lateral load for all columns tested.

Tensioning the column in this way prior to the test ensures that it will behave ideally as a shear column. The overall lateral load capacity of the column in the testing apparatus is 192 kips, larger than the expected lateral load.

Bending Columns

The bending column footing is tensioned with 6 vertical steel rods of diameter $d_b = 1.25''$ and yield stress $f_y = 150$ ksi. Each rod is tensioned to 95 kips, well below the rod's yield capacity of 187.5 kips. Through statics, it is determined that this tensioning produces the force necessary to resist 192 kips of lateral load.

The column top box is also tensioned with 4 lateral steel rods of diameter $d_b =$

1.0″ and yield stress $f_y = 150$ ksi. It is not necessary to post-tension these rods since they will simply transfer the lateral load from the actuator to the top of the column. These rods have a combined lateral load capacity of 750 kips.

Tensioning the column in this way prior to the test ensures that it will behave ideally as a bending column. The overall lateral load capacity of the column in the testing apparatus is 192 kips, larger than the expected lateral load for all columns tested.

5.2.2 Instrumentation

Each column is intrumented with several measuring instruments. String potentiometers are attached along the face of the column to measure lateral deflection. Internal strain gages are used to measure strain of the longitudinal steel and transverse steel. Surface strain gages are applied horizontally to measure strain in the column surface. These may be seen in Figures 5.5 and 5.6.

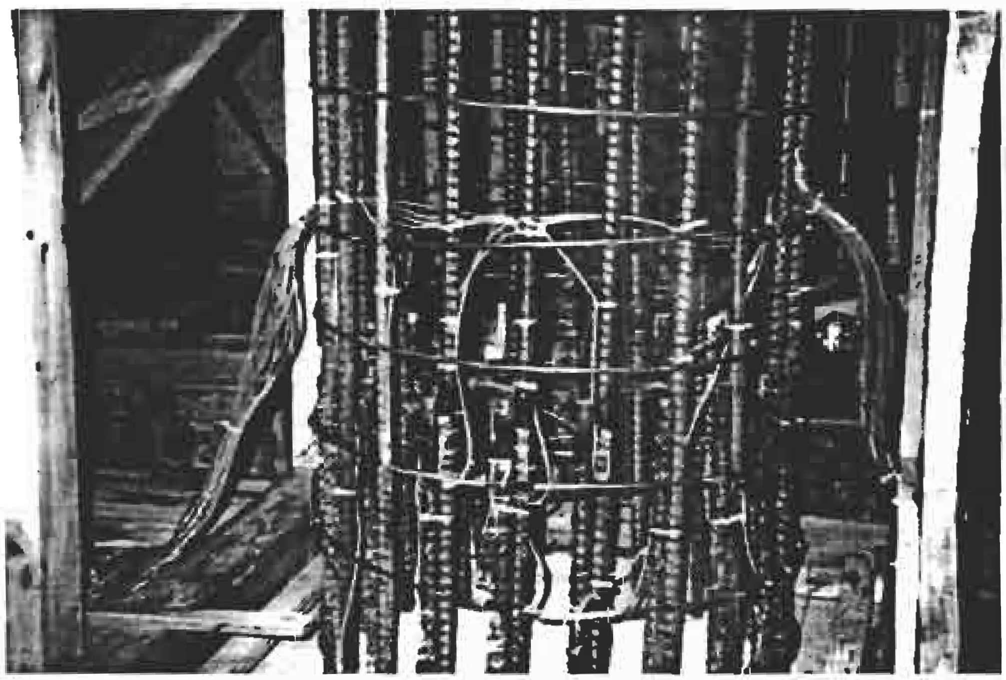

Figure 5.5: Interior Strain Gages

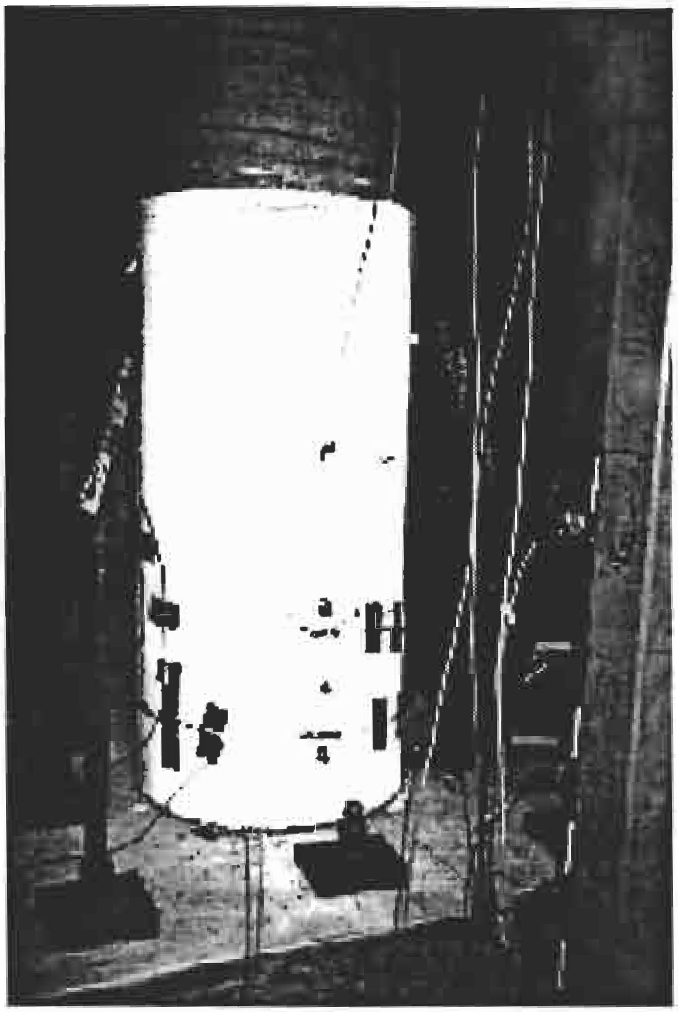

Figure 5.6: Surface Strain Gages

Shear Enhancement Circular Columns

Seven string potentiometers are attached to the face of the column at 6″, 12″, 18″, 30″, 48″, 66″, 84″, 90″, and 96″.

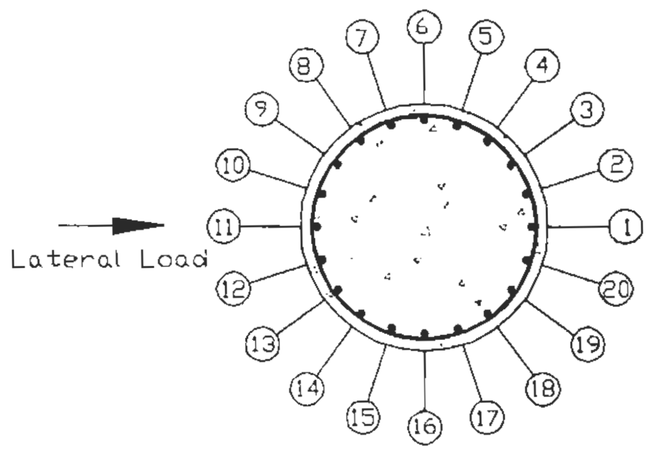

Figure 5.7: Locations of Column Rebar for Shear Enhancement Circular Columns

The locations of the strain gages are labeled in relation to the longitudinal reinforcement, as shown in Table 5.1 and Figure 5.7. For example, the strain gage labeled SC16-88 is located on the surface of the column corresponding to rebar #16, and 88″ from the base of the column.(Note: "I" indicates an inclination of 45°.)

Table 5.1: Sensor Locations for Shear Enhancement Circular Columns

Column Surface (SC)		Vertical Bars (SV)		Transverse Bars (SH)	
Rebar #	Height (in)	Rebar #	Height (in)	Rebar #	Height (in)
16	88	20	92	16	93
11	88	12	92	6	93
6	88	11	92	1	88
1	88	2	92	16	53
16I	80	1	92	6	53
16I	16	20	48	16	48
16	6	14	48	6	48
11	6	12	48	1	8
6	6	11	48	16	3
1	6	10	48	6	3
		2	48		
		1	48		
		20	4		
		12	4		
		11	4		
		10	4		
		1	4		

Lap Splice Enhancement Circular Columns

Seven string potentiometers are attached to the face of the column at 6″, 12″, 18″, 30″, 60″, 90″, 120″, and 144″ from the base of the column.

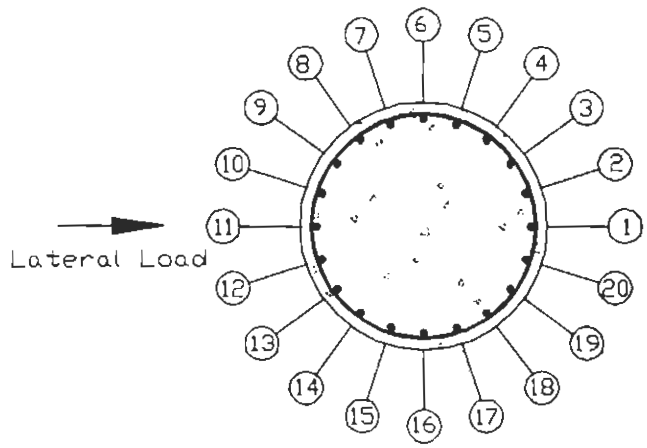

Figure 5.8: Locations of Column Rebar for Lap Splice Enhancement Circular Columns

The locations of the gages are labeled in relation to the longitudinal reinforcement, as shown in Table 5.2 and Figure 5.8. For example, the strain gage labeled SC1-16 is located on the surface of the column corresponding to rebar #1, and 16″ from the base of the column. (Note: "V" indicates a vertical orientation of the strain gage, and "I" indicates an inclination of 45°.)

Table 5.2: Sensor Locations for Lap Splice Enhancement Circular Columns

Column Surface (SC)		Vert. Bars (SV)		Starter Bars (SVS)		Trans. Bars (SH)	
Rebar #	Height	Rebar #	Height	Rebar #	Height	Rebar #	Height
1	16	1	72	1	13	6	72
6V	16	2	72	11	13	16	72
11	16	10	72	1	3	1	12
16I	16	11	72	2	3	11	12
1	8	12	72	10	3	1	7
6	8	20	72	11	3	6	7
11	8	1	15	12	3	11	7
16	8	2	15	20	3	16	7
		10	15			1	2
		11	15			11	2
		12	15				
		20	15				

Lap Splice Enhancement Rectangular Columns

Seven string potentiometers are attached to the face of the column at 6″, 12″, 18″, 30″, 60″, 90″, 120″, and 144″ from the base of the column.

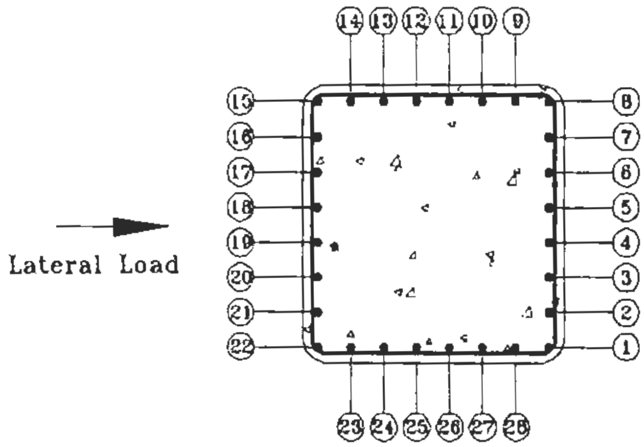

Figure 5.9: Locations of Column Rebar for Lap Splice Enhancement Rectangular Columns

The locations of the gages are labeled in relation to the longitudinal reinforcement, as shown in Table 5.3 and Figure 5.9. For example, the strain gage labeled SC25/26-16 is located on the surface of the column between bars 25 and 26, and 16″ from the base of the column. (Note: "I" indicates an inclination of 45°).

Table 5.3: Sensor Locations for Lap Splice Enhancement Rectangular Columns

Column Surface (SC)		Vert. Bars (SV)		Starter Bars (SVS)		Trans. Bars (SH)	
Rebar #	Height	Rebar #	Height	Rebar #	Height	Rebar #	Height
25/26	16	19	72	18	13	18/19	12
18/19	16	18	72	5	13	4/5	12
11/12	16	15	72	19	3	25/26	7
4/5	16	5	72	18	3	11/12	7
25/26I	8	4	72	16	3	18/19	2
18/19	8	1	72	5	3	4/5	2
11/12	8	19	15	4	3		
4/5	8	18	15	1	3		
		15	15				
		5	15				
		4	15				
		1	15				

Shear Enhancement Rectangular Columns

Seven string potentiometers are attached to the face of the column at 6″, 12″, 18″, 30″, 48″, 66″, 84″, and 90″ from the base of the column. One is attached to the back of the shear arm corresponding to 96″, the top of the column.

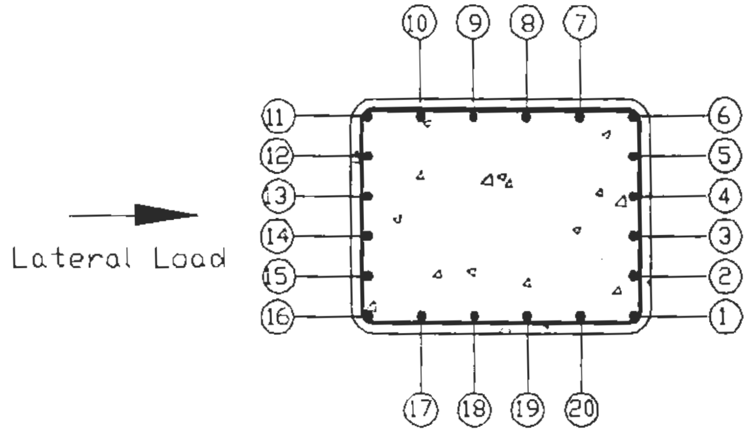

Figure 5.10: Locations of Column Rebar for Shear Enhancement Rectangular Columns

The locations of the gages are labeled in relation to the longitudinal reinforcement, as shown in Table 5.4 and Figure 5.10. For example, the strain gage labeled SC18/19-92 is located on the surface of the column between bars 18 and 19, and 92″ from the base of the column.

Table 5.4: Sensor Locations for Shear Enhancement Rectangular Columns

Column Surface (SC)		Vertical Bars (SV)		Transverse Bars (SH)	
Rebar #	Height (in)	Rebar #	Height (in)	Rebar #	Height (in)
18/19	92	14	92	3/4	93
3/4	92	13	92	13/14	93
18/19	84	11	92	18/19	8
3/4	84	4	92	8/9	8
18/19	72	3	92	3/4	3
18/19	60	1	92	13/14	3
3/4	60	14	48		
18/19	60	3	48		
18/19	48	14	4		
3/4	48	13	4		
18/19	36	11	4		
3/4	36	4	4		
18/19	24	3	4		
18/19	12	1	4		
3/4	12				

5.2.3 Applied Axial Load

Just before the column was tested, an axial load was applied to the top of the column by means of a pair of hydraulic jacks located on top of the column. The jacks were anchored to the strong floor by steel rods as shown in Figures 5.2 and 5.4. The applied axial load satisfies Caltrans requirements for 10% of the column's concrete strength based on the original design strength of 3250 psi. Both the shear and lap splice enhancement circular columns were loaded with 145 kips of axial load. The rectangular lap splice enhancement columns were loaded with 187 kips of axial load. The rectangular shear columns were loaded with 152 kips of axial load.

5.3 Testing Procedure

5.3.1 Data Acquisition

Data from the load cell, the string potentiometers, and the strain gages were recorded using a computer program, "WorkbenchMac, Version 3.1" [Strawberry Tree Inc.]. Data from all sources were logged at 5 readings per second throughout each load level of the test.

5.3.2 Loading Regime

Table 5.5: Loading Regime for All Test Columns

Load (kips)	Displacement (in)	No. of Cycles
$0.25H_y$		3
$0.50H_y$		3
$0.75H_y$		3
$1.00H_y$	Δ_1	3
	$1.0\Delta_y$	3
	$1.5\Delta_y$	3
	$2.0\Delta_y$	3
	$3.0\Delta_y$	3
	$4.0\Delta_y$	3
	$5.0\Delta_y$	3
	$6.0\Delta_y$	3

The column is first loaded with an axial load as prescribed in Section 5.2.3.

The first four levels of the test are applied using lateral load control, as per Caltrans guidelines, given in Table 5.5. The test is stopped at the calculated first yield lateral load. The yield displacement, Δ_y, is determined from

$$\Delta_y = \frac{H_i}{H_y}\Delta_1$$

where Δ_1 is the average of the measured displacements corresponding to the first yield lateral load capacity, H_y, in the push and pull directions, and H_i is the ideal flexural lateral load capacity. The remainder of the test is performed using displacement control in multiples of Δ_y, as shown in Table 5.5. This loading regime was followed closely for each column testing.

Chapter 6

EXPERIMENTAL RESULTS

6.1 Column Behavior

6.1.1 Shear Enhancement Circular Columns

As-built Columns

For the first as-built column (CS-1), it was found that at ductility 1, with a lateral load of $H = 103$ kips, shear cracking at an angle of 30° occured until the column could no longer carry a lateral load. For the second as-built column (CS-2), it was found that at ductility 0.9, with a lateral load of $H = 88.56$ kips, shear cracking at an angle of 30° occured until the column could no longer carry a lateral load. This may be seen in Figure 6.1.

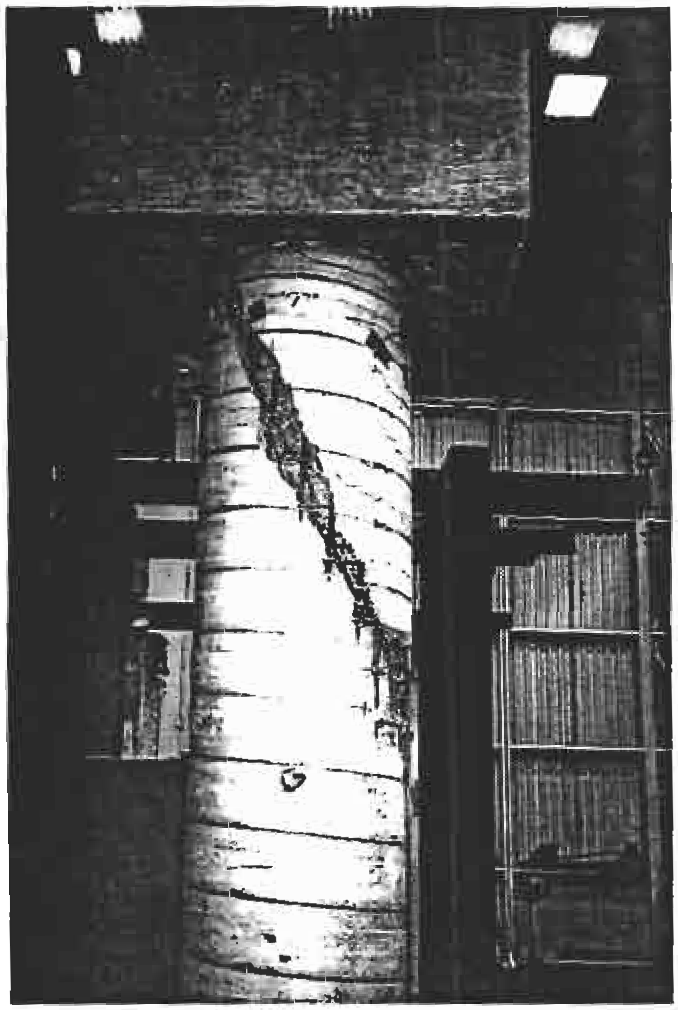

Figure 6.1: Failure of As-built Shear Enhancement Circular Column

Retrofitted Columns

The first two retrofitted shear enhancement columns (CS-2 & CS-3) behaved similarly. At ductility 3, cracking sounds were heard. The columns reached their maximum load carrying capacity at ductility 4. Each continued to carry 80% of their maximum lateral load until about ductility 10. This may be seen in load-displacement plots in Figures F.2 and F.3 in the appendix.

For specimen CS-5, it was found that at ductility 2, cracking sounds were heard. The column reached its maximum lateral load carrying capacity at ductility 3.2. It continued to carry 80% of its maximum lateral load until about ductility 5. This may be seen in load-displacement plots in Figure F.4 in the appendix.

It is apparent that neither of the jacketed columns failed in shear, but rather in extreme concrete crushing within the plastic hinge regions. The composite jackets showed no signs of tensile failure.

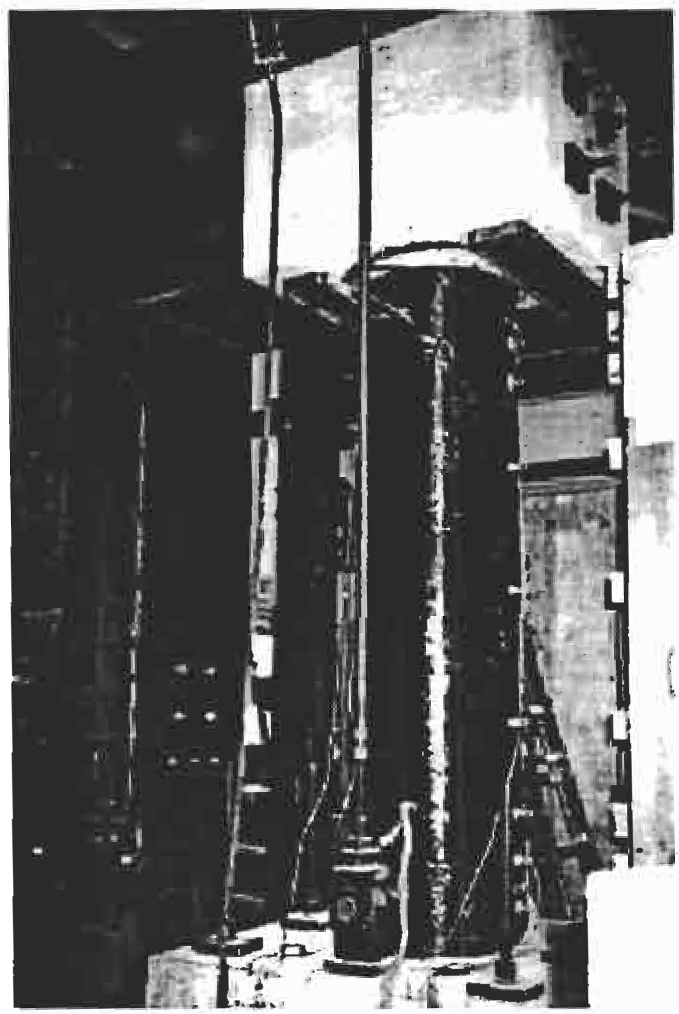

Figure 6.2: Failure of Retrofitted Shear Enhancement Circular Column

6.1.2 Lap Splice Enhancement Circular Columns

As-built Column

At ductility 2, with a lateral load of $H = 36$ kips, vertical concrete cracking occured in the bottom 18″ of the column. This is apparently due to the lap splice failing, causing the concrete to spall. This may be seen in Figure 6.3 and the load-displacement plot shown in Figure F.4 in the appendix.

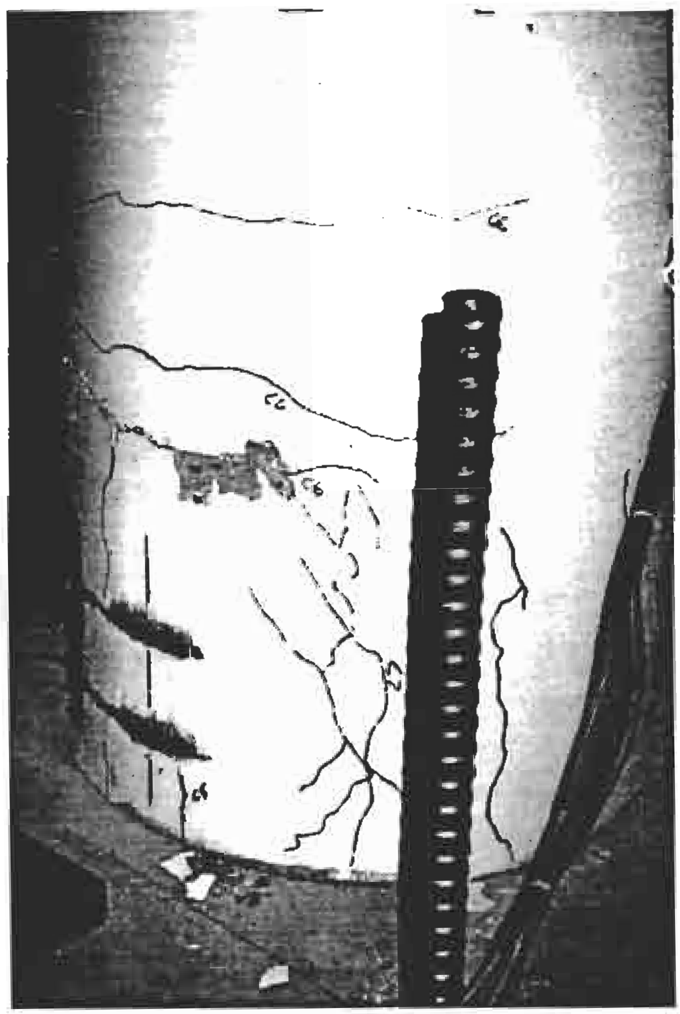

Figure 6.3: Failure of As-built Lap Splice Enhancement Circular Column

Retrofitted Columns

The retrofitted lap splice enhancement circular columns did not behave similarly. The two columns CF-3 and CF-4 performed differently than the other columns tested as a result of under-design. At ductility 2, cracking sounds were heard. At ductility 3, the columns reached their maximum lateral loads of $H = 36$ kips. At this point, the concrete at the base of the column began to crush. The columns continued to carry 80% of their maximum lateral load until ductility 5. This may be seen in the load-displacement plots in Figures F.5 to F.6.

The column CF-8 also performed differently than the other columns tested as a result of a fabrication flaw. At ductility 2, cracking sounds were heard. At ductility 3, the column reached its maximum lateral load of $H = 37$ kips. At this point, the column rapidly lost its lateral load carrying capacity. This may be seen in the load-displacement plot in Figure F.9.

The remainder of the columns behaved similar to each other. At ductility 2, cracking sounds were heard. At ductility 4, the columns reached their maximum lateral load of $H = 43$ kips. At this point, the concrete at the base of the column began to crush. The columns continued to carry 80% of their maximum lateral load until ductility 6. This may be seen in the load-displacement plots in Figures F.8 to F.12.

It is apparent that all of the jacketed columns failed due to lap splice slippage. The composite jackets showed no signs of tensile failure. This is shown in Figure 6.4.

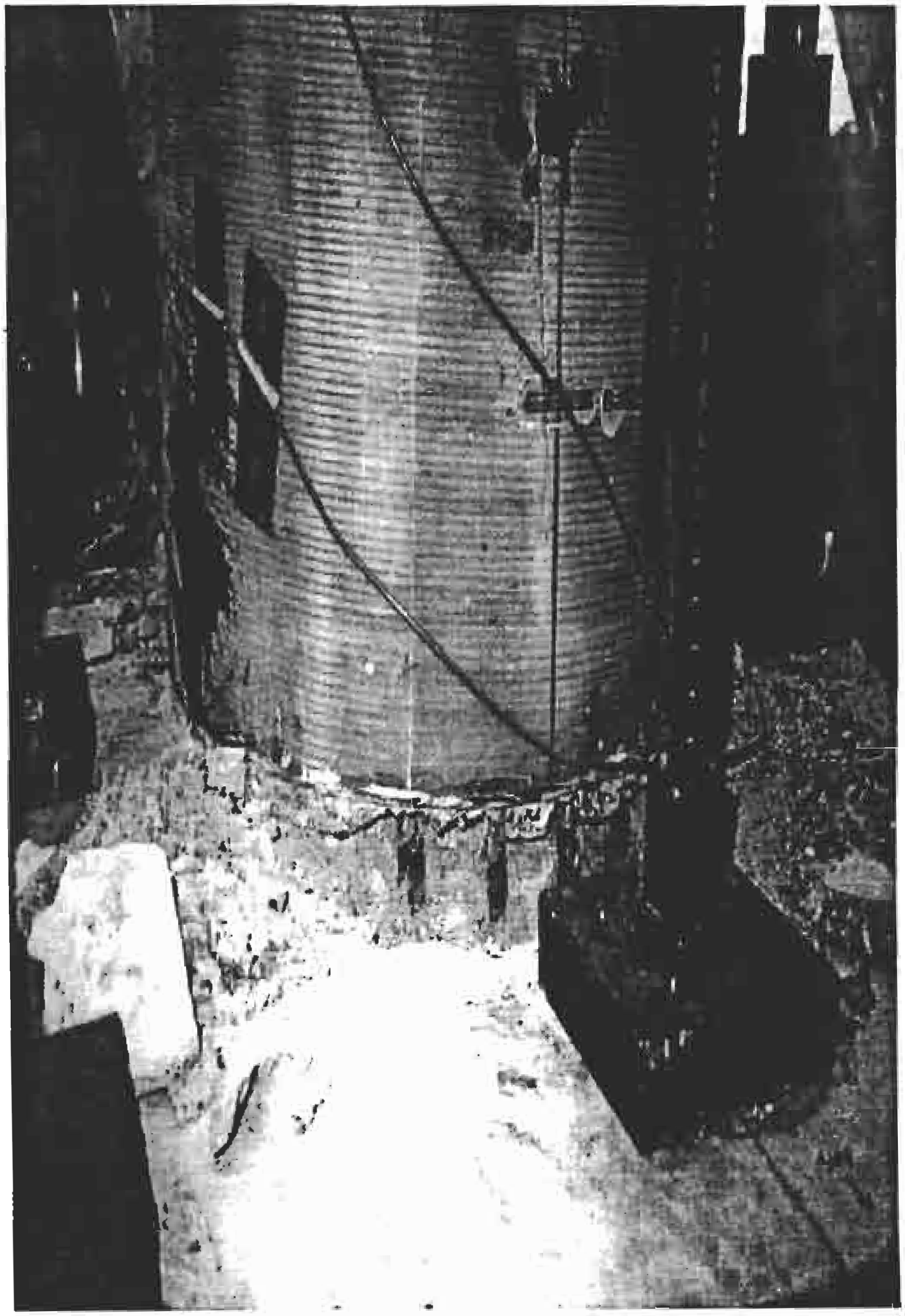

Figure 6.4: Failure of Retrofitted Lap Splice Enhancement Circular Column

6.1.3 Lap Splice Enhancement Rectangular Columns

As-built Column

At ductility 0.5, with a lateral load of $H = 52$ kips, vertical concrete cracking occured in the bottom 18″ of the column. This is apparently due to the lap splice failing, causing the concrete to spall. This may be seen in Figure 6.5 and the load-displacement plot in Figure F.13.

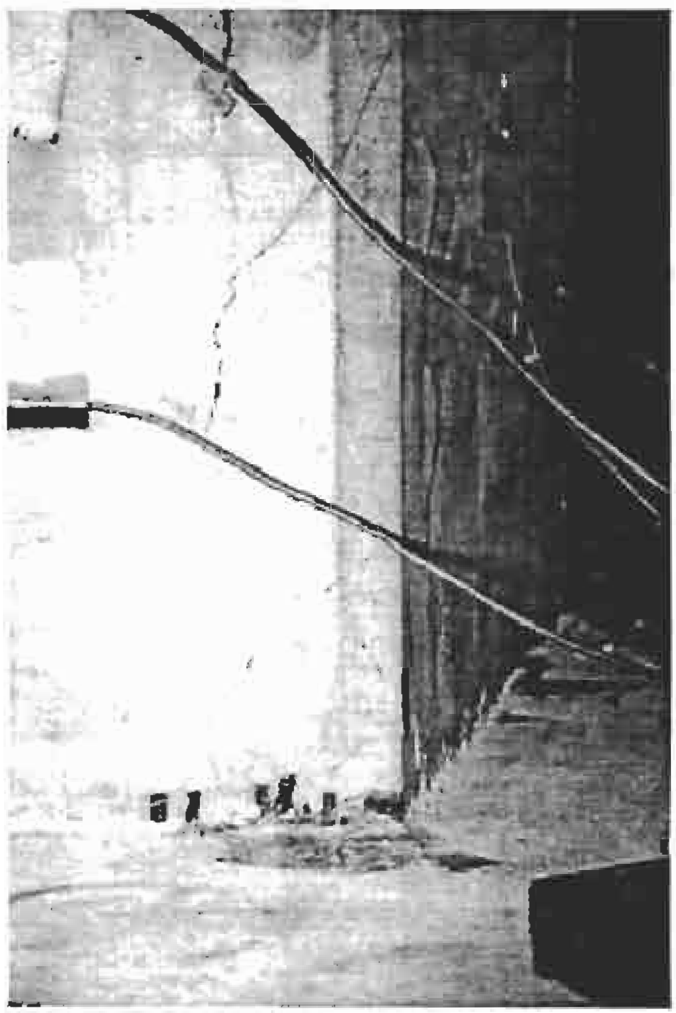

Figure 6.5: Failure of As-built Lap Splice Enhancement Rectangular Column

Retrofitted Columns

Each of columns RF-2, RF-3, and RF-6 behaved similarly. At ductility 1, the columns reached a lateral load capacity of about 70 kips, at which time, the lap splices failed. This may be seen in the load-displacement plot in Figures F.14, F.15, and F.17.

For column RF-5, it was found that at ductility 1.7, it reached a lateral load capacity of 81 kips, at which time, the lap splice failed. This may be seen in the load-displacement plot in Figure F.16.

It is apparent that each of the jacketed columns failed due to lap splice slippage. The composite jackets showed no signs of tensile failure. This failure is shown in Figure 6.6.

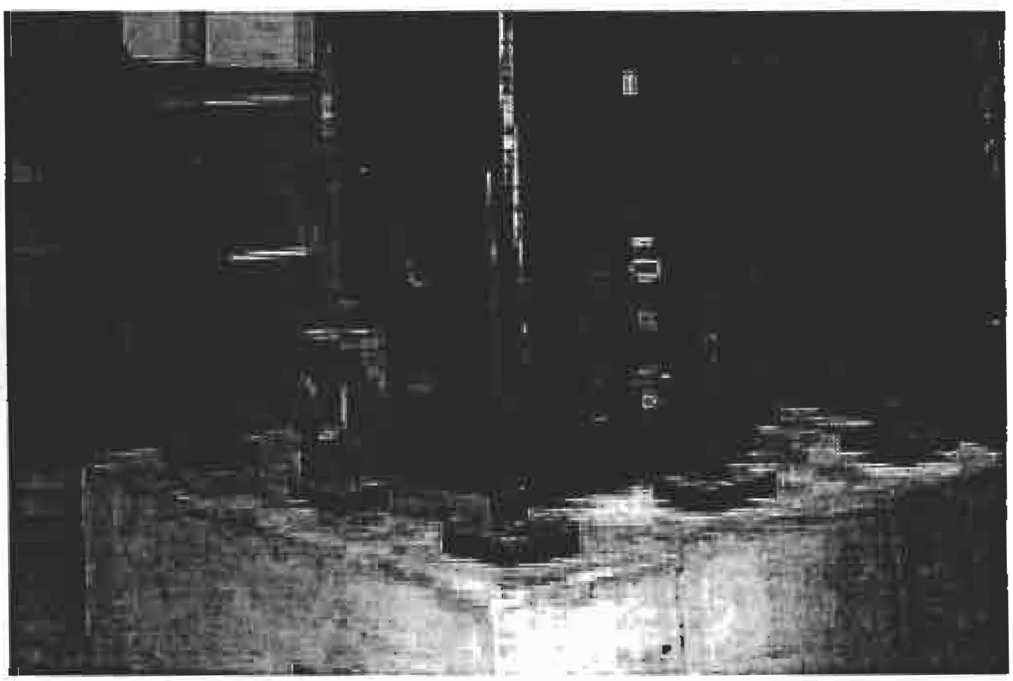

Figure 6.6: Failure of Retrofitted Lap Splice Enhancement Rectangular Column

6.1.4 Shear Enhancement Rectangular Columns

As-built Column

During the first cycle of the third load level, at ductility 1, with a lateral load of $H = 60$ kips, shear cracking at an angle of 30° occured until the column could no longer carry a lateral load. This may be seen in Figure 6.7 and the load-displacement plot in Figure F.16.

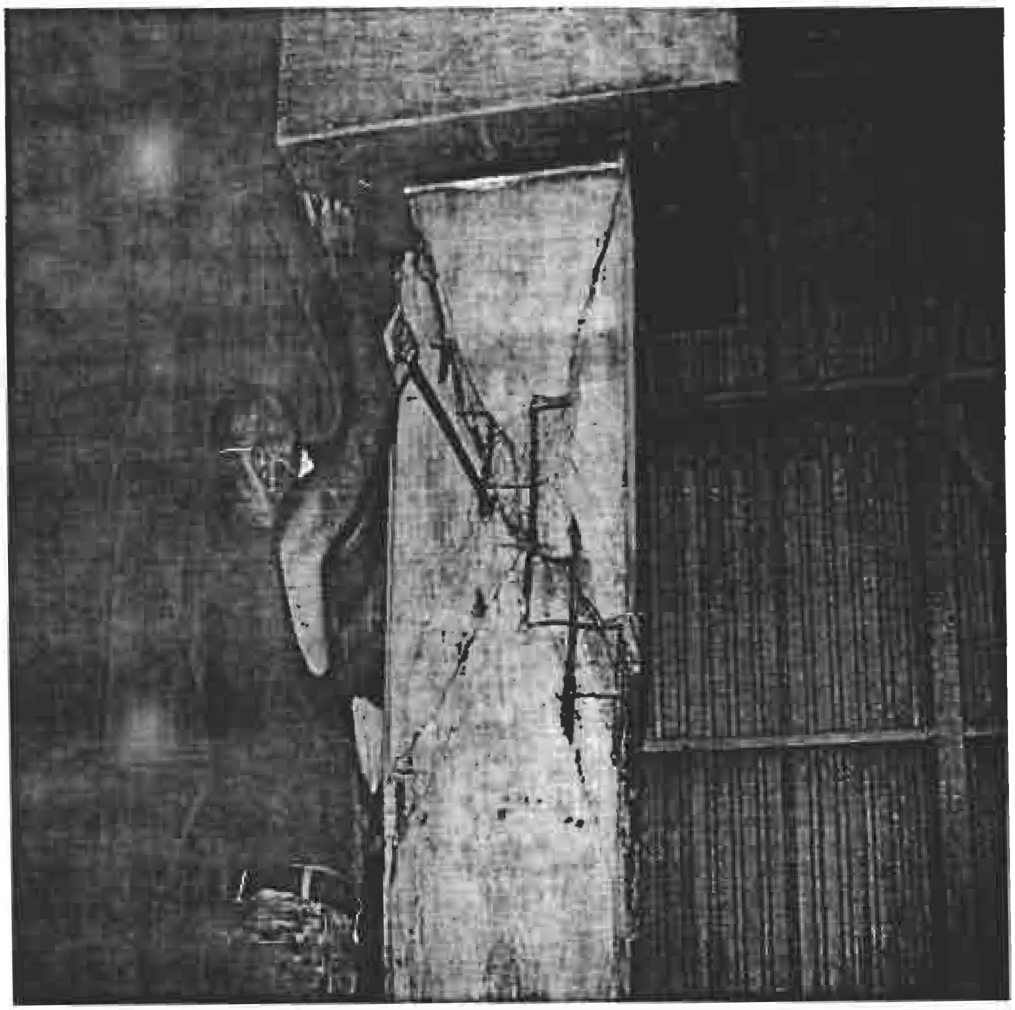

Figure 6.7: Failure of As-built Shear Enhancement Rectangular Column

Retrofitted Columns

Each of the shear enhancement rectangular columns behaved similarly. At ductility 1.5, cracking sounds were heard. At ductility 3, the jacket began to dilate within the plastic hinge regions, in the top and bottom 8″ of the columns. This dilation continued through the remainder of the test. The columns reached their maximum load carrying capacity at about ductility 3. They continued to carry 80% of their maximum lateral load up to ductility 6. This may be seen in load-displacement plots in Figures F.17 to F.22.

It is apparent that none of the jacketed columns failed in shear, but rather in extreme concrete crushing within the plastic hinge regions. The composite jackets showed no signs of tensile failure. This failure is shown in Figure 6.8.

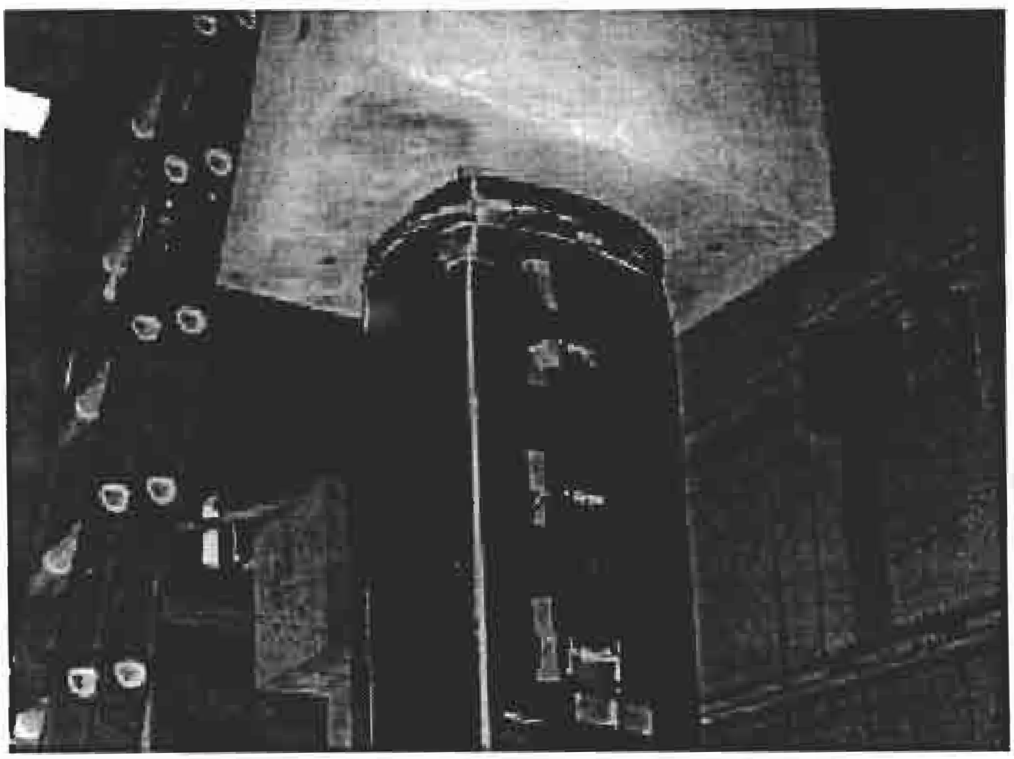

Figure 6.8: Failure of Retrofitted Shear Enhancement Rectangular Column

Table 6.1: Column Failure Modes

	H_u (kip)	Failure Mode
Circular Shear Enhancement Columns		
As-built CS-1	103.05	Shear
Specimen CS-3	114.85	Concrete Crushing
Specimen CS-2	118.63	Concrete Crushing
As-built CS-4	88.56	Shear
Specimen CS-5	123.11	Concrete Crushing
Circular Lap Splice Enhancement Columns		
As-built CF-2	35.79	Lap Splice Slipping
Specimen CF-4	36.27	Lap Splice Slipping
Specimen CF-3	40.56	Lap Splice Slipping
As-built CF-1	36.35	Lap Splice Slipping
Specimen CF-6	43.08	Lap Splice Slipping
Specimen CF-8	37.76	Lap Splice Slipping
Specimen CF-5	43.48	Lap Splice Slipping
Specimen CF-9	44.41	Lap Splice Slipping
Specimen CF-7	43.56	Lap Splice Slipping
Rectangular Lap Splice Enhancement Columns		
As-built RF-1	52.67	Lap Splice Slipping
Specimen RF-3	70.74	Lap Splice Slipping
Specimen RF-2	71.00	Lap Splice Slipping
Specimen RF-5	81.87	Lap Splice Slipping
Specimen RF-6	73.37	Lap Splice Slipping
Rectangular Shear Enhancement Columns		
As-built RS-1	59.89	Shear
Specimen RS-4	135.10	Concrete Crushing
Specimen RS-2	130.78	Concrete Crushing
Specimen RS-3	131.25	Concrete Crushing
Specimen RS-5	137.82	Concrete Crushing
Specimen RS-6	140.29	Concrete Crushing
Specimen RS-7	133.99	Concrete Crushing

6.2 Data Analysis

6.2.1 Displacement Profile

Data obtained from the string potentiometers are plotted against the column height for each load level to obtain the maximum column profile for each cycle of loading as shown in Appendix F.

6.2.2 Force-Displacement Relationships

Throughout the test, data are collected for the lateral load versus top displacement. Strain gages located on the load cell indicated the lateral load on the column. A string potentiometer located at the top of the column recorded the lateral displacement of the column. Data obtained from these records are plotted in Appendix G.

From these data, a load-displacement envelope may be obtained for each column. These envelopes are plotted in comparison to other columns in Figures 6.9 to 6.12.

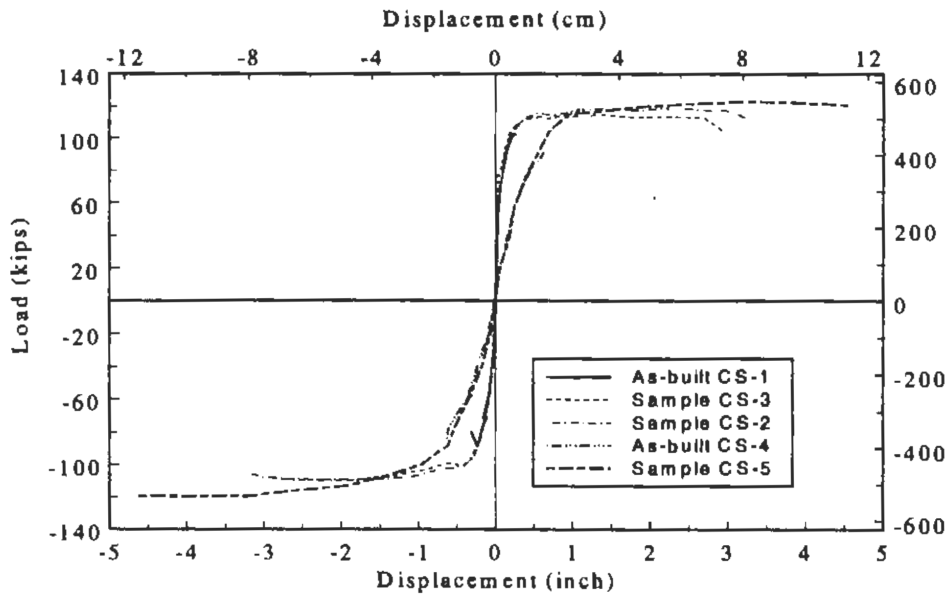

Figure 6.9: Experimental Load-Displacement Envelopes for Shear Enhancement Circular Columns

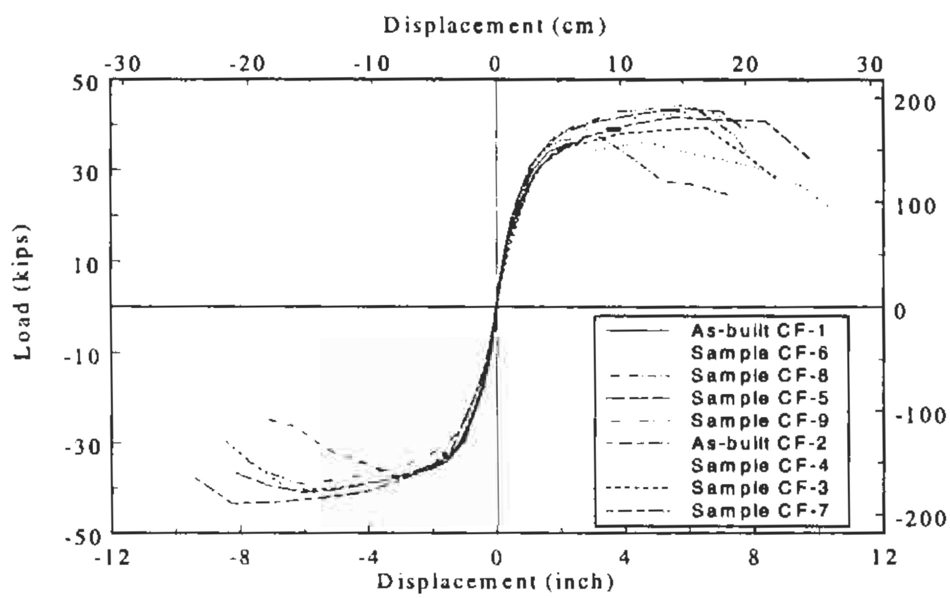

Figure 6.10: Experimental Load-Displacement Envelopes for Lap Splice Enhancement Circular Columns

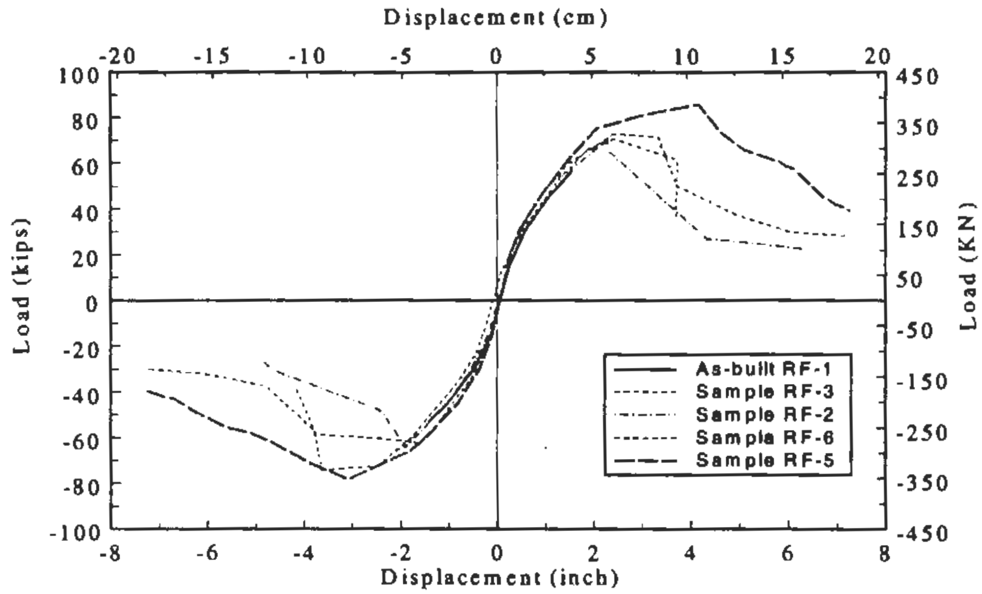

Figure 6.11: Experimental Load-Displacement Envelopes for Lap Splice Enhancement Rectangular Columns

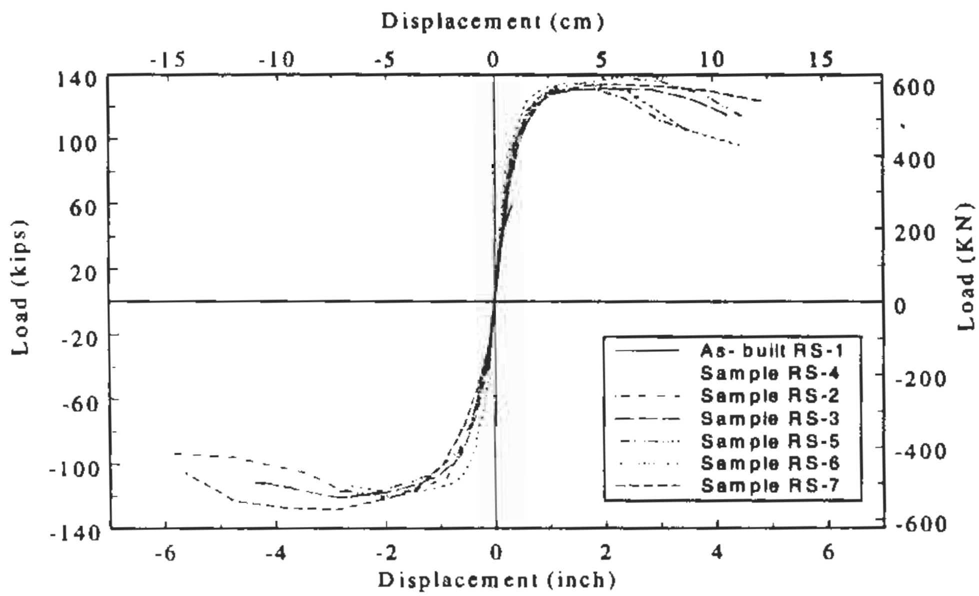

Figure 6.12: Experimental Load-Displacement Envelopes for Shear Enhancement Rectangular Columns

6.2.3 Strain Gage Analysis

Data obtained from the strain gages are logged in the form of voltage values, E_o, and converted to strain using the equation

$$\epsilon = \frac{4E_o}{V \times GF \times \text{gain} \times \text{mult}} \tag{6.1}$$

where V is the voltage of the power supply, GF is the gage factor of 2.09 for surface gages, and 2.085 for interior strain gages. Gain and mult are the gain and multiplication settings of the conditioner which were set at 1.5 and 200, respectively.

6.3 Displacement Ductility

The average column displacement, Δ, is found from the data files at a load level, H, within the elastic zone. The ideal yield displacement, Δ_y is then obtained as follows

$$\Delta_y = \frac{H_i}{H}\Delta \tag{6.2}$$

The lateral load carrying capacity of the column dropped significantly after displacement Δ_u. The displacement ductility, μ_Δ, is then found to be

$$\mu_\Delta = \frac{\Delta_u}{\Delta_y} \tag{6.3}$$

These values are calculated as shown in Table 6.2.

Table 6.2: Experimental Evaluation of Column Ductility

	H_i (kip)	H (kip)	Δ (in)	Δ_y (in)	Δ_u (in)	μ_Δ
Circular Shear Enhancement Columns						
As-built CS-1	100.50	73.75	0.114	0.281	0.263	0.9
Specimen CS-3	104.60	74.00	0.082	0.293	2.953	10.1
Specimen CS-2	104.18	74.00	0.098	0.299	3.249	10.9
As-built CS-4	122.50	88.56	0.549	0.759	0.688	0.9
Specimen CS-5	136.09	94.50	0.613	0.883	4.549	5.2
Circular Lap Splice Enhancement Columns						
As-built CF-2	33.58	24.60	0.855	1.167	2.351	2.0
Specimen CF-4	34.33	24.70	1.020	1.418	7.883	5.6
Specimen CF-3	34.27	24.70	0.880	1.221	7.746	6.3
As-built CF-1	33.83	24.60	0.782	1.076	2.666	2.5
Specimen CF-6	34.49	25.08	0.813	1.118	7.790	7.0
Specimen CF-8	35.15	24.67	0.742	1.057	4.034	3.8
Specimen CF-5	35.00	24.17	0.715	1.035	5.921	5.7
Specimen CF-9	35.15	24.67	0.860	1.226	7.397	6.0
Specimen CF-7	34.53	25.50	1.017	1.377	8.344	6.1
Rectangular Lap Splice Enhancement Columns						
As-built RF-1	78.99	52.00	1.363	2.070	1.398	0.7
Specimen RF-3	85.16	52.00	1.211	1.983	2.422	1.2
Specimen RF-2	87.64	57.42	1.562	2.384	2.278	1.0
Specimen RF-5	89.25	59.50	1.373	2.06	4.765	2.3
Specimen RF-6	86.74	57.33	1.565	2.367	3.637	1.5
Rectangular Shear Enhancement Columns						
As-built RS-1	118.04	41.03	0.116	0.334	0.325	1.0
Specimen RS-4	132.50	88.00	0.226	0.341	2.387	7.0
Specimen RS-2	130.68	88.00	0.417	0.619	3.606	5.8
Specimen RS-3	131.00	94.50	0.504	0.698	4.300	6.2
Specimen RS-5	132.99	95.00	0.531	0.743	4.523	6.1
Specimen RS-6	134.04	94.50	0.602	0.854	4.248	5.0
Specimen RS-7	134.04	94.50	0.617	0.875	3.844	4.4

6.4 Interpretation of Strain Gage Analysis

6.4.1 Shear Enhancement Circular Columns

As-built Column

Observations are made for the as-built column from the strain gage analysis. The surface strain gages measured strains of about $\epsilon = 0.0005$. The transverse steel did not reach a strain corresponding to steel yielding. The longitudinal steel reached strains of about $\epsilon = 0.002$ at the base of the column and $\epsilon = 0.004$ at the top of the column, larger than the yield strain of the steel ($\epsilon_y = 0.0015$). These results correspond to the expected column performance.

Retrofitted Columns

Observations are also made for the retrofitted columns from the strain gage analysis. The surface of the column developed lateral strains in excess of $\epsilon_j = 0.003$, but not greater than the allowed jacket strain of $\epsilon_j = 0.004$. The transverse steel at the top and bottom of the column reached strains in excess of $\epsilon_y = 0.0016$ corresponding to steel yielding. The longitudinal steel reached strains of $\epsilon = 0.006$, much larger than the yield stain of the steel ($\epsilon_y = 0.0015$) but less than the ultimate strain of the steel ($\epsilon_u = 0.12$). These results correspond to the expected column performance.

6.4.2 Lap Splice Enhancement Circular Columns

As-built Column

Observations are made for the as-built column from the strain gage analysis. The surface strain gages measured strains of about $\epsilon = 0.0005$. The transverse steel reached strains of about $\epsilon = 0.001$ corresponding to steel yielding. The longitudinal steel reached strains of about $\epsilon = 0.0025$, larger than the yield strain of the steel ($\epsilon_y = 0.0015$). The longitudinal steel starter bars reached strains of about $\epsilon = 0.006$, much larger than the yield strain of the steel ($\epsilon_y = 0.0015$). These results correspond to the expected column performance.

Retrofitted Columns

Observations are also made for the retrofitted column from the strain gage analysis. The surface of the column developed transverse strains of $\epsilon_j = 0.0008$, but not greater than the allowed jacket strain of $\epsilon_j = 0.001$. The transverse steel at the bottom of the column reached strains of $\epsilon_y = 0.001$, indicating steel yielding. The longitudinal steel reached strains of $\epsilon = 0.003$, larger than the yield strain of the steel ($\epsilon_y = 0.0015$) but less than the ultimate strain of the steel ($\epsilon_u = 0.12$). The longitudinal steel starter bars reached strains in excess of $\epsilon = 0.006$, also larger than the yield strain of the steel ($\epsilon_y = 0.0015$) but less than the ultimate strain of the steel ($\epsilon_u = 0.12$). These results correspond to the expected column performance.

6.4.3 Lap Splice Enhancement Rectangular Columns

As-built Column

Observations are made for the as-built column from the strain gage analysis. The surface strain gages measured negligible strains in the horizontal direction, but strains of about $\epsilon = 0.001$ in the vertical direction. The transverse steel had negligible steel strains. The longitudinal steel as well as the starter bars reached strains of about $\epsilon = 0.004$, larger than the yield strain of the steel ($\epsilon_y = 0.002$). These results correspond to the expected column performance.

Retrofitted Columns

Observations are also made for the retrofitted columns from the strain gage analysis. The surface of the column developed transverse strains of $\epsilon_j = 0.0009$, but not greater than the allowed jacket strain of $\epsilon_j = 0.001$. The transverse steel at the base of the column reached strains of $\epsilon_y = 0.001$, indicating steel yielding. The longitudinal steel reached strains of $\epsilon = 0.003$, larger than the yield strain of the steel ($\epsilon_y = 0.002$) but less than the ultimate strain of the steel ($\epsilon_u = 0.12$). The longitudinal steel starter bars reached strains of $\epsilon = 0.002$, near to the yield strain of the steel ($\epsilon_y = 0.002$) and less than the ultimate strain of the steel ($\epsilon_u = 0.12$). These results correspond to the expected column performance.

6.4.4 Shear Enhancement Rectangular Columns

As-built Column

Observations are made for the as-built column from the strain gage analysis. The surface strain gages measured negligible strains, probably as a result of gage failure due to surface cracking. The transverse steel did not reach a strain corresponding to steel yielding. The longitudinal steel reached strains of about $\epsilon = 0.0025$, larger than the yield strain of the steel ($\epsilon_y = 0.0015$). These results correspond to the expected column performance.

Retrofitted Columns

Observations are also made for the retrofitted columns from the strain gage analysis. The surface of the column developed lateral strains in excess of $\epsilon_j = 0.003$, but not greater than the allowed jacket strain of $\epsilon_j = 0.004$. The transverse steel at the top and bottom of the column reached strains in excess of $\epsilon_y = 0.0016$ corresponding to steel yielding. The longitudinal steel reached strains of $\epsilon = 0.005$, much larger than the yield strain of the steel ($\epsilon_y = 0.0015$) but less than the ultimate strain of the steel ($\epsilon_u = 0.12$). These results correspond to the expected column performance.

Chapter 7

SUMMARY OF FINDINGS

7.1 Conclusions

By testing multiple similar columns retrofitted with advanced composite material jackets, it may be concluded that:

- Advanced composite jacket retrofit systems can significantly enhance the ductility of old circular and rectangular bridge columns with insufficient shear reinforcement.

- Advanced composite jacket retrofit systems can significantly enhance the ductility of old circular bridge columns with lap splices in the plastic hinge region.

- The performance of advanced composite jacket systems can be predicted by a standard analysis using equivalent steel hoops and a moment-curvature analysis.

- The lateral stiffness of the columns is not affected by the composite jackets contrary to steel jackets which alter the lateral stiffness, and consequently, the bridge dynamic characteristics.

- Under the design procedure reported in this document, the rectangular composite jacket cannot develop the strength necessary to inhibit lap splice slippage in rectangular columns.

- Fabrication and application of the composite jacket systems must be carefully controlled in order for the jacket to achieve the necessary confining strength as was demonstrated in specimen CF-8.

7.2 Proposed Future Investigations

Future testing is required to study the following issues:

- The confinement effectiveness coefficient, K_e, must be developed further. There are many variables which may affect the confinement effectiveness of the composite jacket, including the bonding of the composite jacket to the column surface, the strength of the concrete, and the shape and size of the column cross section.

- An analytical model must be developed which would relate the extreme fiber concrete strain, ϵ_c, to the lateral strain in the composite jacket ϵ_j. This model should take into consideration the jacket thickness, the elastic modulus of the jacket, and the cross section of the column. It will then be possible to model the confinement provided by the composite jacket at each step of a moment curvature analysis.

- Further testing must be performed on rectangular lap splice columns using various composite jacket designs. One possible design would be an elliptical jacket with rigid inserts within the plastic hinge region.

Nomenclature

A_{vj} = equivalent transverse steel area of the jacket
A_v = transverse steel area within a section of depth s
A_{tb} = cross sectional area of the transverse steel
A_e = effective area in shear equal to $0.8A_{gross}$
b = width of the column cross section
c = depth of the compression block
d_{bl} = nominal diameter of the longitudinal reinforcement
d' = center to center depth of transverse reinforcement
d = depth of the column cross section
Δ_1 = lateral displacement at first yield
Δ_p = plastic displacement
Δ_u = ultimate displacement
Δ_y = idealized yield displacement
E_j = elastic modulus of the composite jacket
E_s = Young's modulus of the transverse reinforcement
ϵ_{cu} = ultimate strain in the concrete at confinement failure
ϵ_{cuj} = concrete strain at composite jacket failure
ϵ_{cut} = concrete strain at transverse steel failure
ϵ_j = jacket design strain
ϵ_{su} = ultimate strain of the longitudinal column steel
ϵ_{sj} = expected maximum strain in the composite jacket
f'_c = actual concrete strength
f'_{cc} = confined concrete compressive strength
f'_l = overall lateral confinement
f_{lj} = lateral confining pressure by the composite jacket
f_{lt} = lateral confining pressure by the transverse reinforcement
f_{ye} = yield stress of the longitudinal reinforcement
f_{yt} = yield stress of transverse steel
f_{uj} = ultimate strength of the composite jacket
f_j = stress in the jacket corresponding to a jacket strain
H_y = lateral load capacity at column yield
h = half the height of the column
h_e = effective column height for half of the column
K_c = confinement effectiveness coefficient
k = concrete shear stength coefficient
L_p = equivalent plastic hinge length
M_y = yield moment
M_i = ideal moment
M_u = ultimate moment

μ_Δ = displacement ductility
N' = required number of composite jacket layers
N = number of composite jacket layers
P = applied axial load
p = confinement pressure provided by the jacket
ϕ_1 = first yield curvature
ϕ_y = ideal yield curvature
ϕ_u = ultimate curvature
ρ_{sj} = volumetric ratio of the composite jacket
ρ_{st} = volumetric ratio of confinement steel
ρ_x = confinement steel ratio in the strong direction
ρ_y = confinement steel ratio in the weak direction
s' = equivalent steel transverse reinforcement spacing
s = transverse reinforcement spacing
θ° = angle of shear crack with respect to the vertical axis
θ_p = plastic rotation
t'_j = required thickness of the jacket
t_l = thickness of one layer of composite jacket material
V' = overall column shear strength
V_c = shear strength due to concrete
V_{cj} = shear strength due to composite jacket
V_s = shear strength due to lateral steel
V_p = shear strength due to axial load

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Appendix A

COMPOSITE JACKET APPLICATION

A.1 Shear Enhancement Circular Columns

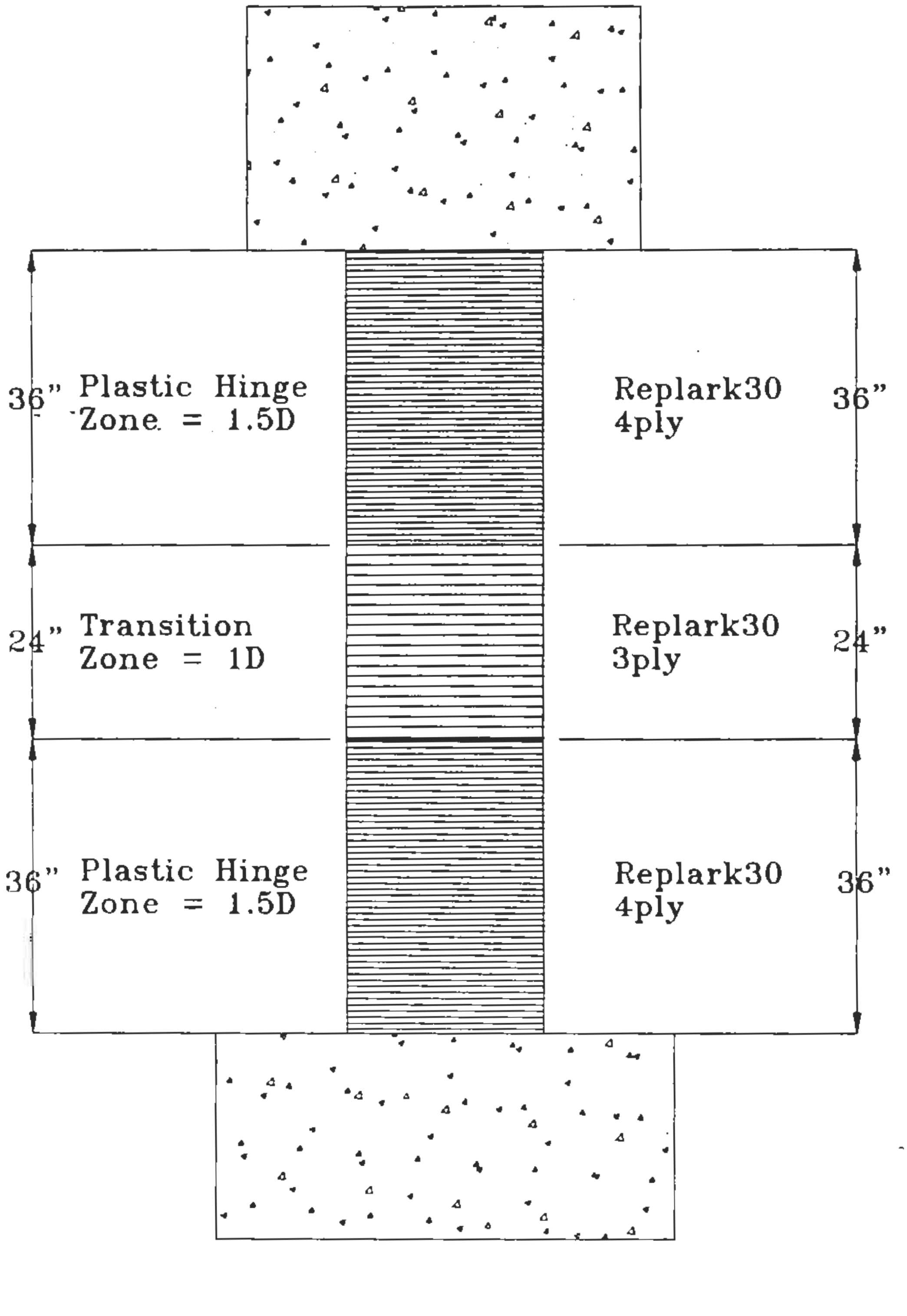

Figure A.1: Composite Jacket for Shear Enhancement Circular Column CS-3

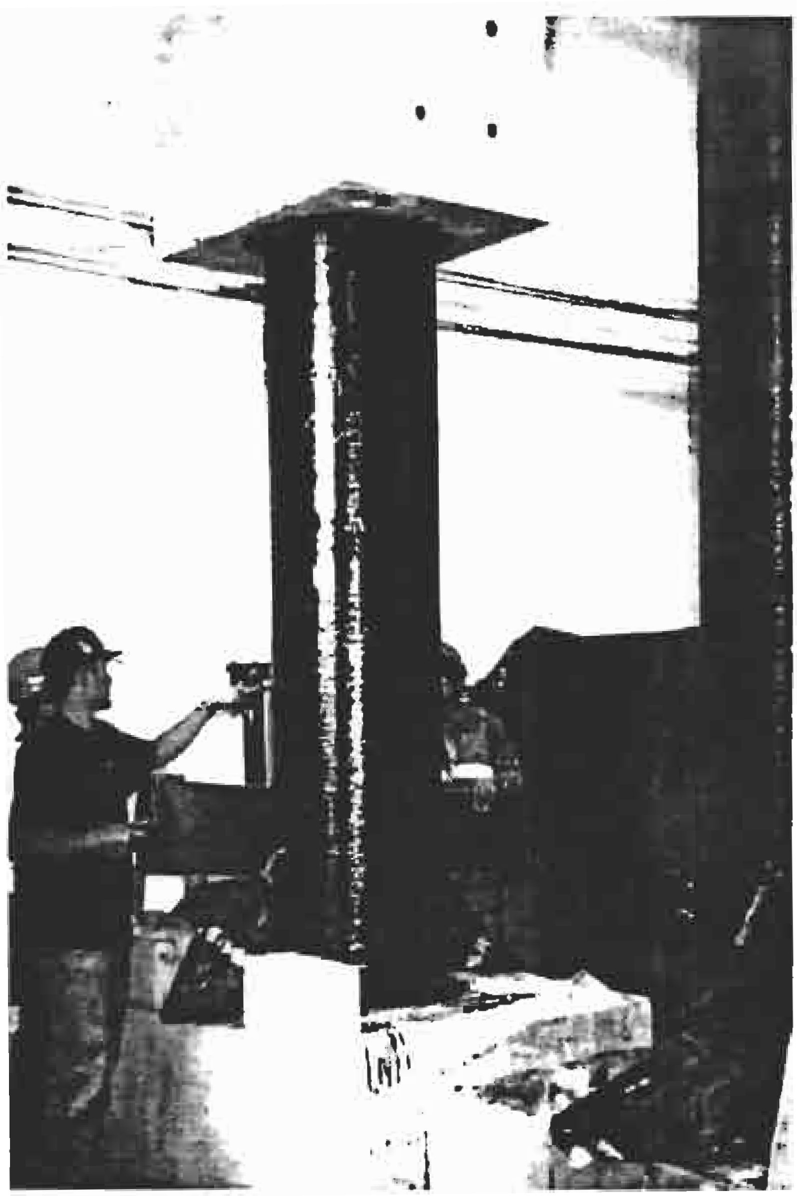

Figure A.2: Jacket Application for Shear Enhancement Circular Column CS-3

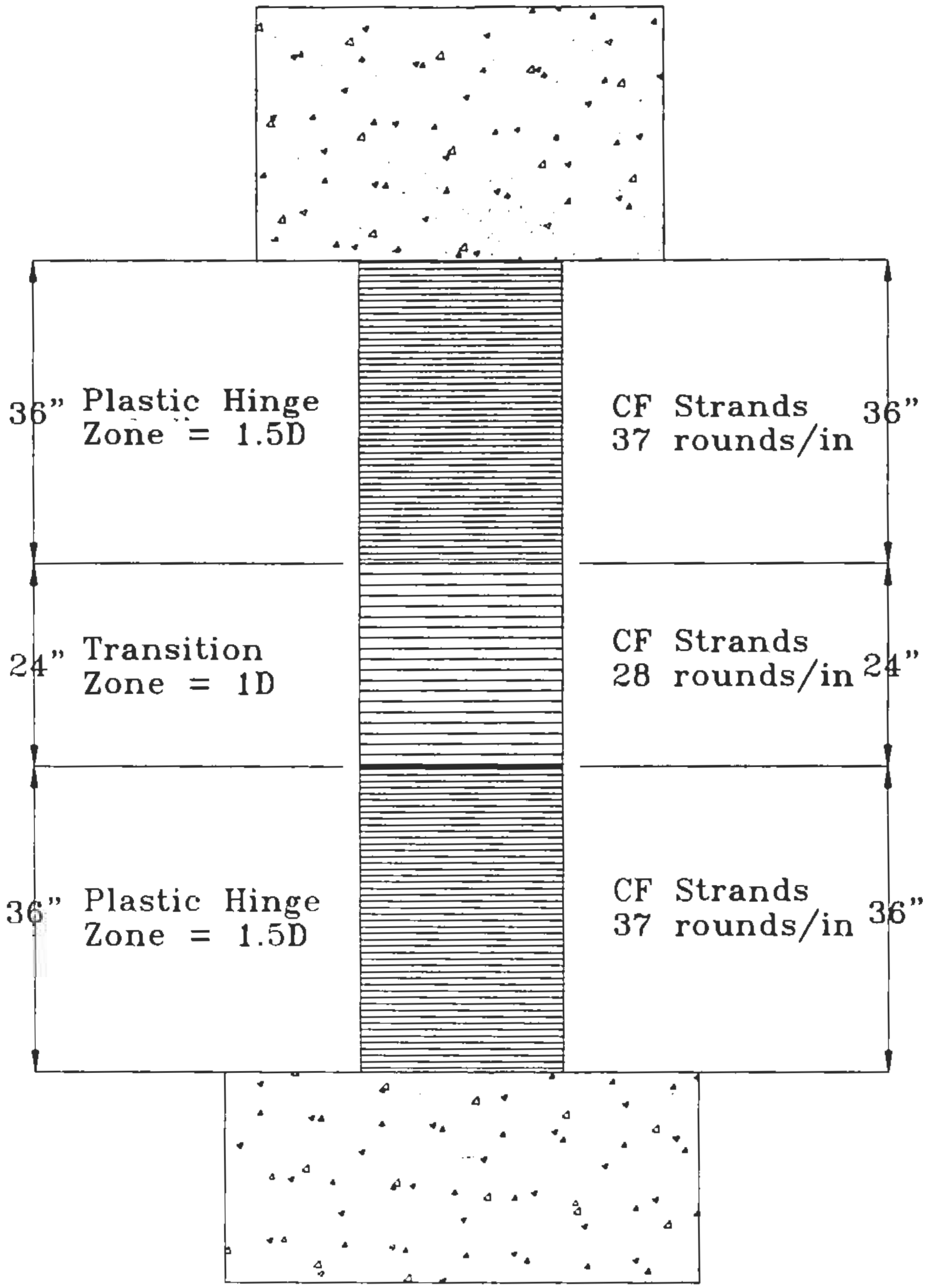

Figure A.3: Composite Jacket for Shear Enhancement Circular Column CS-2

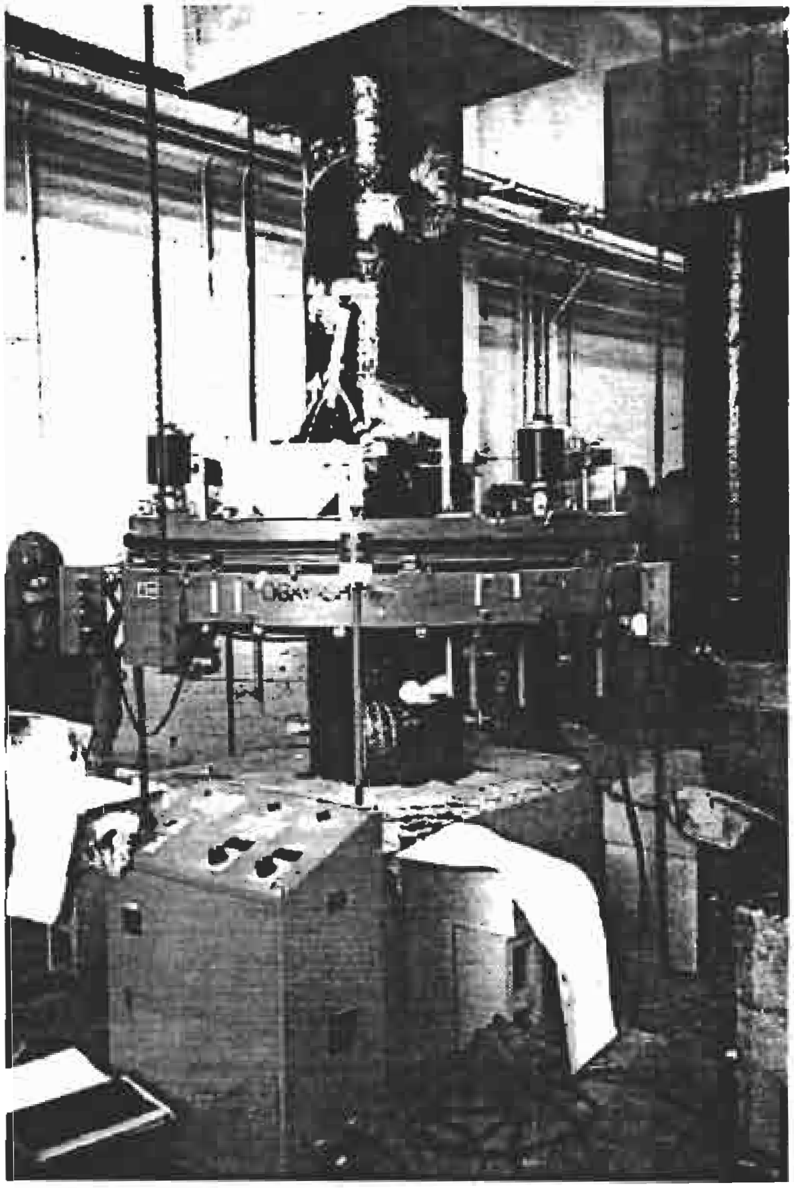

Figure A.4: Jacket Application for Shear Enhancement Circular Column CS-2

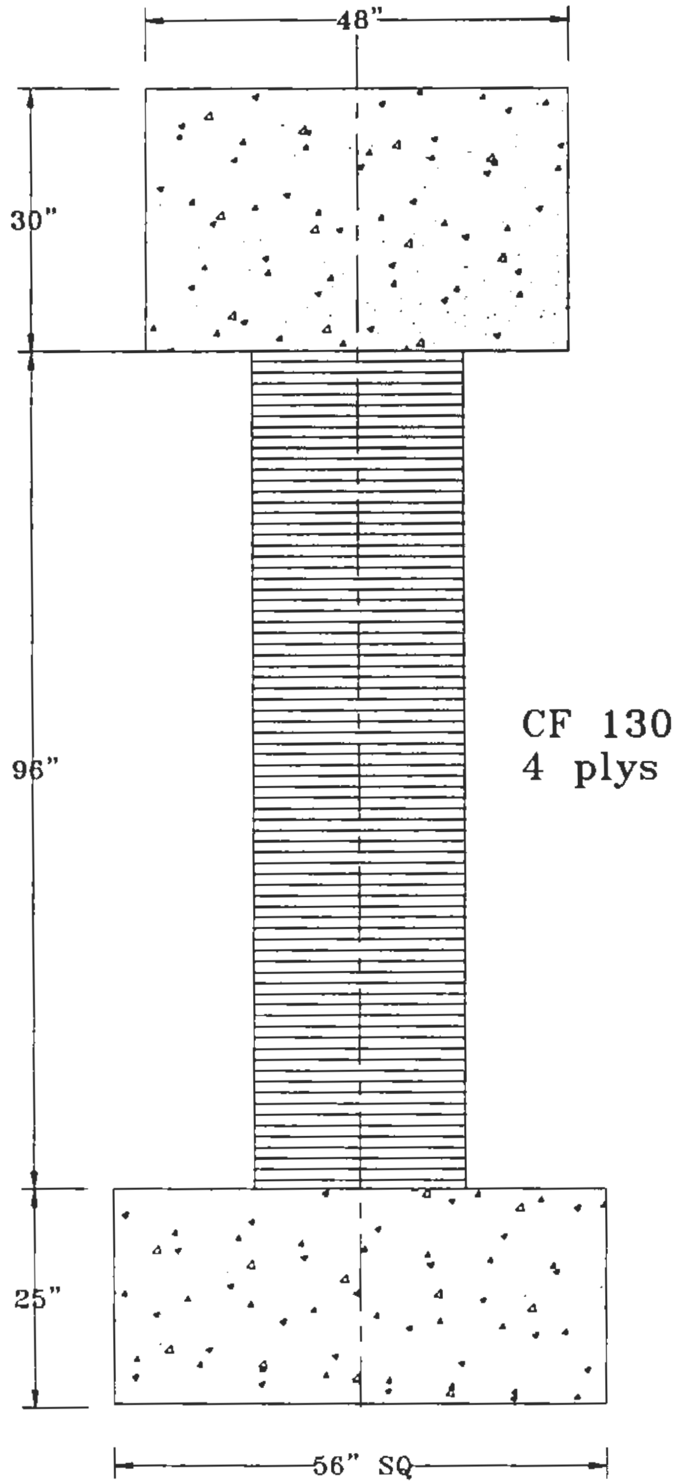

Figure A.5: Composite Jacket for Shear Enhancement Circular Column CS-5

Figure A.6: Jacket Application for Shear Enhancement Circular Column CS-5

A.2 Lap Splice Enhancement Circular Columns

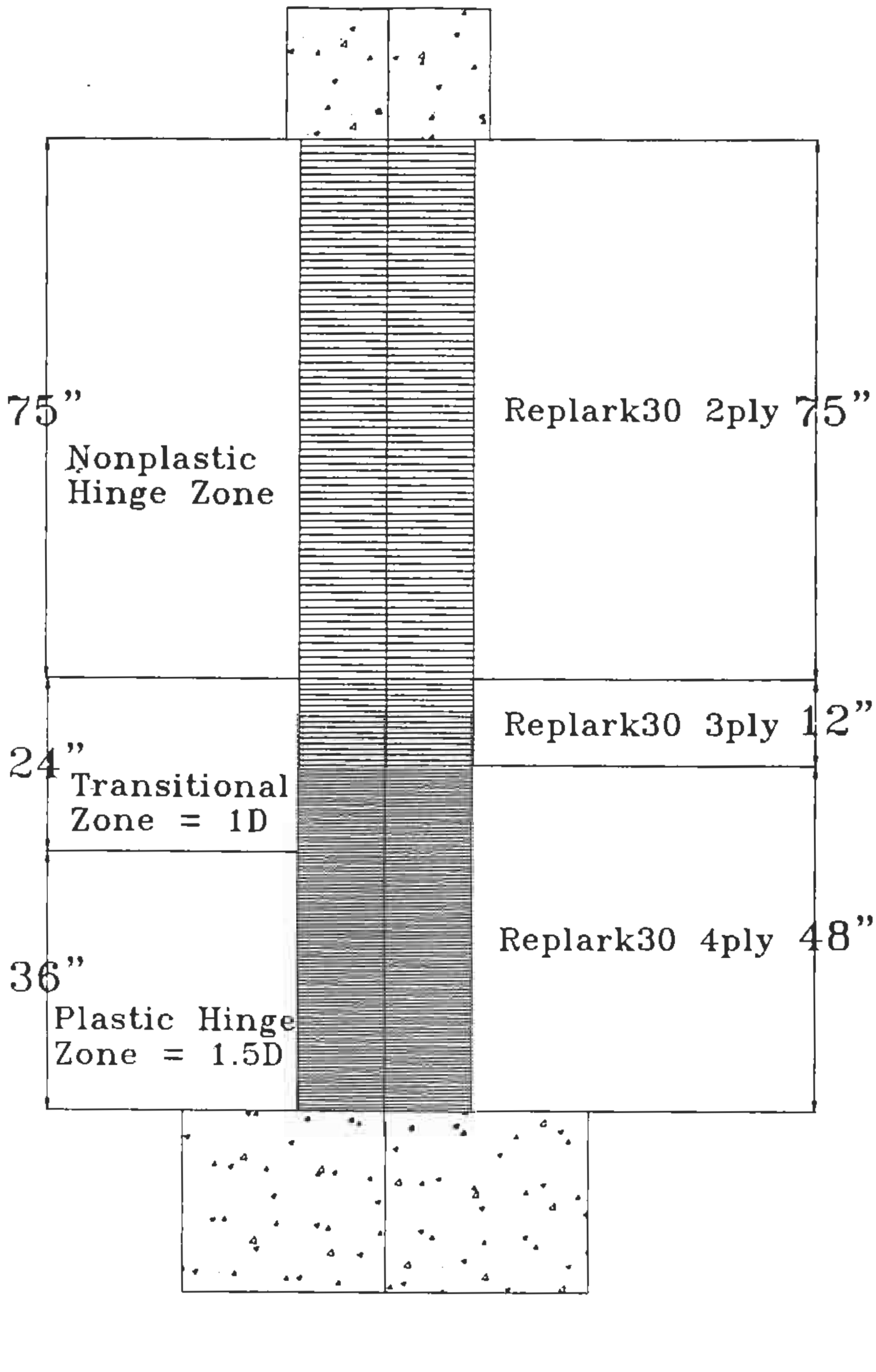

Figure A.7: Composite Jacket for Lap Splice Enhancement Circular Column CF-4

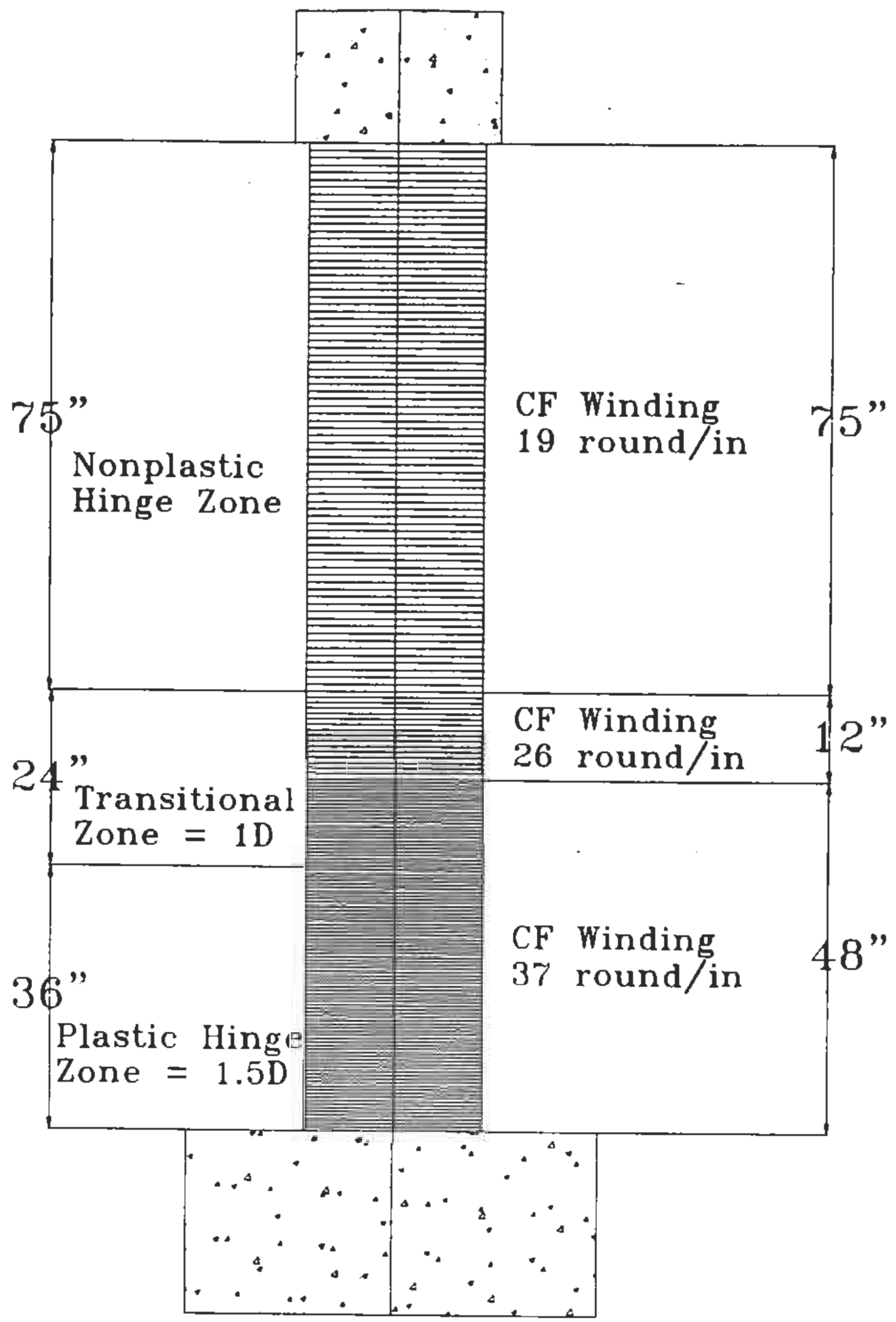

Figure A.8: Composite Jacket for Lap Splice Enhancement Circular Column CF-3

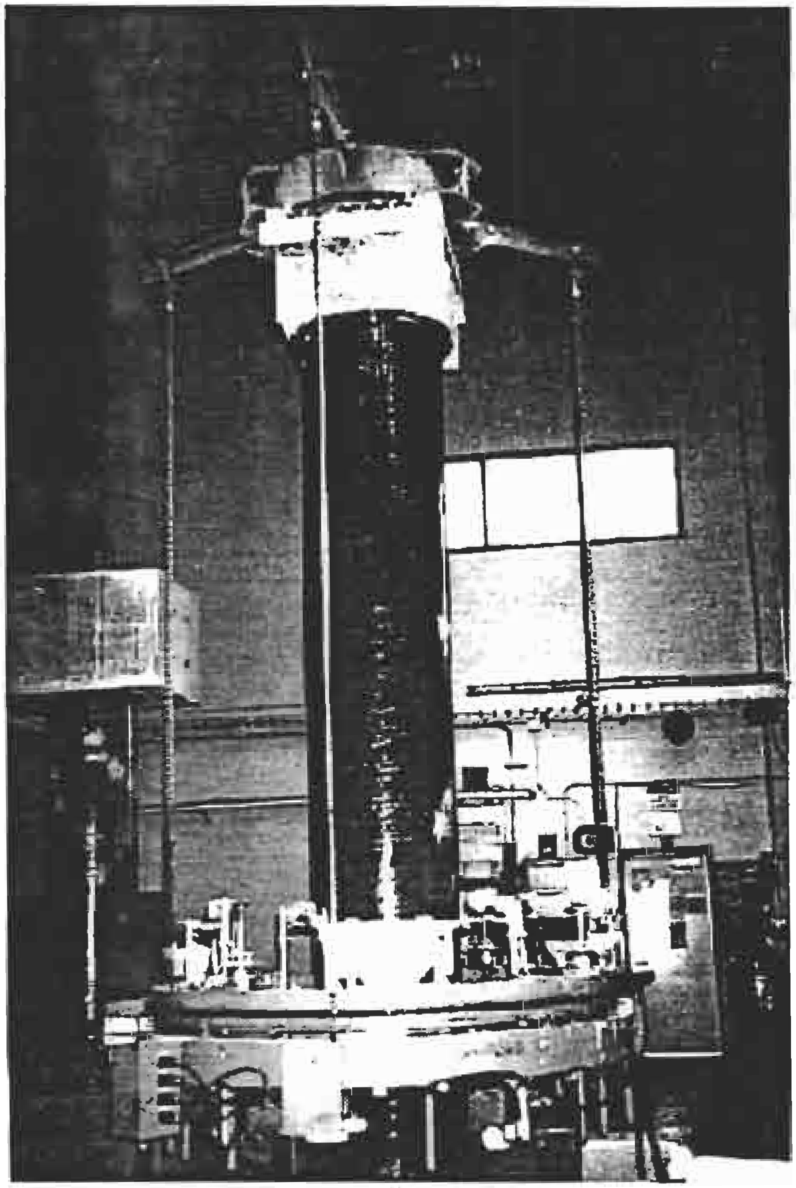

Figure A.9: Jacket Application for Lap Splice Enhancement Circular Column CF-3

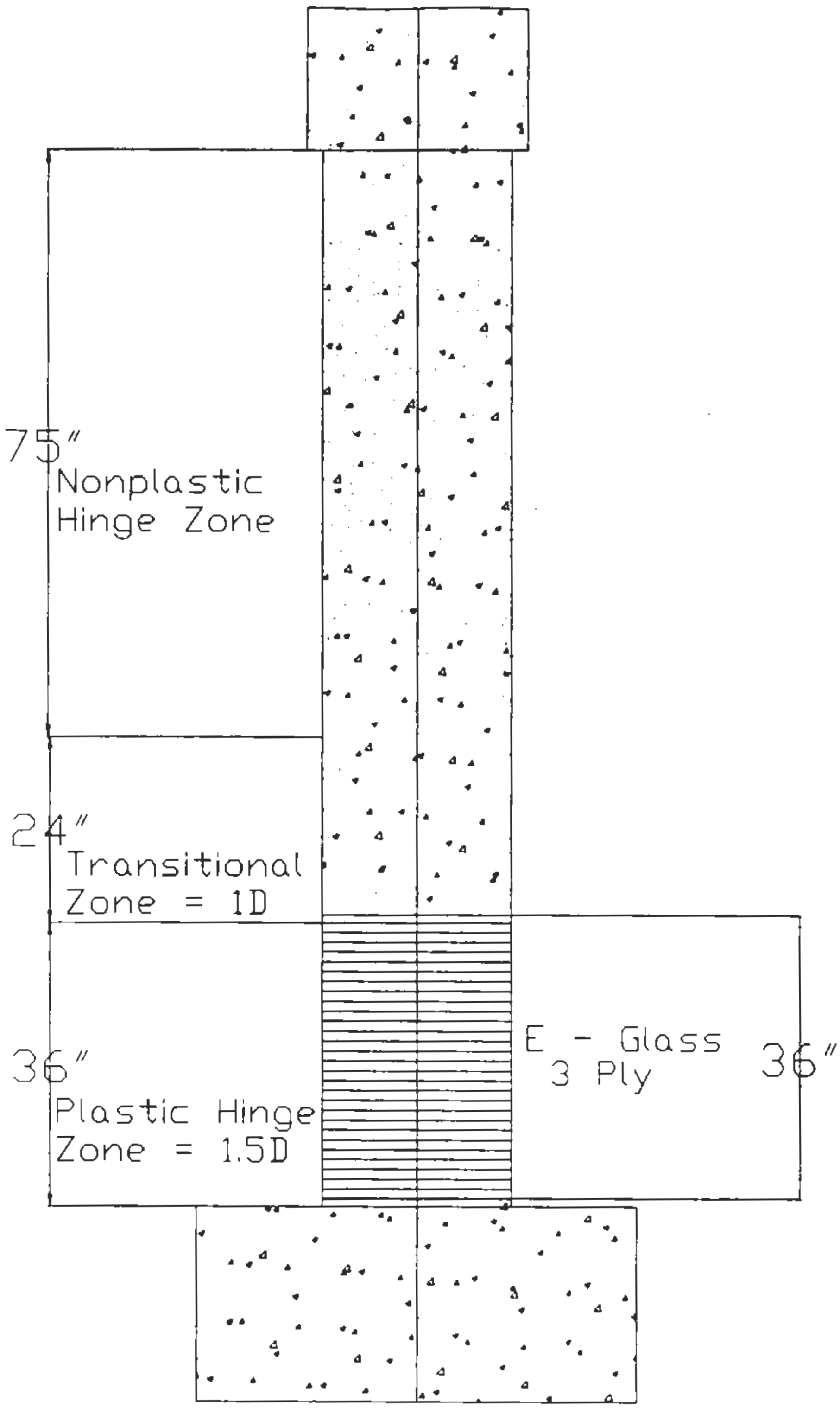

Figure A.10: Composite Jacket for Lap Splice Enhancement Circular Column CF-6

Figure A.11: Jacket Application for Lap Splice Enhancement Circular Column CF-6

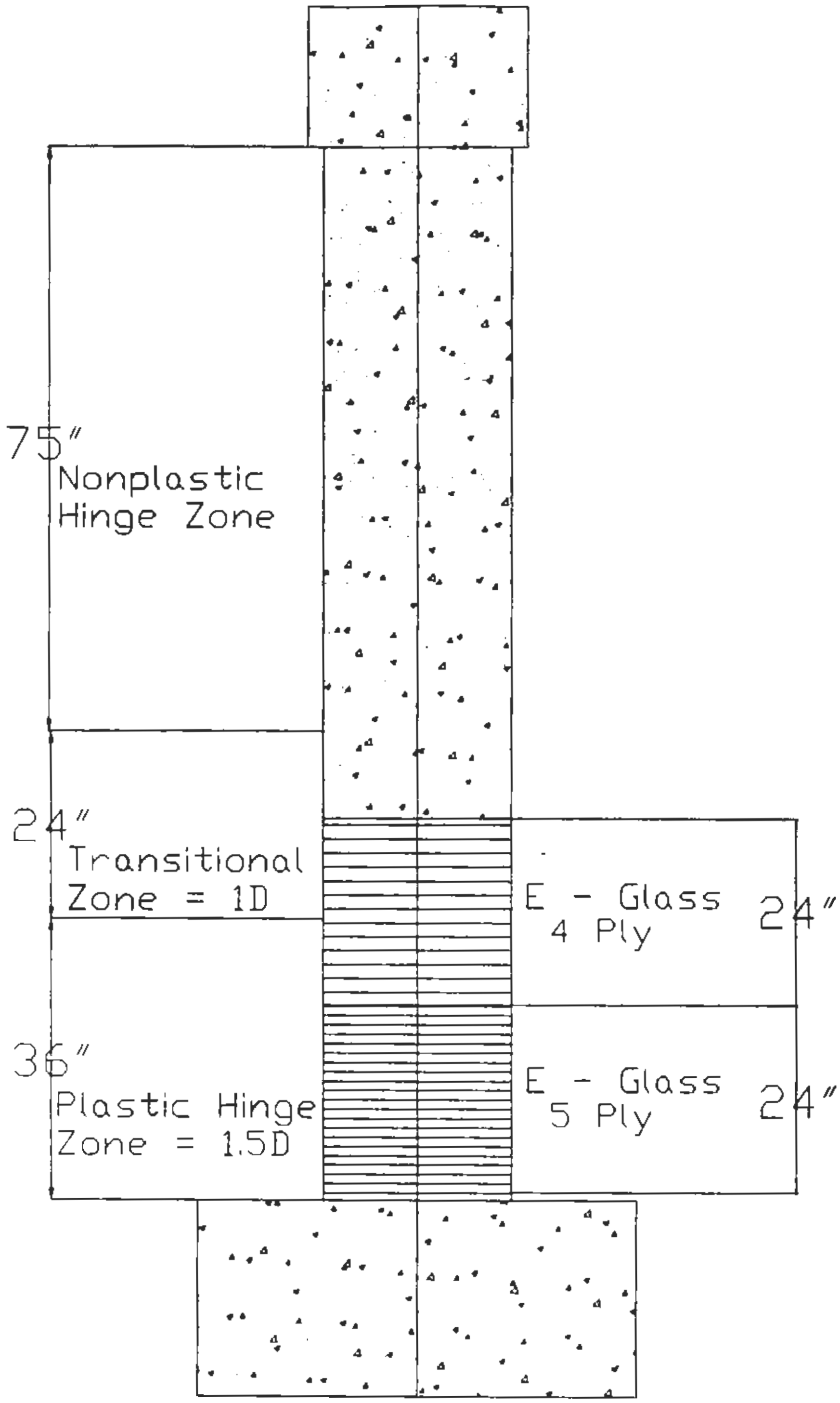

Figure A.12: Composite Jacket for Lap Splice Enhancement Circular Column CF-8

Figure A.13: Jacket Application for Lap Splice Enhancement Circular Column CF-8

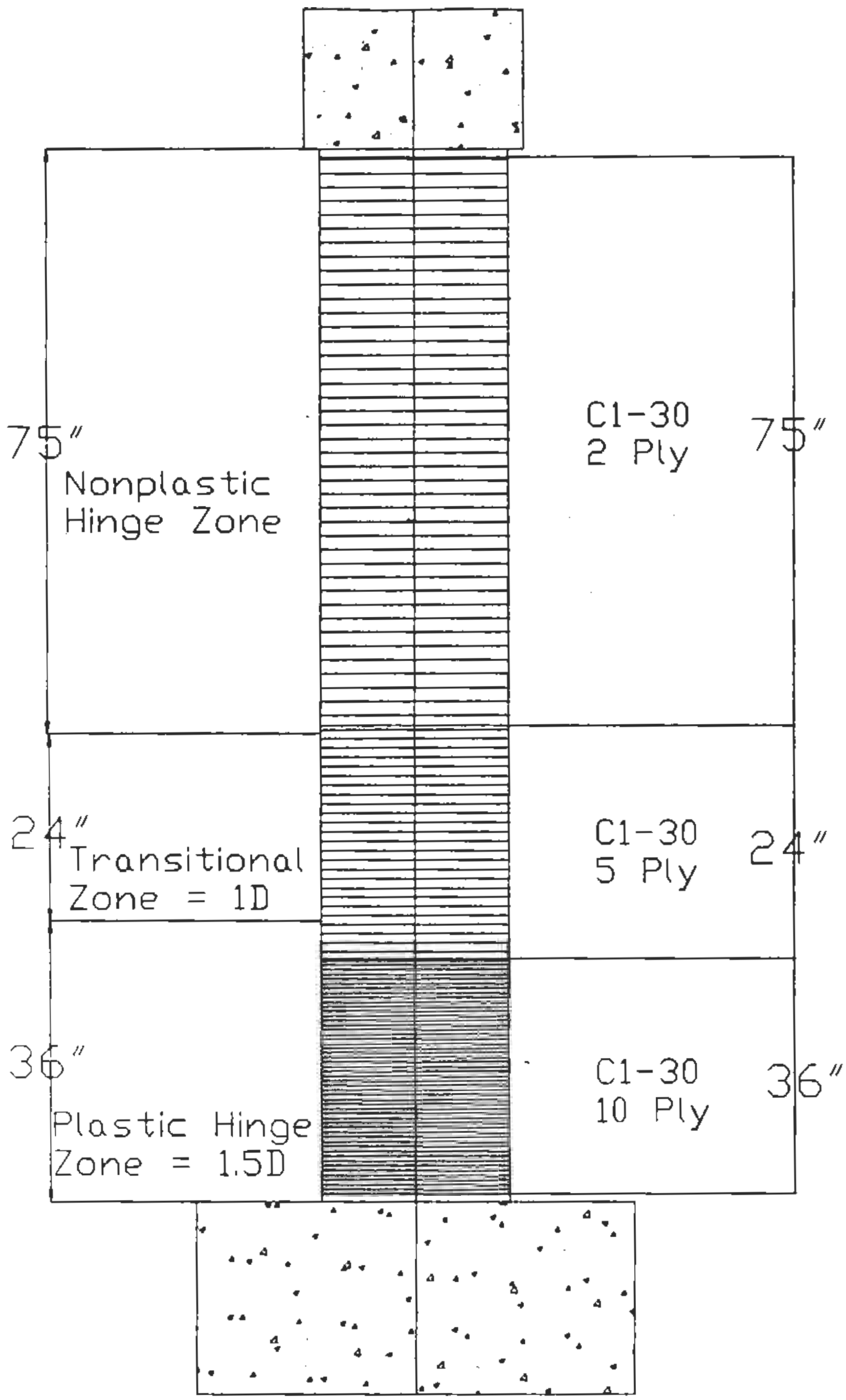

Figure A.14: Composite Jacket for Lap Splice Enhancement Circular Column CF-5

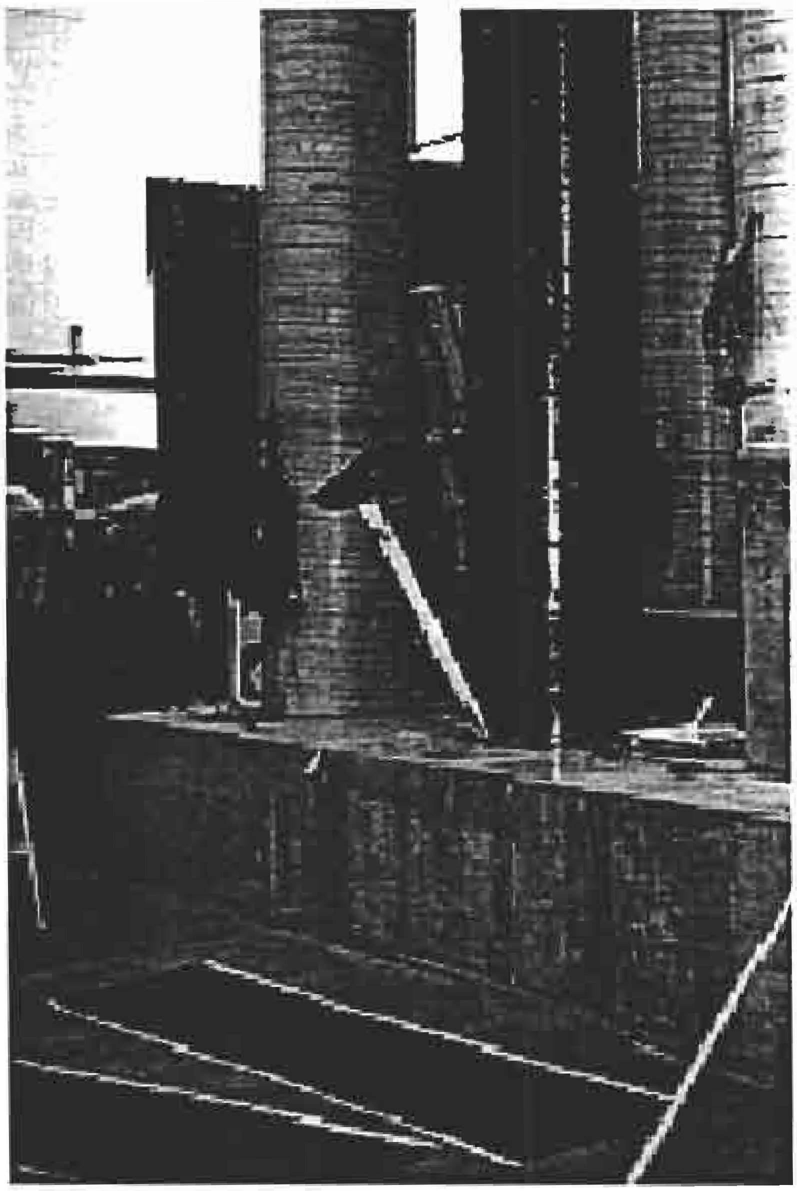

Figure A.15: Jacket Application for Lap Splice Enhancement Circular Column CF-5

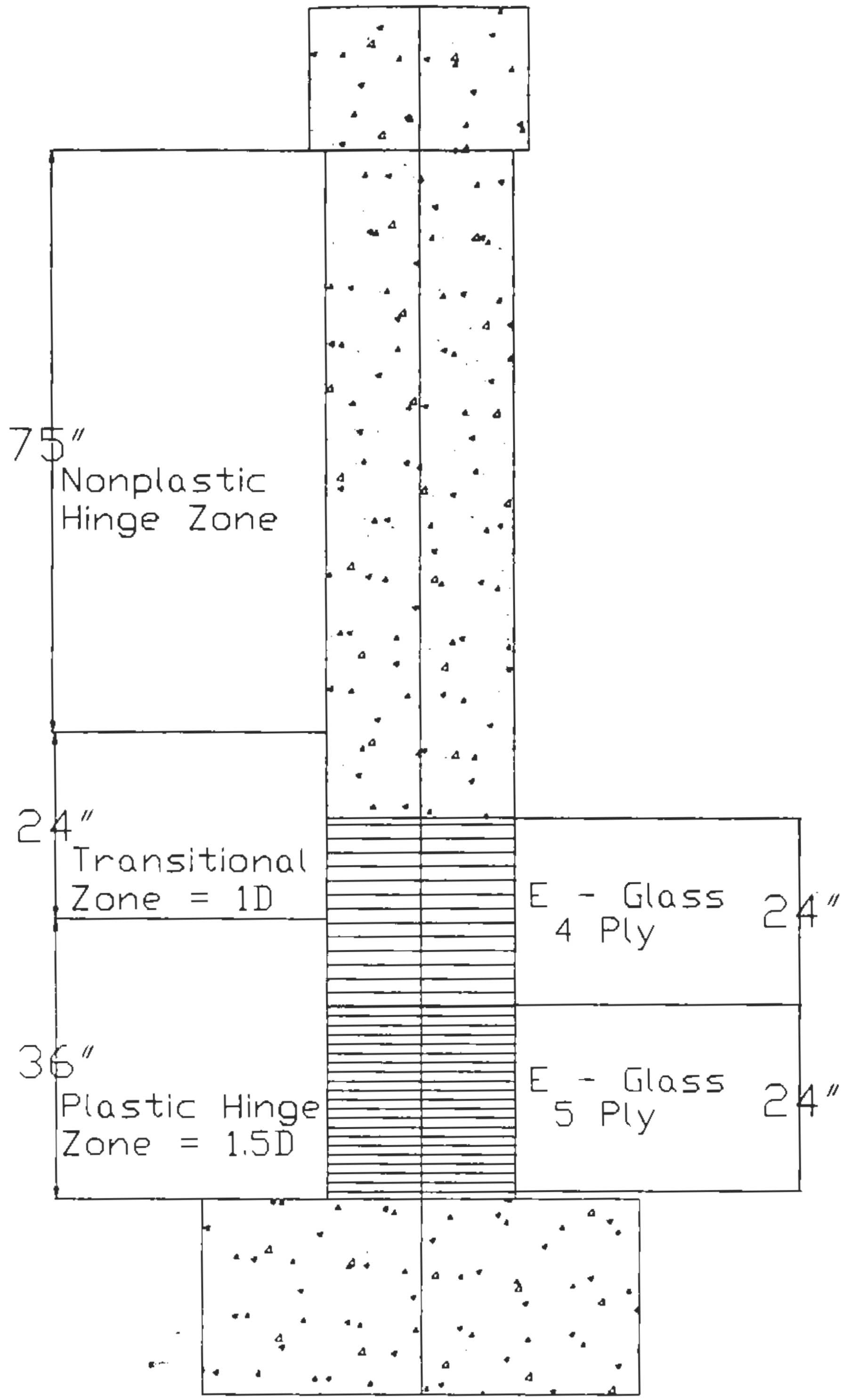

Figure A.16: Composite Jacket for Lap Splice Enhancement Circular Column CF-9

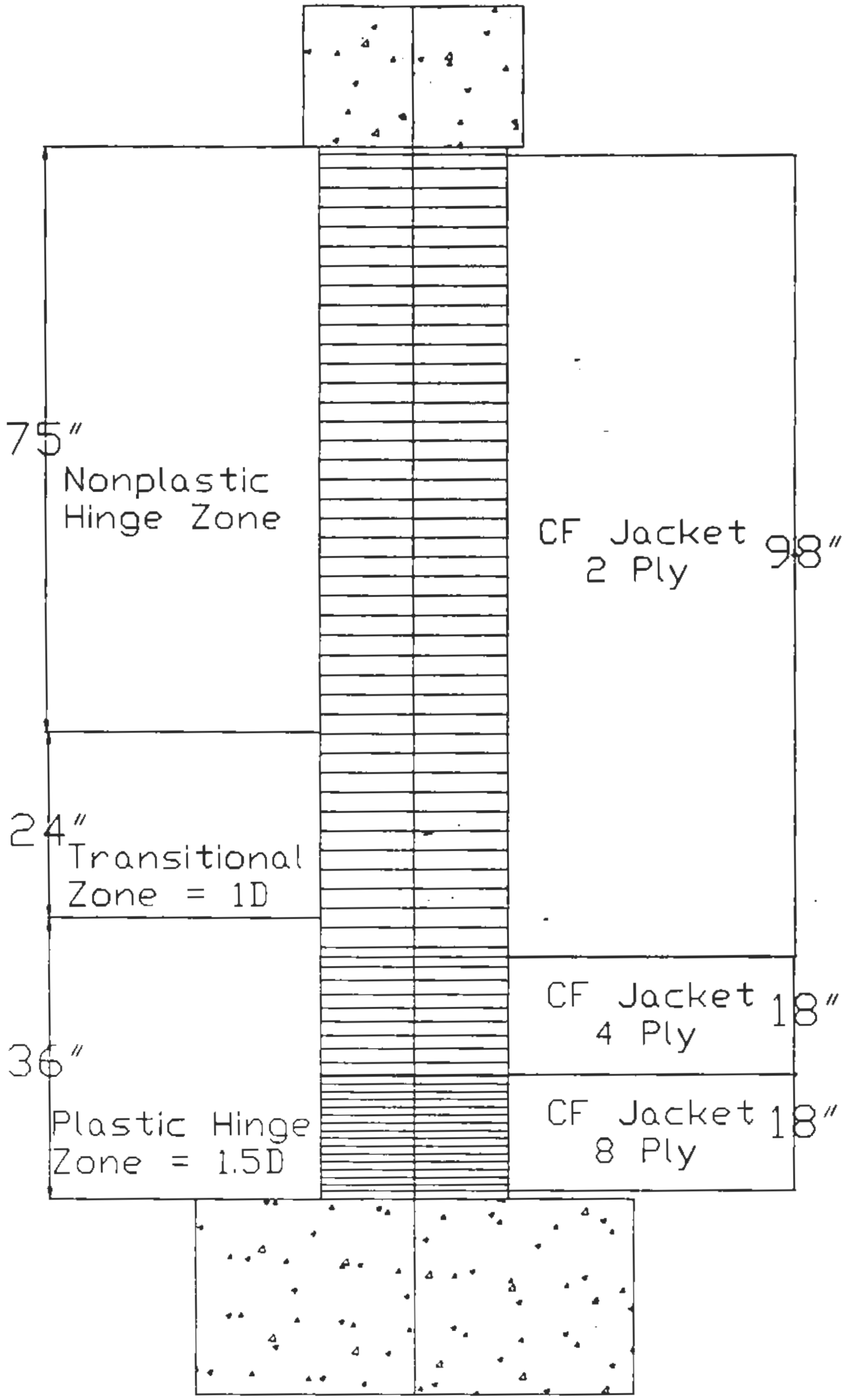

Figure A.17: Composite Jacket for Lap Splice Enhancement Circular Column CF-7

Figure A.18: Jacket Application for Lap Splice Enhancement Circular Column CF-7

A.3 Lap Splice Enhancement Rectangular Columns

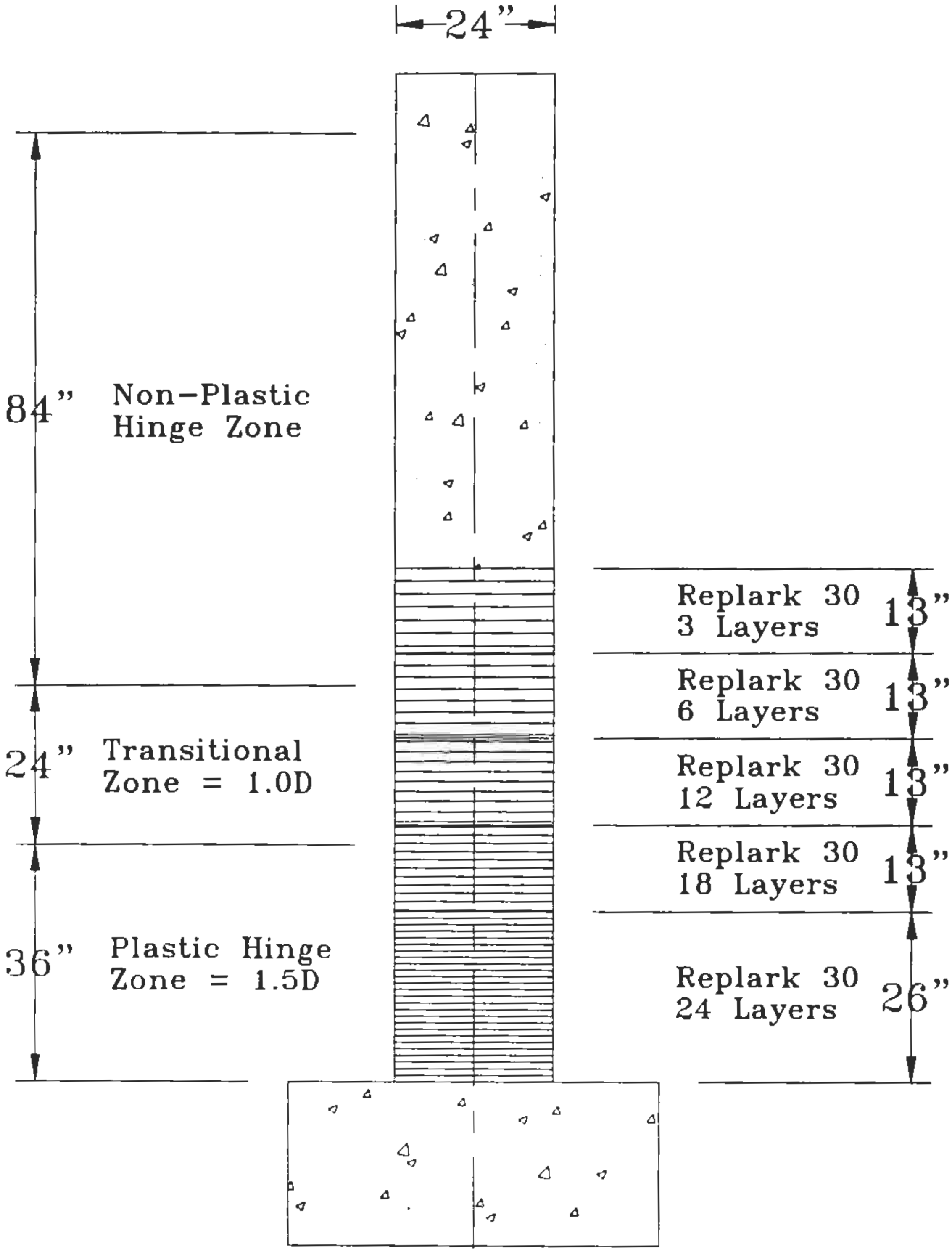

Figure A.19: Composite Jacket for Lap Splice Enhancement Rectangular Column RF-3

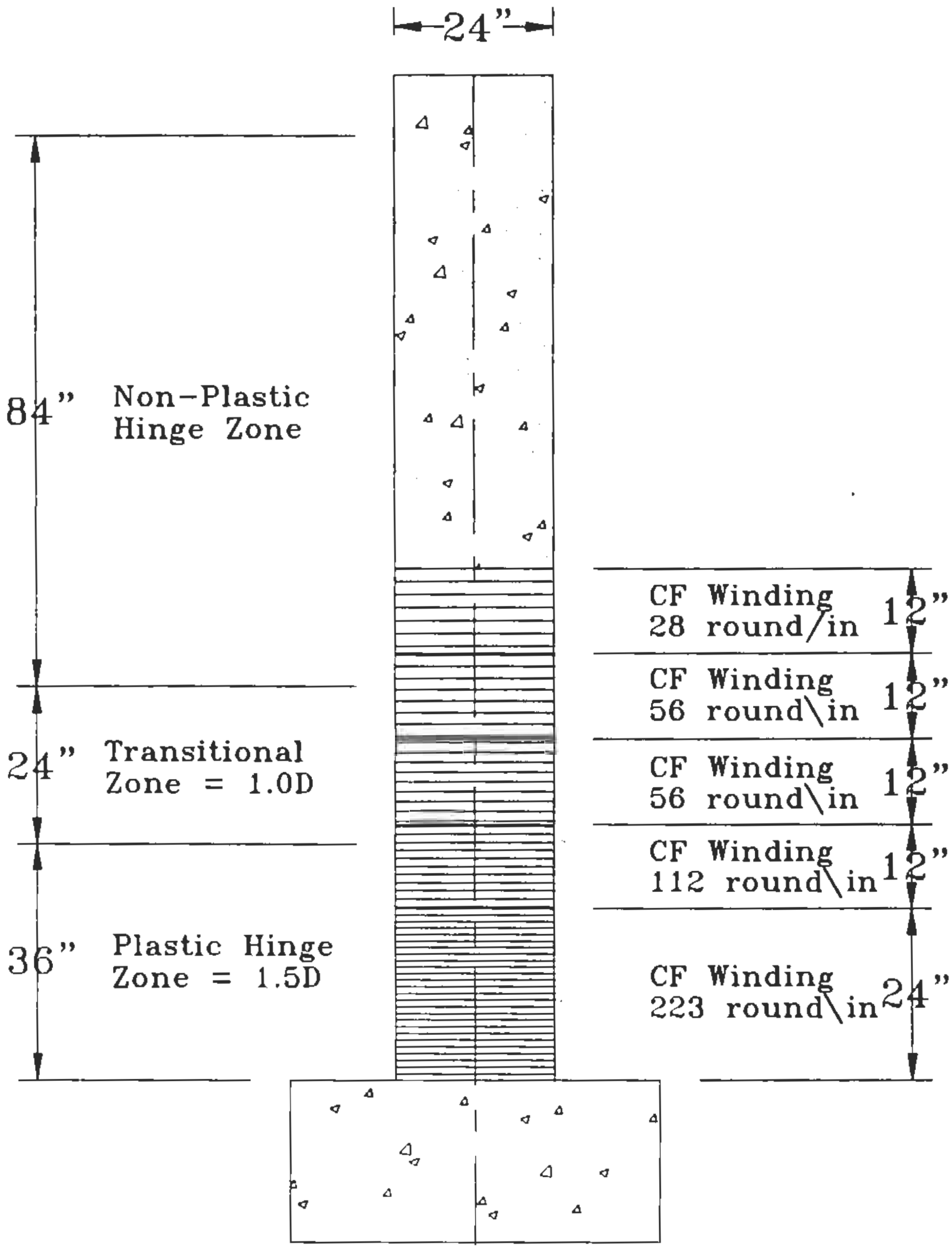

Figure A.20: Composite Jacket for Lap Splice Enhancement Rectangular Column RF-2

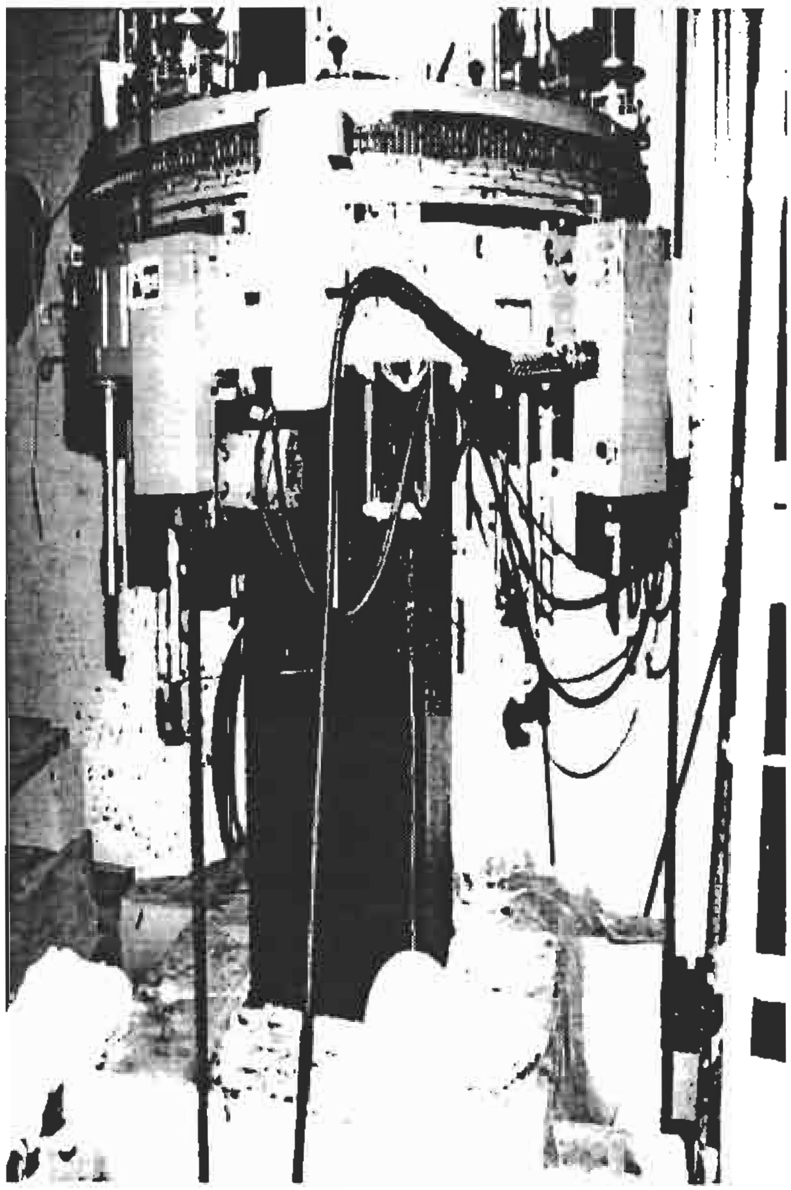

Figure A.21: Jacket Application for Lap Splice Enhancement Rectangular Column RF-2

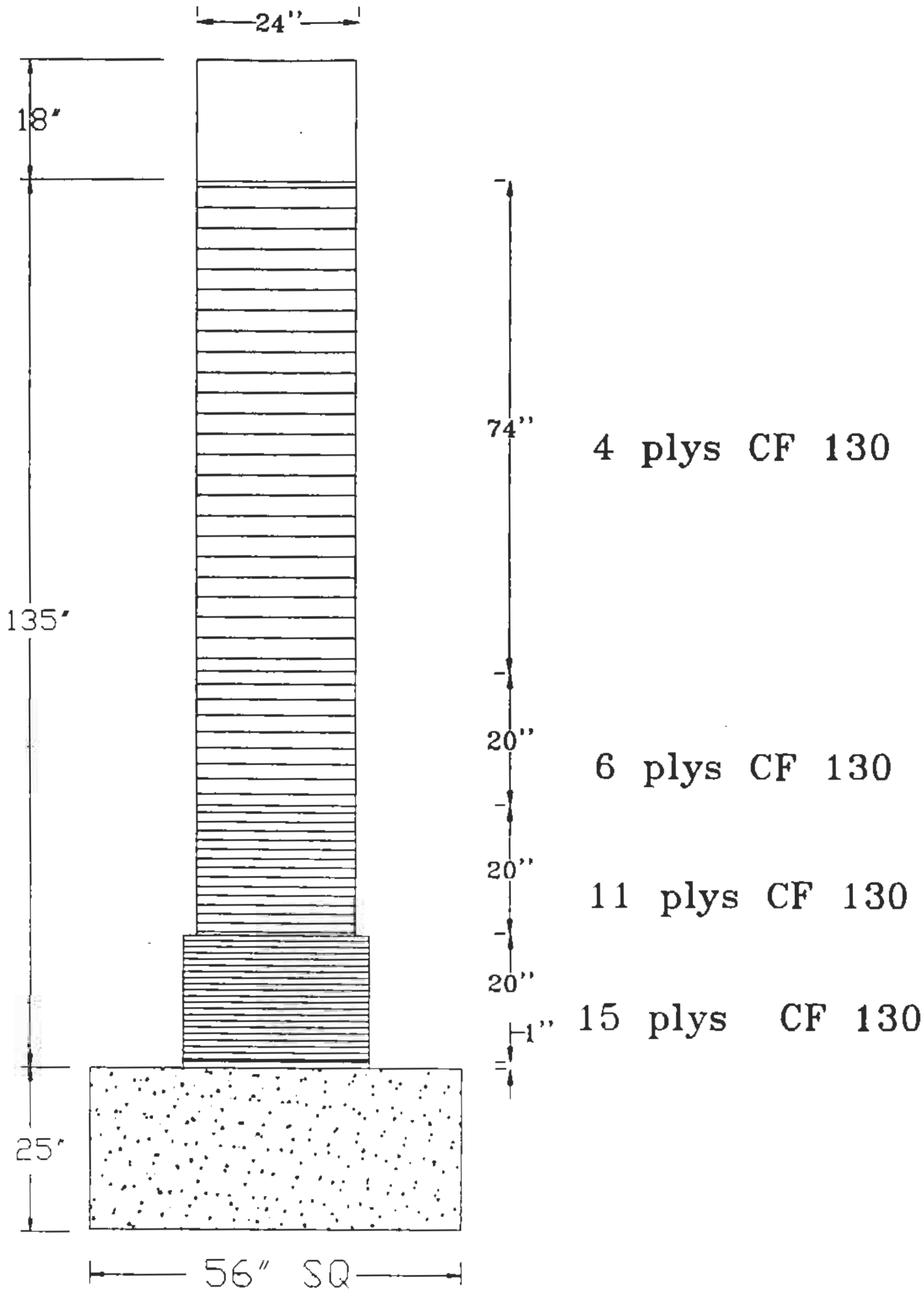

Figure A.22: Composite Jacket for Lap Splice Enhancement Rectangular Column RF-5

Figure A.23: Jacket Application for Lap Splice Enhancement Rectangular Column RF-5

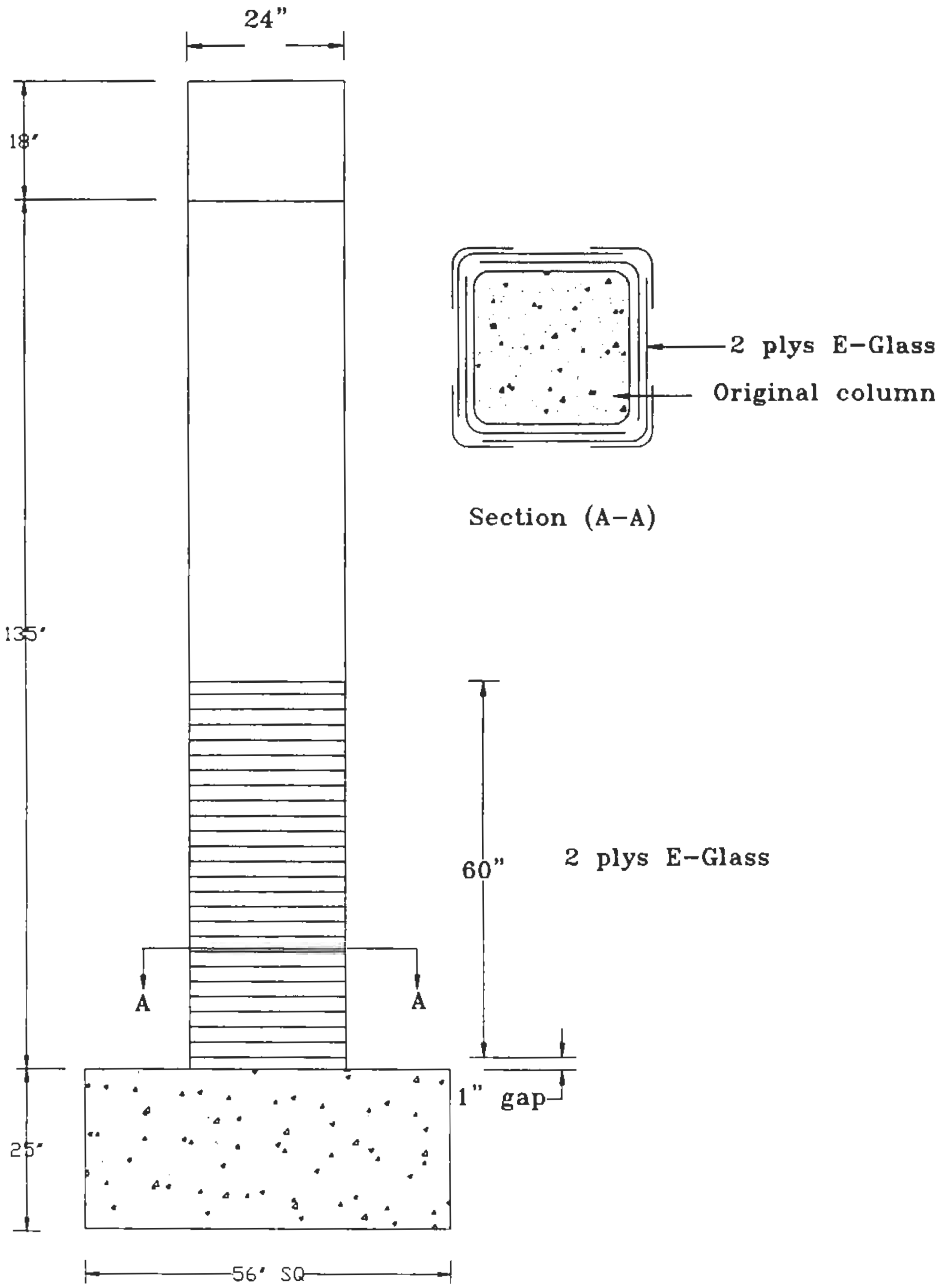

Figure A.24: Composite Jacket for Lap Splice Enhancement Rectangular Column RF-6

A.4 Shear Enhancement Rectangular Columns

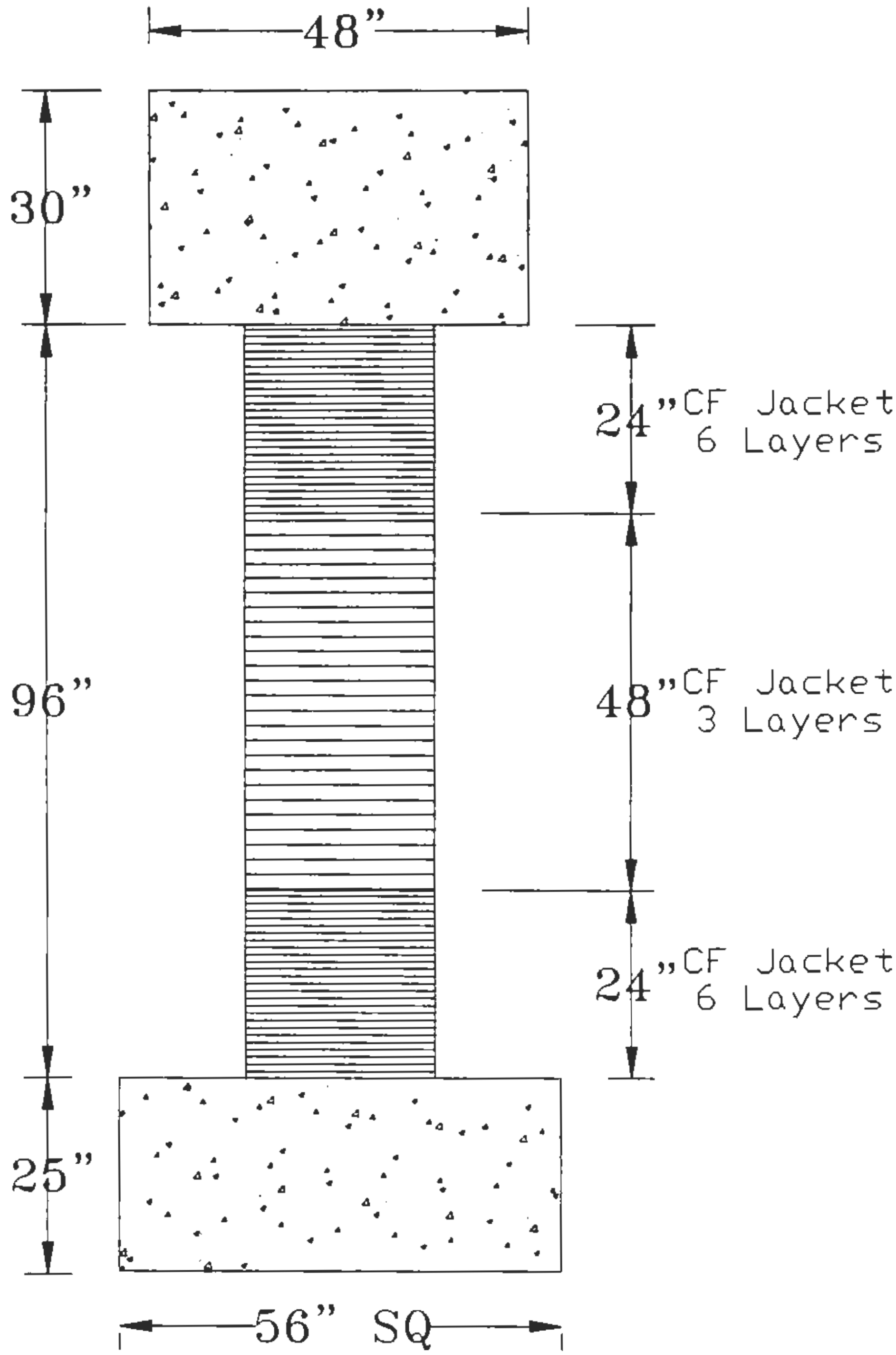

Figure A.25: Composite Jacket for Shear Enhancement Rectangular Column RS-4

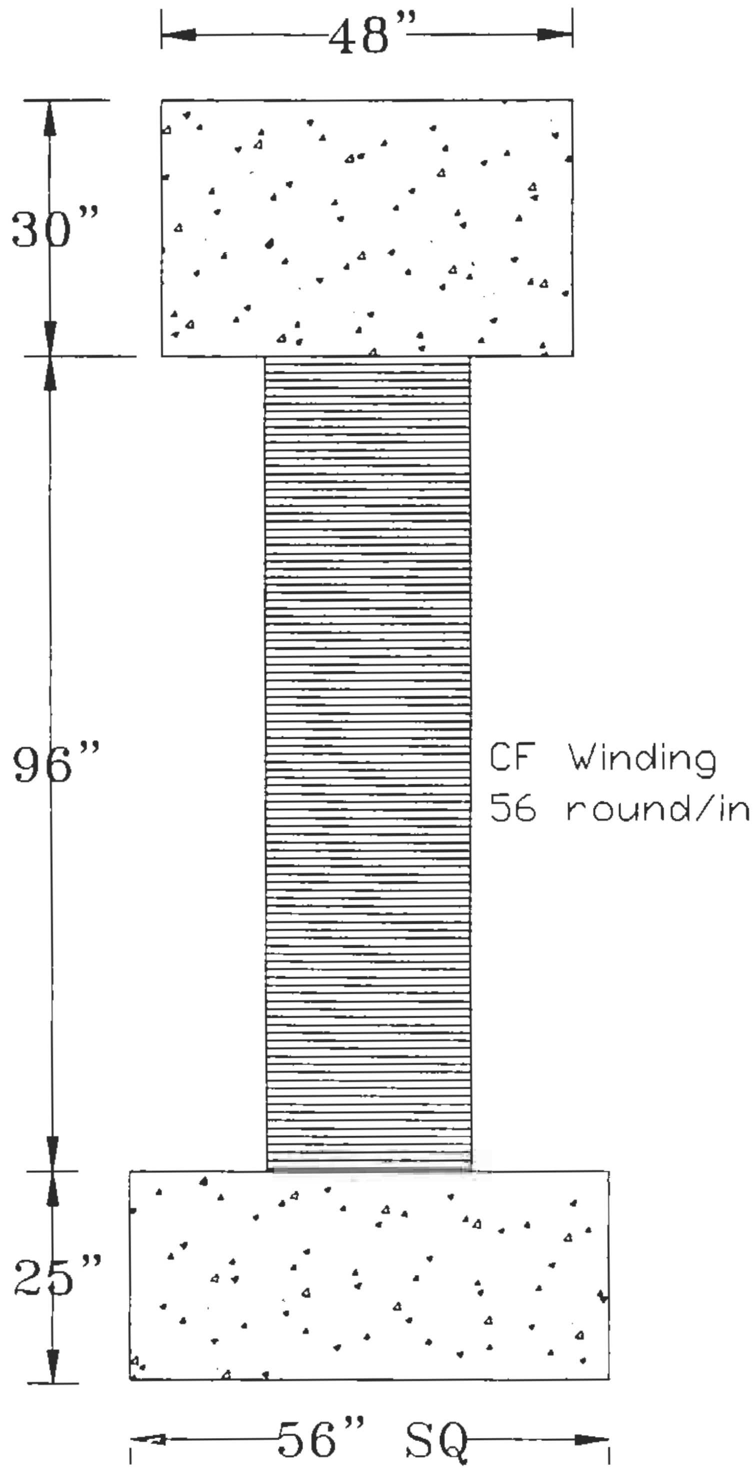

Figure A.26: Composite Jacket for Shear Enhancement Rectangular Column RS-2

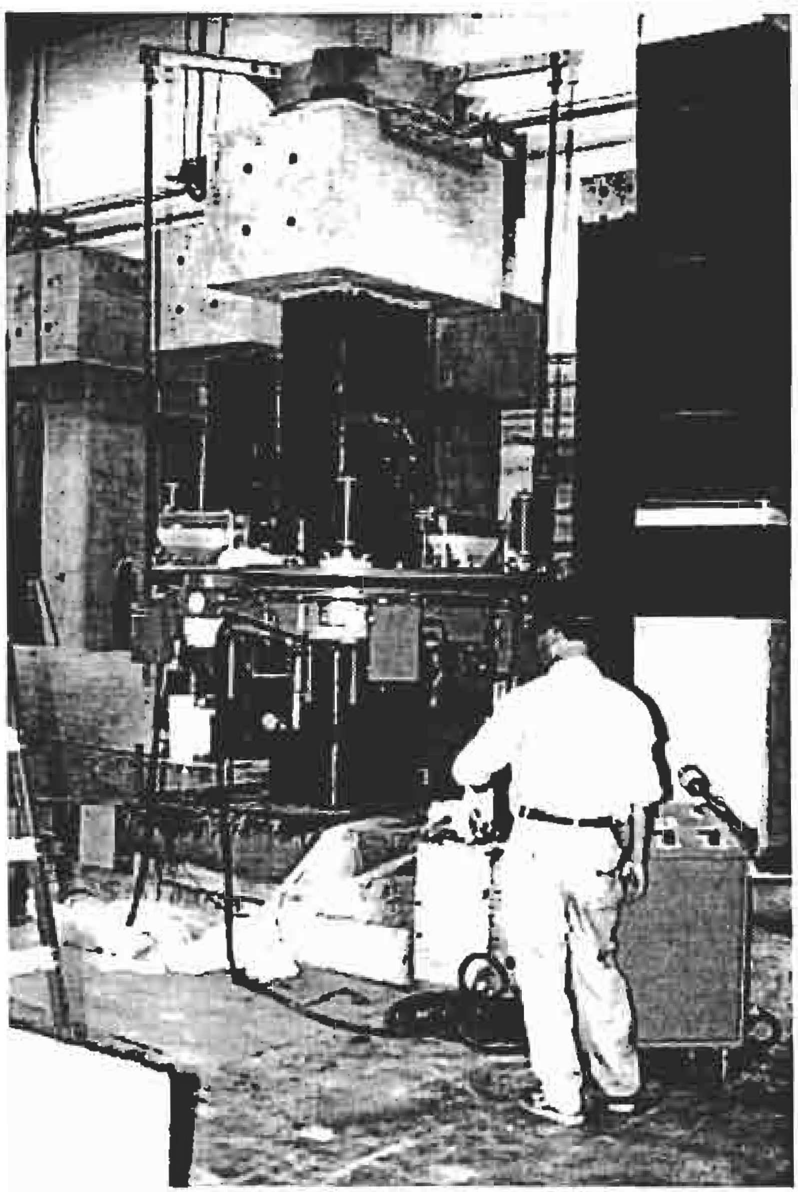

Figure A.27: Jacket Application for Shear Enhancement Rectangular Column RS-2

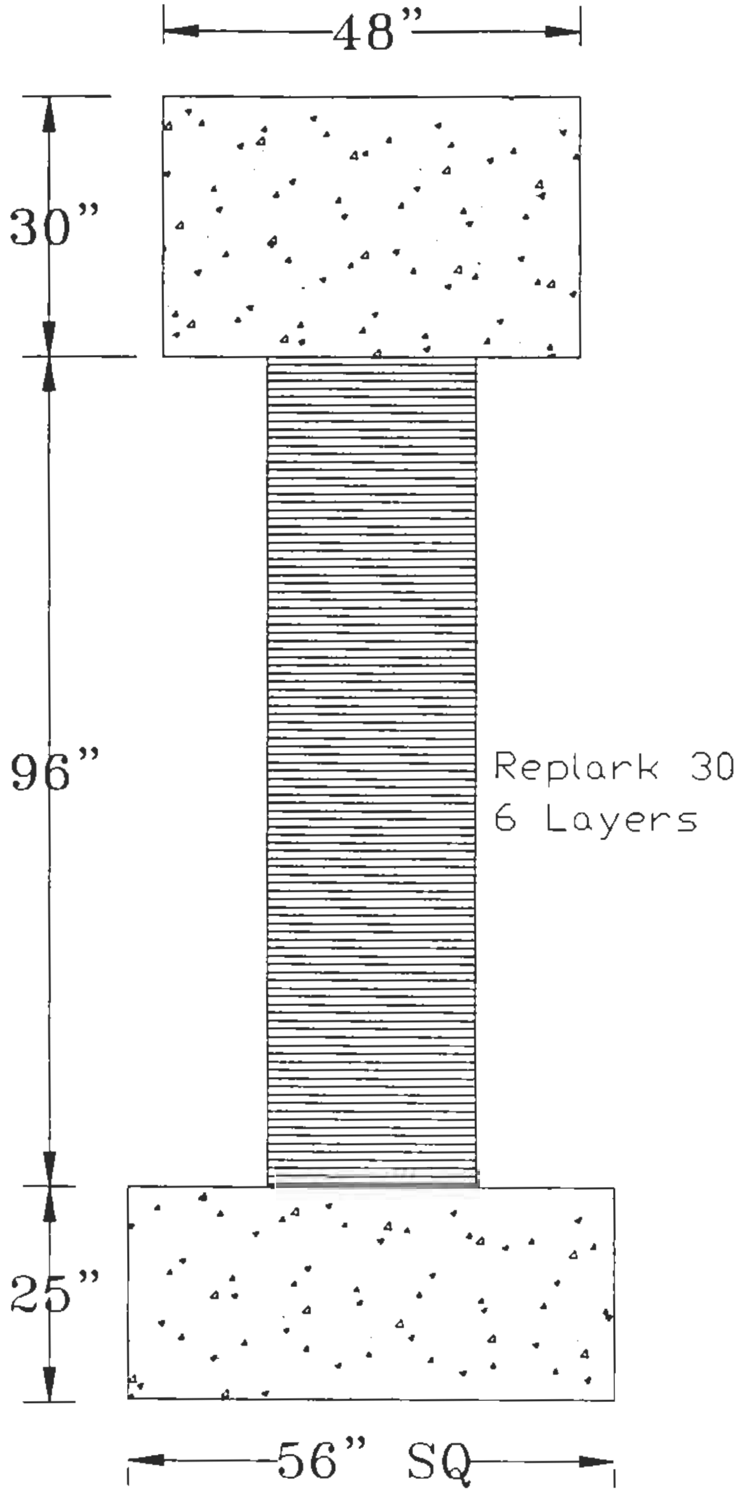

Figure A.28: Composite Jacket for Shear Enhancement Rectangular Column RS-3

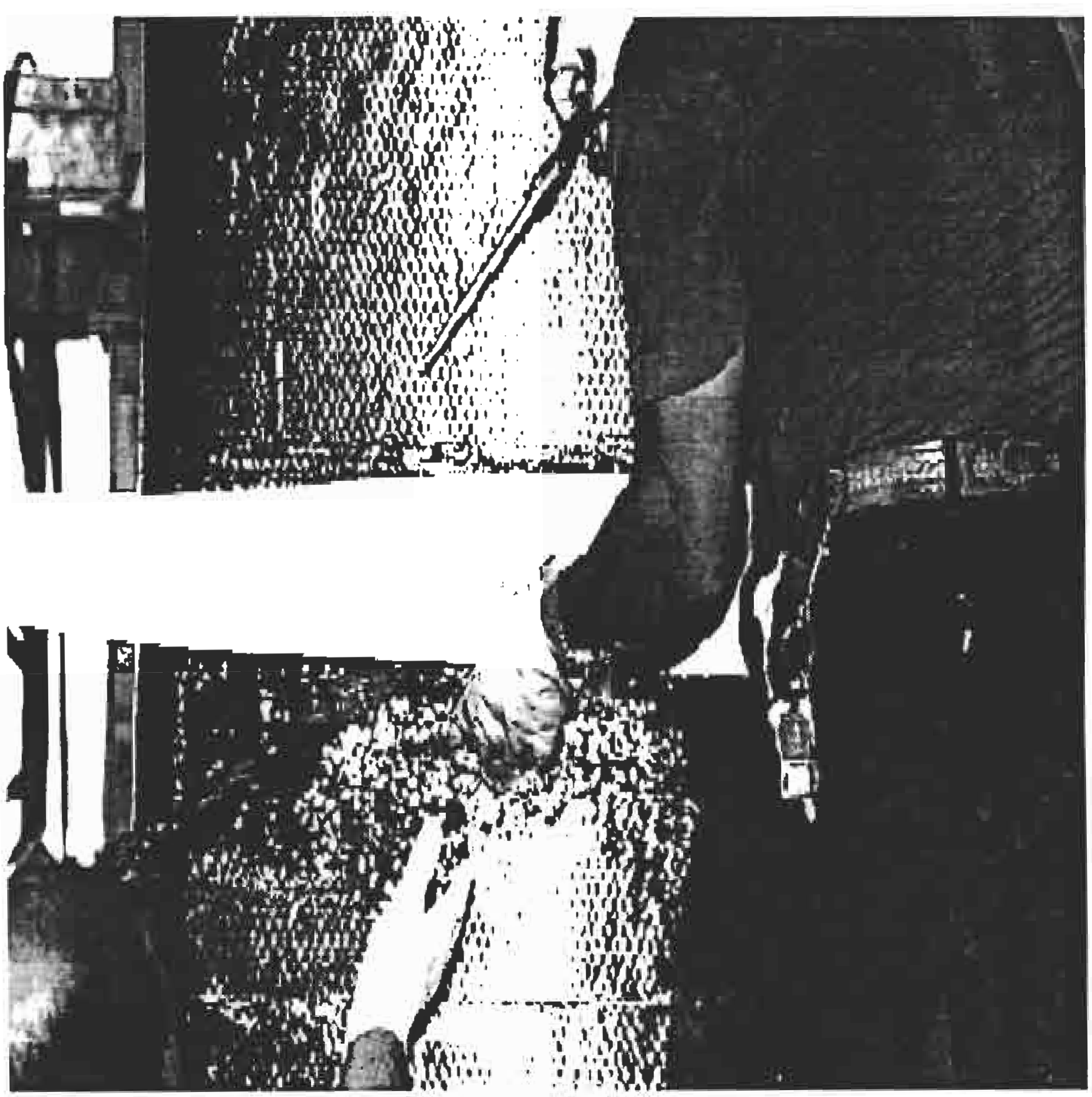

Figure A.29: Jacket Application for Shear Enhancement Rectangular Column RS-3

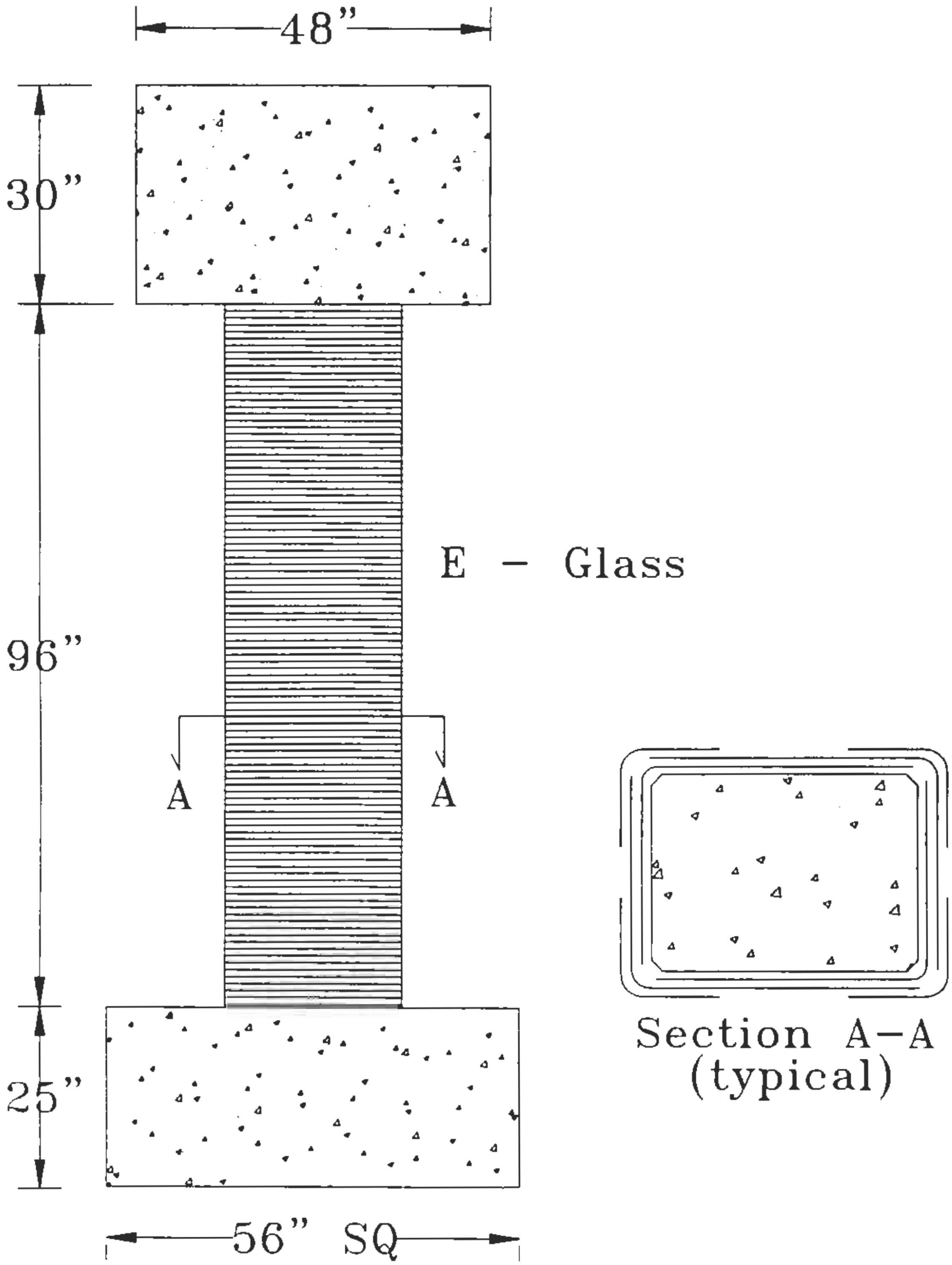

Figure A.30: Composite Jacket for Shear Enhancement Rectangular Column RS-5

Figure A.31: Jacket Application for Shear Enhancement Rectangular Column RS-5

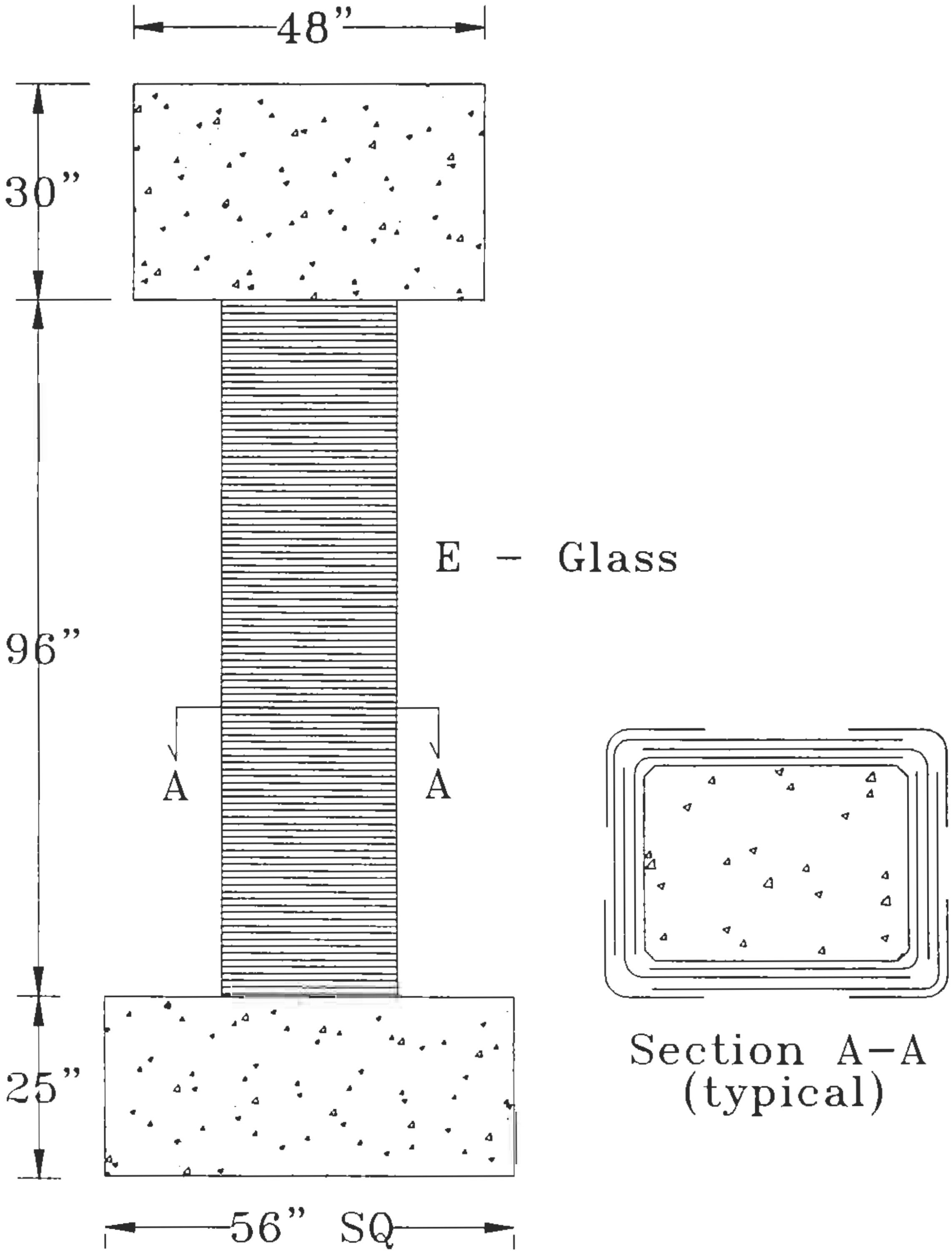

Figure A.32: Composite Jacket for Shear Enhancement Rectangular Column RS-6

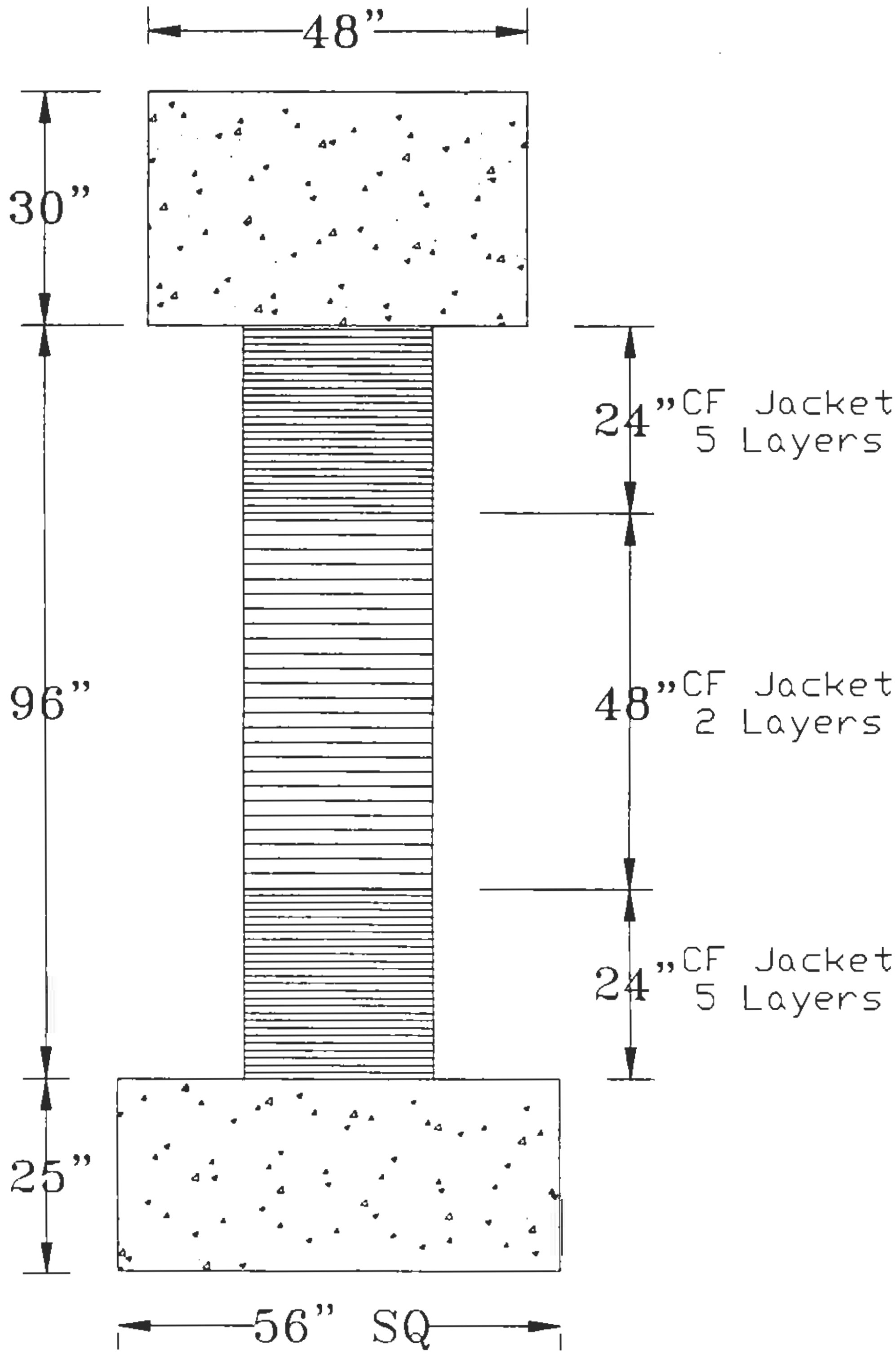

Figure A.33: Composite Jacket for Shear Enhancement Rectangular Column RS-7

Appendix B

MOMENT-CURVATURE ANALYSES

B.1 Shear Enhancement Circular Columns

Table B.1: Output Data for As-built Shear Enhancement Circular Column CS-1

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00016	-8.64	0.000008	52	
2	0.00018	-7.01	0.000009	59	
3	0.00020	-5.57	0.000011	67	
4	0.00022	-4.37	0.000013	75	
5	0.00024	-3.26	0.000016	83	
6	0.00026	-2.30	0.000018	91	
7	0.00029	-1.49	0.000022	100	
8	0.00032	-0.72	0.000025	109	
9	0.00036	-0.10	0.000030	120	
10	0.00039	0.48	0.000034	131	
11	0.00044	1.01	0.000040	143	
12	0.00048	1.44	0.000046	157	
13	0.00053	1.82	0.000052	172	
14	0.00059	2.16	0.000060	189	
15	0.00065	2.50	0.000069	207	
16	0.00072	2.74	0.000078	228	
17	0.00080	2.98	0.000088	250	
18	0.00088	3.17	0.000100	275	
19	0.00097	3.36	0.000113	301	Begin Yield of Steel
20	0.00108	3.65	0.000129	320	
21	0.00119	3.94	0.000148	337	
22	0.00132	4.27	0.000170	349	
23	0.00145	4.61	0.000197	361	
24	0.00161	4.94	0.000228	370	
25	0.00178	5.23	0.000263	379	
26	0.00196	5.52	0.000303	386	
27	0.00217	5.76	0.000348	392	
28	0.00240	5.95	0.000397	395	
29	0.00265	6.10	0.000450	400	
30	0.00293	6.24	0.000509	402	
31	0.00324	6.38	0.000578	403	
32	0.00359	6.53	0.000655	402	
33	0.00396	6.62	0.000737	402	
⋆	0.00400	6.62	0.000745	402	Ideal Yield of Steel
34	0.00438	6.67	0.000823	402	
35	0.00484	6.67	0.000909	403	
36	0.00536	6.67	0.001005	401	
37	0.00592	6.67	0.001111	397	
⋆	0.00643	6.60	0.001189	399	Tranverse Steel Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.2: Output Data for Shear Enhancement Circular Column CS-2

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00030	-1.06	0.000023	104	
2	0.00033	-0.38	0.000027	114	
3	0.00037	0.24	0.000031	124	
4	0.00041	0.77	0.000036	136	
5	0.00045	1.25	0.000042	149	
6	0.00050	1.68	0.000048	163	
7	0.00055	2.02	0.000055	179	
8	0.00061	2.35	0.000063	196	
9	0.00067	2.64	0.000072	215	
10	0.00074	2.88	0.000081	235	
11	0.00082	3.07	0.000092	259	
12	0.00090	3.26	0.000104	284	
13	0.00100	3.50	0.000118	307	Begin Yield of Steel
14	0.00103	3.55	0.000122	312	
15	0.00114	3.84	0.000140	329	
16	0.00126	4.18	0.000161	343	
17	0.00139	4.46	0.000185	356	
18	0.00154	4.80	0.000214	366	
19	0.00170	5.14	0.000248	374	
20	0.00188	5.38	0.000284	386	
21	0.00208	5.71	0.000331	389	
22	0.00230	5.95	0.000381	394	
23	0.00254	6.14	0.000434	399	
24	0.00281	6.29	0.000492	405	
25	0.00311	6.48	0.000563	409	
26	0.00344	6.67	0.000645	410	
27	0.00380	6.82	0.000733	413	
28	0.00420	6.96	0.000834	413	
29	0.00464	7.06	0.000939	416	
⋆	0.00500	7.13	0.001027	417	Ideal Yield of Steel
30	0.00513	7.15	0.001059	417	
⋆	0.00546	7.18	0.001134	419	Tranverse Steel Failure
31	0.00568	7.20	0.001183	420	
32	0.00628	7.20	0.001307	428	
33	0.00694	7.20	0.001445	434	
34	0.00767	7.20	0.001598	440	
35	0.00848	7.20	0.001766	445	
36	0.00937	7.15	0.001933	453	
37	0.01036	7.10	0.002116	459	
38	0.01146	7.06	0.002317	463	
39	0.01266	7.01	0.002537	467	
40	0.01400	6.91	0.002752	472	Maximum Concrete Strain

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.3: Output Data for Shear Enhancement Circular Column CS-3

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00029	-1.20	0.000022	102	
2	0.00032	-0.48	0.000026	112	
3	0.00035	0.14	0.000030	122	
4	0.00039	0.72	0.000035	134	
5	0.00043	1.20	0.000040	146	
6	0.00048	1.63	0.000046	160	
7	0.00053	2.02	0.000053	175	
8	0.00059	2.30	0.000060	192	
9	0.00065	2.64	0.000069	210	
10	0.00072	2.88	0.000078	231	
11	0.00079	3.07	0.000089	254	
12	0.00087	3.31	0.000101	278	
13	0.00097	3.50	0.000114	303	Begin Yield of Steel
14	0.00099	3.55	0.000118	308	
15	0.00110	3.84	0.000135	325	
16	0.00122	4.13	0.000154	341	
17	0.00134	4.46	0.000178	353	
18	0.00149	4.75	0.000205	366	
19	0.00164	5.09	0.000238	374	
20	0.00182	5.38	0.000274	384	
21	0.00201	5.66	0.000317	391	
22	0.00222	5.95	0.000367	395	
23	0.00245	6.14	0.000419	400	
24	0.00271	6.34	0.000479	404	
25	0.00300	6.53	0.000548	408	
26	0.00331	6.72	0.000628	409	
27	0.00366	6.86	0.000713	412	
28	0.00405	7.01	0.000812	413	
29	0.00448	7.10	0.000915	416	
30	0.00495	7.20	0.001031	418	
⋆	0.00500	7.20	0.001043	418	Ideal Yield of Steel
⋆	0.00542	7.25	0.001141	422	Tranverse Steel Failure
31	0.00547	7.25	0.001152	422	
32	0.00605	7.30	0.001286	426	
33	0.00669	7.30	0.001422	432	
34	0.00740	7.30	0.001572	440	
35	0.00818	7.25	0.001720	449	
36	0.00904	7.25	0.001902	454	
37	0.00999	7.20	0.002082	460	
38	0.01105	7.15	0.002278	465	
39	0.01221	7.10	0.002494	468	
40	0.01350	7.01	0.002704	474	Maximum Concrete Strain

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.4: Output Data for As-built Shear Enhancement Circular Column CS-4

Step	ϵ_c	$y_{N.A.}$	Curvature ϕ	Moment(K-ft)	Comments
1	0.0001	-29.47	0.000002	16	
2	0.00011	-22.56	0.000003	21	
3	0.00012	-16.8	0.000004	28	
4	0.00014	-12	0.000006	38	
5	0.00015	-11.47	0.000006	42	
6	0.00017	-9.41	0.000008	51	
7	0.00018	-7.68	0.000009	59	
8	0.0002	-6.19	0.000011	67	
9	0.00022	-4.9	0.000013	75	
10	0.00025	-3.74	0.000016	83	
11	0.00027	-2.74	0.000019	92	
12	0.0003	-1.87	0.000022	101	
13	0.00033	-1.06	0.000026	111	
14	0.00037	-0.38	0.00003	121	
15	0.00041	0.24	0.000035	133	
16	0.00045	0.77	0.00004	145	
17	0.0005	1.2	0.000046	160	
18	0.00055	1.63	0.000053	175	
19	0.00061	2.02	0.000061	192	
20	0.00067	2.3	0.000069	211	
21	0.00074	2.59	0.000079	231	
22	0.00082	2.83	0.00009	254	
23	0.00091	3.02	0.000101	279	
24	0.001	3.22	0.000114	307	
25	0.00111	3.41	0.000129	337	
26	0.00123	3.5	0.000145	369	
27	0.00136	3.7	0.000163	397	Begin Yield of Steel
28	0.0015	3.94	0.000186	418	
29	0.00166	4.18	0.000212	436	
30	0.00183	4.46	0.000243	450	
31	0.00203	4.7	0.000278	463	
32	0.00224	4.94	0.000318	472	
33	0.00248	5.14	0.000361	482	
34	0.00274	5.33	0.000411	489	
35	0.00303	5.52	0.000467	490	
36	0.00335	5.62	0.000524	492	
37	0.0037	5.66	0.000584	494	
⋆	0.004	5.7	0.000636	494	Ideal Yield of Steel
38	0.00409	5.71	0.000651	494	
39	0.00452	5.71	0.000719	494	
40	0.005	5.57	0.000777	491	
⋆	0.00543	5.44	0.000829	488	Transverse Steel Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.5: Output Data for Shear Enhancement Circular Column CS-5

Step	ϵ_c	$y_{N.A.}$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00029	-1.25	0.000022	106	
2	0.00032	-0.53	0.000026	115	
3	0.00035	0.14	0.000030	126	
4	0.00039	0.67	0.000035	138	
5	0.00043	1.20	0.000040	150	
6	0.00048	1.63	0.000046	165	
7	0.00053	2.02	0.000053	180	
8	0.00059	2.35	0.000061	197	
9	0.00065	2.64	0.000069	216	
10	0.00072	2.93	0.000079	237	
11	0.00079	3.12	0.000089	261	
12	0.00087	3.36	0.000101	286	
13	0.00097	3.50	0.000114	314	
14	0.00107	3.65	0.000128	345	
15	0.00118	3.79	0.000144	378	Begin Yield of Steel
16	0.00131	3.98	0.000163	406	
17	0.00144	4.22	0.000186	428	
18	0.00160	4.51	0.000213	445	
19	0.00176	4.80	0.000245	460	
20	0.00195	5.09	0.000282	473	
21	0.00216	5.33	0.000323	486	
22	0.00238	5.57	0.000371	497	
23	0.00264	5.86	0.000429	503	
24	0.00291	6.10	0.000493	507	
25	0.00322	6.24	0.000559	515	
26	0.00356	6.38	0.000634	518	
27	0.00394	6.48	0.000713	527	
28	0.00435	6.58	0.000802	534	
29	0.00481	6.67	0.000903	541	
$\star$	0.00500	6.69	0.000942	544	Ideal Yield of Steel
30	0.00532	6.72	0.001007	550	
$\star$	0.00535	6.72	0.001013	551	Tranverse Steel Failure
31	0.00588	6.72	0.001113	561	
32	0.00650	6.72	0.001231	567	
33	0.00718	6.67	0.001349	574	
34	0.00794	6.67	0.001491	576	
35	0.00878	6.58	0.001619	584	
36	0.00971	6.53	0.001774	586	
37	0.01073	6.43	0.001927	591	
38	0.01186	6.34	0.002095	593	
39	0.01312	6.29	0.002296	592	
40	0.01450	6.14	0.002476	596	Maximum Concrete Strain

$\star$ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

B.2 Lap Splice Enhancement Circular Columns

Table B.6: Output Data for As-built Lap Splice Enhancement Circular Column CF-1

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00016	-8.26	0.000008	53	
2	0.00018	-6.67	0.000009	61	
3	0.00020	-5.28	0.000011	69	
4	0.00022	-4.08	0.000013	76	
5	0.00024	-3.02	0.000016	84	
6	0.00026	-2.11	0.000019	93	
7	0.00029	-1.30	0.000022	102	
8	0.00032	-0.58	0.000026	111	
9	0.00036	0.05	0.000030	122	
10	0.00039	0.62	0.000035	133	
11	0.00044	1.10	0.000040	146	
12	0.00048	1.58	0.000046	159	
13	0.00053	1.97	0.000053	175	
14	0.00059	2.30	0.000061	192	
15	0.00065	2.59	0.000069	210	
16	0.00072	2.83	0.000079	231	
17	0.00080	3.07	0.000089	254	
18	0.00088	3.26	0.000101	279	
19	0.00097	3.46	0.000114	304	Begin Yield of Steel
20	0.00108	3.74	0.000130	323	
21	0.00119	4.08	0.000150	339	
22	0.00132	4.42	0.000173	352	
23	0.00145	4.70	0.000199	365	
24	0.00161	5.04	0.000231	373	
25	0.00178	5.33	0.000266	383	
26	0.00196	5.62	0.000308	389	
27	0.00217	5.90	0.000356	393	
28	0.00240	6.10	0.000407	397	
29	0.00265	6.24	0.000461	401	
30	0.00293	6.38	0.000522	403	
31	0.00324	6.53	0.000593	404	
32	0.00359	6.62	0.000667	406	
33	0.00396	6.72	0.000751	406	
⋆	0.00400	6.72	0.000759	406	Ideal Yield of Steel
34	0.00438	6.77	0.000838	406	
35	0.00484	6.82	0.000935	402	
36	0.00536	6.77	0.001024	403	
37	0.00592	6.77	0.001132	400	
⋆	0.00632	6.71	0.001194	401	Tranverse Steel Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.7: Output Data for As-built Lap Splice Enhancement Circular Column CF-2

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00016	-8.88	0.000008	51	
2	0.00018	-7.20	0.000009	58	
3	0.00020	-5.76	0.000011	66	
4	0.00022	-4.51	0.000013	74	
5	0.00024	-3.41	0.000016	82	
6	0.00026	-2.45	0.000018	90	
7	0.00029	-1.58	0.000022	99	
8	0.00032	-0.86	0.000025	108	
9	0.00036	-0.19	0.000029	119	
10	0.00039	0.38	0.000034	130	
11	0.00044	0.91	0.000039	142	
12	0.00048	1.34	0.000045	156	
13	0.00053	1.78	0.000052	171	
14	0.00059	2.11	0.000060	187	
15	0.00065	2.40	0.000068	206	
16	0.00072	2.69	0.000077	226	
17	0.00080	2.93	0.000088	248	
18	0.00088	3.12	0.000099	272	
19	0.00097	3.31	0.000112	298	Begin Yield of Steel
20	0.00108	3.60	0.000128	317	
21	0.00119	3.89	0.000147	334	
22	0.00132	4.22	0.000169	347	
23	0.00145	4.51	0.000194	360	
24	0.00161	4.85	0.000225	369	
25	0.00178	5.14	0.000259	378	
26	0.00196	5.42	0.000299	385	
27	0.00217	5.71	0.000345	388	
28	0.00240	5.90	0.000394	392	
29	0.00265	6.05	0.000446	396	
30	0.00293	6.19	0.000505	399	
31	0.00324	6.34	0.000573	400	
32	0.00359	6.43	0.000644	403	
33	0.00396	6.53	0.000724	403	
⋆	0.00400	6.53	0.000732	403	Ideal Yield of Steel
34	0.00438	6.58	0.000808	402	
35	0.00484	6.62	0.000901	400	
36	0.00536	6.62	0.000996	398	
37	0.00592	6.58	0.001092	398	
38	0.00655	6.53	0.001196	398	
⋆	0.00651	6.53	0.001189	398	Tranverse Steel Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.8: Output Data for Lap Splice Enhancement Circular Column CF-3

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00030	-1.30	0.000023	102	
2	0.00033	-0.58	0.000026	112	
3	0.00037	0.05	0.000031	122	
4	0.00041	0.58	0.000035	134	
5	0.00045	1.06	0.000041	146	
6	0.00050	1.49	0.000047	160	
7	0.00055	1.87	0.000054	175	
8	0.00061	2.21	0.000062	192	
9	0.00067	2.50	0.000070	211	
10	0.00074	2.74	0.000080	231	
11	0.00082	2.98	0.000091	253	
12	0.00090	3.17	0.000102	278	
13	0.00100	3.36	0.000116	302	Begin Yield of Steel
14	0.00103	3.41	0.000120	307	
15	0.00114	3.70	0.000137	325	
16	0.00126	3.98	0.000157	340	
17	0.00139	4.32	0.000181	352	
18	0.00154	4.66	0.000210	363	
19	0.00170	4.99	0.000243	371	
20	0.00188	5.28	0.000280	380	
21	0.00208	5.57	0.000324	387	
22	0.00230	5.81	0.000372	391	
23	0.00254	6.00	0.000424	397	
24	0.00281	6.19	0.000484	400	
25	0.00311	6.34	0.000549	406	
26	0.00344	6.53	0.000628	408	
27	0.00380	6.72	0.000720	407	
28	0.00420	6.86	0.000818	408	
29	0.00464	6.96	0.000922	412	
$\star$	0.00500	7.03	0.001008	411	Ideal Yield of Steel
30	0.00513	7.06	0.001039	411	
31	0.00568	7.10	0.001159	415	
32	0.00628	7.10	0.001282	422	
$\star$	0.00642	7.10	0.001311	423	Tranverse Steel Failure
33	0.00694	7.10	0.001417	428	
34	0.00767	7.10	0.001566	434	
35	0.00848	7.06	0.001715	442	
36	0.00937	7.01	0.001878	449	
37	0.01036	7.01	0.002076	453	
38	0.01146	6.91	0.002251	460	
39	0.01266	6.86	0.002466	464	
40	0.01400	6.82	0.002701	467	Maximum Concrete Strain

Table B.9: Output Data for Lap Splice Enhancement Circular Column CF-4

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00031	-1.15	0.000024	104	
2	0.00034	-0.48	0.000027	114	
3	0.00038	0.14	0.000032	125	
4	0.00042	0.67	0.000037	136	
5	0.00046	1.15	0.000043	149	
6	0.00051	1.58	0.000049	163	
7	0.00057	1.92	0.000056	179	
8	0.00063	2.26	0.000064	196	
9	0.00069	2.54	0.000073	215	
10	0.00076	2.78	0.000083	236	
11	0.00085	2.98	0.000094	259	
12	0.00093	3.17	0.000106	284	
13	0.00103	3.36	0.000120	307	Begin Yield of Steel
14	0.00107	3.46	0.000125	312	
15	0.00118	3.74	0.000143	329	
16	0.00131	4.08	0.000165	342	
17	0.00144	4.37	0.000189	355	
18	0.00160	4.70	0.000219	365	
19	0.00176	5.04	0.000253	373	
20	0.00195	5.28	0.000290	383	
21	0.00216	5.57	0.000335	389	
22	0.00238	5.81	0.000385	393	
23	0.00264	6.00	0.000439	397	
24	0.00291	6.19	0.000502	400	
25	0.00322	6.38	0.000573	403	
26	0.00356	6.53	0.000651	407	
27	0.00394	6.72	0.000745	407	
28	0.00435	6.82	0.000839	411	
29	0.00481	6.91	0.000945	412	
⋆	0.00500	6.95	0.000990	412	Ideal Yield of Steel
30	0.00532	7.01	0.001065	412	
31	0.00588	7.06	0.001189	415	
⋆	0.00648	7.06	0.001311	423	Tranverse Steel Failure
32	0.00650	7.06	0.001315	423	
33	0.00718	7.06	0.001453	429	
34	0.00794	7.06	0.001607	434	
35	0.00878	7.01	0.001759	442	
36	0.00971	6.96	0.001926	449	
37	0.01073	6.91	0.002109	455	
38	0.01186	6.86	0.002310	459	
39	0.01312	6.82	0.002530	463	
40	0.01450	6.77	0.002771	466	Maximum Concrete Strain

Table B.10: Output Data for Lap Splice Enhancement Circular Column CF-5

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00045	1.10	0.000041	147	
2	0.00050	1.54	0.000048	161	
3	0.00055	1.92	0.000055	176	
4	0.00061	2.21	0.000062	193	
5	0.00067	2.50	0.000071	211	
6	0.00074	2.74	0.000080	232	
7	0.00082	2.98	0.000091	254	
8	0.00091	3.17	0.000103	279	
9	0.00100	3.36	0.000116	303	Begin Yield of Steel
10	0.00111	3.60	0.000132	321	
11	0.00123	3.94	0.000152	336	
12	0.00136	4.27	0.000176	348	
13	0.00150	4.56	0.000202	361	
14	0.00166	4.90	0.000233	370	
15	0.00183	5.18	0.000269	381	
16	0.00203	5.52	0.000313	386	
17	0.00224	5.76	0.000359	393	
18	0.00248	6.00	0.000413	397	
19	0.00274	6.19	0.000471	403	
20	0.00303	6.38	0.000539	407	
21	0.00335	6.62	0.000622	408	
22	0.00370	6.82	0.000713	410	
23	0.00409	6.96	0.000811	414	
24	0.00452	7.10	0.000923	415	
25	0.00500	7.20	0.001041	420	Ideal Yield of Steel
26	0.00552	7.30	0.001174	424	
27	0.00611	7.34	0.001312	432	
⋆	0.00638	7.36	0.001376	436	Tranverse Steel Failure
28	0.00675	7.39	0.001465	442	
29	0.00746	7.44	0.001637	451	
30	0.00825	7.49	0.001829	460	
31	0.00912	7.49	0.002022	470	
32	0.01008	7.54	0.002259	476	
33	0.01115	7.54	0.002498	485	
34	0.01233	7.54	0.002761	492	
35	0.01363	7.54	0.003052	498	
36	0.01506	7.49	0.003339	507	
37	0.01665	7.49	0.003691	511	
38	0.01841	7.44	0.004037	518	
⋆	0.02000	7.44	0.004386	520	Maximum Concrete Strain

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.11: Output Data for Lap Splice Enhancement Circular Column CF-6

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00048	1.01	0.000044	149	
2	0.00053	1.44	0.000050	163	
3	0.00059	1.78	0.000057	178	
4	0.00065	2.11	0.000066	195	
5	0.00072	2.35	0.000074	214	
6	0.00079	2.59	0.000084	235	
7	0.00088	2.83	0.000096	257	
8	0.00097	2.98	0.000107	282	
9	0.00107	3.22	0.000122	304	Begin Yield of Steel
10	0.00112	3.31	0.000128	312	
11	0.00123	3.60	0.000147	329	
12	0.00136	3.94	0.000169	342	
13	0.00151	4.27	0.000195	354	
14	0.00167	4.61	0.000225	364	
15	0.00184	4.94	0.000261	372	
16	0.00204	5.18	0.000299	383	
17	0.00225	5.47	0.000345	387	
18	0.00249	5.71	0.000396	392	
19	0.00275	5.95	0.000455	395	
20	0.00304	6.10	0.000515	402	
21	0.00336	6.34	0.000594	403	
22	0.00372	6.53	0.000679	407	
23	0.00411	6.72	0.000778	408	
24	0.00454	6.86	0.000885	410	
⋆	0.00500	6.96	0.000992	414	Ideal Yield of Steel
25	0.00502	6.96	0.000997	414	
26	0.00555	7.06	0.001123	417	
27	0.00614	7.10	0.001254	424	
⋆	0.00672	7.14	0.001384	431	Tranverse Steel Failure
28	0.00679	7.15	0.001400	432	
29	0.00750	7.15	0.001547	442	
30	0.00829	7.20	0.001728	450	
31	0.00917	7.25	0.001929	458	
32	0.01014	7.25	0.002133	468	
33	0.01121	7.25	0.002358	477	
34	0.01239	7.30	0.002633	481	
35	0.01369	7.30	0.002911	488	
36	0.01514	7.25	0.003186	498	
37	0.01674	7.25	0.003522	503	
38	0.01850	7.25	0.003894	507	
⋆	0.02000	7.21	0.004176	512	Maximum Concrete Strain

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.12: Output Data for Lap Splice Enhancement Circular Column CF-7

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00048	1.06	0.000044	149	
2	0.00053	1.44	0.000050	163	
3	0.00059	1.78	0.000057	179	
4	0.00065	2.11	0.000066	196	
5	0.00072	2.40	0.000075	215	
6	0.00079	2.64	0.000085	235	
7	0.00088	2.83	0.000096	258	
8	0.00097	3.02	0.000108	283	
9	0.00107	3.22	0.000122	305	Begin Yield of Steel
10	0.00121	3.60	0.000144	325	
11	0.00134	3.89	0.000165	340	
12	0.00148	4.22	0.000190	352	
13	0.00163	4.56	0.000219	363	
14	0.00181	4.90	0.000254	371	
15	0.00200	5.18	0.000293	380	
16	0.00221	5.47	0.000338	385	
17	0.00244	5.71	0.000388	390	
18	0.00270	5.90	0.000442	396	
19	0.00298	6.10	0.000505	400	
20	0.00330	6.29	0.000577	405	
21	0.00364	6.53	0.000666	405	
22	0.00403	6.67	0.000756	410	
23	0.00445	6.82	0.000859	413	
24	0.00492	6.96	0.000977	414	
$\star$	0.00500	6.98	0.000996	414	Ideal Yield of Steel
25	0.00544	7.06	0.001101	416	
26	0.00602	7.10	0.001229	424	
27	0.00665	7.15	0.001372	431	
$\star$	0.00669	7.15	0.001382	431	Tranverse Steel Failure
28	0.00735	7.20	0.001532	438	
29	0.00813	7.20	0.001693	450	
30	0.00899	7.25	0.001891	458	
31	0.00993	7.30	0.002112	465	
32	0.01098	7.30	0.002334	474	
33	0.01214	7.30	0.002581	482	
34	0.01342	7.30	0.002853	489	
35	0.01484	7.30	0.003154	495	
36	0.01640	7.25	0.003452	504	
37	0.01813	7.25	0.003816	508	
$\star$	0.02000	7.25	0.004209	511	Maximum Concrete Strain

$\star$ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.13: Output Data for Lap Splice Enhancement Circular Column CF-8

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00049	1.58	0.000047	161	
2	0.00054	1.97	0.000054	176	
3	0.00060	2.30	0.000062	193	
4	0.00066	2.54	0.000070	211	
5	0.00073	2.83	0.000080	232	
6	0.00081	3.02	0.000090	254	
7	0.00089	3.22	0.000102	279	
8	0.00099	3.41	0.000115	303	Begin Yield of Steel
9	0.00112	3.74	0.000135	324	
10	0.00123	4.03	0.000155	340	
11	0.00136	4.37	0.000179	353	
12	0.00151	4.70	0.000207	364	
13	0.00167	5.04	0.000239	373	
14	0.00184	5.33	0.000276	383	
15	0.00204	5.66	0.000321	388	
16	0.00225	5.90	0.000369	395	
17	0.00249	6.14	0.000425	399	
18	0.00275	6.34	0.000486	404	
19	0.00304	6.53	0.000556	410	
20	0.00336	6.77	0.000643	410	
21	0.00372	6.91	0.000731	416	
22	0.00411	7.10	0.000839	415	
23	0.00454	7.25	0.000956	417	
⋆	0.00500	7.34	0.001074	422	Ideal Yield of Steel
24	0.00502	7.34	0.001079	422	
25	0.00555	7.44	0.001218	428	
26	0.00614	7.49	0.001360	441	
⋆	0.00626	7.51	0.001394	443	Tranverse Steel Failure
27	0.00679	7.58	0.001537	449	
28	0.00750	7.63	0.001718	459	
29	0.00829	7.68	0.001920	468	
30	0.00917	7.73	0.002146	476	
31	0.01014	7.73	0.002373	487	
32	0.01121	7.73	0.002623	497	
33	0.01239	7.73	0.002900	505	
34	0.01369	7.73	0.003206	512	
35	0.01514	7.73	0.003544	518	
36	0.01674	7.73	0.003918	523	
37	0.01850	7.73	0.004331	526	
⋆	0.02000	7.69	0.004640	531	Maximum Concrete Strain

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.14: Output Data for Lap Splice Enhancement Circular Column CF-9

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00049	1.58	0.000047	161	
2	0.00054	1.97	0.000054	176	
3	0.00060	2.30	0.000062	193	
4	0.00066	2.59	0.000070	211	
5	0.00073	2.83	0.000080	232	
6	0.00081	3.02	0.000090	254	
7	0.00089	3.22	0.000102	279	
8	0.00099	3.41	0.000115	303	Begin Yield of Steel
9	0.00112	3.74	0.000135	325	
10	0.00123	4.03	0.000155	341	
11	0.00136	4.37	0.000179	353	
12	0.00151	4.70	0.000207	364	
13	0.00167	5.04	0.000239	373	
14	0.00184	5.33	0.000276	384	
15	0.00204	5.66	0.000321	389	
16	0.00225	5.90	0.000369	396	
17	0.00249	6.14	0.000425	400	
18	0.00275	6.34	0.000486	405	
19	0.00304	6.53	0.000556	410	
20	0.00336	6.77	0.000643	411	
21	0.00372	6.91	0.000731	416	
22	0.00411	7.10	0.000839	416	
23	0.00454	7.25	0.000956	418	
$\star$	0.00500	7.34	0.001074	422	Ideal Yield of Steel
24	0.00502	7.34	0.001079	422	
25	0.00555	7.44	0.001218	428	
26	0.00614	7.49	0.001360	441	
$\star$	0.00626	7.51	0.001393	442	Tranverse Steel Failure
27	0.00679	7.58	0.001537	449	
28	0.00750	7.63	0.001718	459	
29	0.00829	7.68	0.001920	469	
30	0.00917	7.73	0.002146	477	
31	0.01014	7.73	0.002373	488	
32	0.01121	7.73	0.002623	497	
33	0.01239	7.78	0.002933	501	
34	0.01369	7.78	0.003242	508	
35	0.01514	7.73	0.003544	518	
36	0.01674	7.73	0.003918	523	
37	0.01850	7.73	0.004331	527	
38	0.02046	7.68	0.004735	533	
$\star$	0.02000	7.68	0.004628	533	Maximum Concrete Strain

$\star$ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

B.3 Lap Splice Enhancement Rectangular Columns

Table B.15: Output Data for As-built Lap Splice Enhancement Rectangular Column RF-1

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00030	0.14	0.000025	187	
2	0.00033	0.86	0.000030	207	
3	0.00037	1.44	0.000035	228	
4	0.00041	1.97	0.000040	252	
5	0.00045	2.40	0.000047	279	
6	0.00050	2.78	0.000054	309	
7	0.00055	3.12	0.000062	341	
8	0.00061	3.41	0.000070	377	
9	0.00067	3.65	0.000080	417	
10	0.00074	3.89	0.000091	461	
11	0.00082	4.08	0.000103	510	
12	0.00090	4.22	0.000116	563	
13	0.00100	4.37	0.000131	621	
14	0.00111	4.46	0.000147	684	
15	0.00122	4.85	0.000171	716	Begin Yield of Steel
16	0.00135	5.23	0.000200	744	
17	0.00149	5.62	0.000234	768	
18	0.00165	6.05	0.000277	784	
19	0.00182	6.38	0.000325	802	
20	0.00202	6.77	0.000386	812	
21	0.00223	7.06	0.000451	833	
22	0.00247	7.25	0.000519	858	
23	0.00273	7.49	0.000604	878	
24	0.00301	7.68	0.000698	902	
25	0.00333	7.82	0.000798	926	
26	0.00368	7.87	0.000892	938	
⋆	0.00400	7.87	0.000969	948	Ideal Yield of Steel
27	0.00407	7.87	0.000986	950	
28	0.00450	7.82	0.001078	962	
29	0.00498	7.78	0.001178	972	
30	0.00550	7.73	0.001288	979	
31	0.00608	7.63	0.001392	987	
32	0.00672	7.54	0.001506	991	
33	0.00743	7.44	0.001630	993	
34	0.00822	7.30	0.001747	996	
⋆	0.00849	7.25	0.001787	996	Tranverse Steel Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.16: Output Data for Lap Splice Enhancement Rectangular Column RF-2

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00091	4.13	0.000116	558	
2	0.00101	4.27	0.000130	616	
3	0.00111	4.42	0.000147	679	
4	0.00123	4.80	0.000171	713	First Yield of Steel
5	0.00131	5.04	0.000189	733	
6	0.00145	5.47	0.000223	757	
⋆	0.00150	5.59	0.000235	764	Unconfined Lap Splice Failure
7	0.00161	5.86	0.000261	780	
8	0.00178	6.29	0.000311	797	
9	0.00196	6.67	0.000368	814	
10	0.00217	7.06	0.000439	832	
11	0.00240	7.34	0.000515	858	
12	0.00265	7.58	0.000601	887	
13	0.00293	7.87	0.000710	912	
14	0.00324	8.11	0.000834	940	
15	0.00358	8.30	0.000970	967	
16	0.00396	8.40	0.001101	989	
17	0.00438	8.50	0.001250	1009	
18	0.00484	8.54	0.001401	1033	
⋆	0.00500	8.57	0.001461	1039	Ideal Yield of Steel
19	0.00535	8.64	0.001593	1053	
20	0.00592	8.69	0.001787	1079	
21	0.00654	8.78	0.002034	1096	
⋆	0.00720	8.88	0.002304	1111	Tranverse Steel Failure
22	0.00723	8.88	0.002318	1112	
23	0.00800	8.93	0.002603	1131	
24	0.00884	8.98	0.002923	1147	
25	0.00977	9.02	0.003284	1162	
26	0.01080	9.07	0.003690	1174	
27	0.01194	9.12	0.004147	1183	Longitudinal Steel Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.17: Output Data for Lap Splice Enhancement Rectangular Column RF-3

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00099	3.94	0.000123	575	
2	0.00109	4.08	0.000138	634	
3	0.00121	4.27	0.000157	689	First Yield of Steel
4	0.00128	4.51	0.000171	706	
5	0.00142	4.94	0.000201	735	
$\star$	0.00150	5.17	0.000220	748	Unconfined Lap Splice Failure
6	0.00157	5.38	0.000237	759	
7	0.00173	5.81	0.000280	779	
8	0.00192	6.19	0.000330	798	
9	0.00212	6.62	0.000394	812	
10	0.00234	6.96	0.000465	836	
11	0.00259	7.25	0.000545	862	
12	0.00286	7.49	0.000635	892	
13	0.00317	7.78	0.000749	918	
14	0.00350	7.97	0.000868	943	
15	0.00387	8.06	0.000983	966	
16	0.00428	8.16	0.001114	987	
17	0.00473	8.26	0.001263	1007	
$\star$	0.00500	8.31	0.001355	1017	Ideal Yield of Steel
18	0.00523	8.35	0.001433	1025	
19	0.00578	8.40	0.001605	1046	
20	0.00639	8.45	0.001799	1069	
21	0.00706	8.54	0.002044	1085	
$\star$	0.00763	8.58	0.002231	1102	Tranverse Steel Failure
22	0.00781	8.59	0.002291	1107	
23	0.00863	8.69	0.002606	1119	
24	0.00954	8.74	0.002924	1135	
25	0.01055	8.78	0.003280	1149	
26	0.01166	8.83	0.003681	1161	
27	0.01289	8.88	0.004133	1173	Longitudinal Steel Failure

$\star$ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.18: Output Data for Lap splice Enhancement Rectangular Column RF-5

Step	ϵ_c	$y_{N.A.}$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00069	3.65	0.000083	425	
2	0.00076	3.84	0.000093	469	
3	0.00084	4.03	0.000106	518	
4	0.00093	4.18	0.000119	571	
5	0.00103	4.32	0.000134	630	
6	0.00114	4.46	0.000151	688	First Yield of Steel
7	0.00126	4.85	0.000176	720	
8	0.00139	5.28	0.000207	746	
⋆	0.00150	5.56	0.000233	764	Unconfined Lap Splice Failure
9	0.00154	5.66	0.000243	771	
10	0.00170	6.10	0.000288	788	
11	0.00188	6.48	0.000341	806	
12	0.00208	6.86	0.000405	822	
13	0.00230	7.15	0.000474	848	
14	0.00254	7.44	0.000557	872	
15	0.00281	7.73	0.000658	897	
16	0.00311	7.97	0.000771	925	
17	0.00343	8.16	0.000894	956	
18	0.00380	8.30	0.001027	974	
19	0.00420	8.35	0.001151	999	
20	0.00464	8.45	0.001306	1017	
⋆	0.00500	8.49	0.001422	1033	Ideal Yield of Steel
21	0.00513	8.50	0.001464	1039	
22	0.00567	8.54	0.001641	1061	
23	0.00627	8.64	0.001866	1078	
24	0.00693	8.69	0.002093	1099	
⋆	0.00744	8.75	0.002297	1107	Tranverse Steel Failure
25	0.00766	8.78	0.002383	1110	
26	0.00847	8.83	0.002674	1127	
27	0.00936	8.88	0.003002	1140	
28	0.01035	8.93	0.003370	1151	
29	0.01145	8.93	0.003726	1166	
30	0.01265	8.98	0.004184	1171	Longitudinal Steel Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.19: Output Data for Lap splice Enhancement Rectangular Column RF-6

Step	ϵ_c	$y_{N.A.}$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00084	4.03	0.000105	516	
2	0.00093	4.18	0.000119	570	
3	0.00103	4.32	0.000134	628	
4	0.00113	4.46	0.000151	688	First Yield of Steel
5	0.00125	4.85	0.000175	720	
6	0.00139	5.28	0.000206	746	
⋆	0.00150	5.58	0.000234	766	Unconfined Lap Splice Failure
7	0.00153	5.66	0.000242	772	
8	0.00150	5.59	0.000233	769	
9	0.00187	6.48	0.000340	808	
10	0.00207	6.86	0.000403	824	
11	0.00229	7.20	0.000477	847	
12	0.00253	7.44	0.000555	876	
13	0.00280	7.73	0.000655	902	
14	0.00309	7.97	0.000768	930	
15	0.00342	8.21	0.000902	956	
16	0.00378	8.35	0.001037	977	
17	0.00418	8.45	0.001177	998	
18	0.00462	8.50	0.001319	1023	
⋆	0.00500	8.53	0.001443	1041	Ideal Yield of Steel
19	0.00511	8.54	0.001479	1046	
20	0.00565	8.63	0.001685	1064	
21	0.00625	8.74	0.001913	1084	
22	0.00690	8.78	0.002147	1106	
⋆	0.00726	8.83	0.002293	1113	Tranverse Steel Failure
23	0.00763	8.88	0.002446	1120	
24	0.00844	8.93	0.002750	1135	
25	0.00933	8.98	0.003085	1152	
26	0.01031	9.02	0.003465	1165	
27	0.01140	9.07	0.003894	1175	Longitudinal Steel Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

B.4 Shear Enhancement Rectangular Columns

Table B.20: Output Data for As-built Shear Enhancement Rectangular Column RS-1

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00035	0.24	0.000030	152	
2	0.00039	0.91	0.000035	167	
3	0.00043	1.49	0.000041	185	
4	0.00047	2.02	0.000047	204	
5	0.00052	2.45	0.000055	225	
6	0.00058	2.78	0.000063	248	
7	0.00064	3.12	0.000072	274	
8	0.00071	3.41	0.000082	302	
9	0.00078	3.65	0.000093	333	
10	0.00086	3.89	0.000106	365	Begin Yield of Steel
11	0.00095	4.32	0.000124	383	
12	0.00106	4.80	0.000147	398	
13	0.00117	5.23	0.000172	412	
14	0.00129	5.66	0.000204	423	
15	0.00143	6.10	0.000241	432	
16	0.00158	6.48	0.000285	441	
17	0.00174	6.82	0.000336	449	
18	0.00193	7.20	0.000401	454	
19	0.00213	7.54	0.000477	457	
20	0.00235	7.73	0.000551	461	
21	0.00260	7.87	0.000630	463	
22	0.00288	8.02	0.000722	462	
23	0.00318	8.06	0.000808	466	
24	0.00352	8.16	0.000916	466	
25	0.00389	8.21	0.001025	470	
⋆	0.004	8.21	0.001054	472	Ideal Yield of Steel
26	0.00430	8.21	0.001133	478	
27	0.00475	8.21	0.001253	484	
28	0.00525	8.16	0.001368	490	
29	0.00581	8.11	0.001493	495	
30	0.00642	8.02	0.001611	500	
31	0.00710	7.92	0.001739	504	
32	0.00784	7.78	0.001857	507	
⋆	0.00834	7.69	0.001935	508	Tranverse Steel Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.21: Output Data for Shear Enhancement Rectangular Column RS-2

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00061	3.02	0.000068	263	
2	0.00067	3.31	0.000078	289	
3	0.00075	3.55	0.000088	319	
4	0.00082	3.74	0.000100	352	
5	0.00091	4.13	0.000116	374	Begin Yield of Steel
8	0.00097	4.42	0.000128	385	
9	0.00107	4.85	0.000150	400	
10	0.00118	5.33	0.000177	412	
11	0.00131	5.76	0.000210	424	
12	0.00145	6.19	0.000249	433	
13	0.00160	6.58	0.000295	441	
14	0.00177	6.96	0.000351	449	
15	0.00195	7.34	0.000420	454	
16	0.00216	7.68	0.000500	458	
17	0.00239	7.87	0.000579	464	
18	0.00264	8.06	0.000671	465	
19	0.00292	8.21	0.000770	469	
20	0.00323	8.40	0.000897	470	
21	0.00357	8.54	0.001033	476	
22	0.00395	8.64	0.001174	488	
23	0.00436	8.69	0.001317	502	
24	0.00482	8.78	0.001499	511	
⋆	0.00500	8.80	0.001564	515	Ideal Yield of Steel
25	0.00533	8.83	0.001683	523	
26	0.00589	8.83	0.001860	536	
27	0.00651	8.88	0.002088	545	
⋆	0.00699	8.88	0.002241	552	Tranverse Steel Failure
28	0.00720	8.88	0.002308	555	
29	0.00796	8.88	0.002552	564	
30	0.00880	8.88	0.002821	572	
31	0.00973	8.88	0.003119	578	
32	0.01076	8.83	0.003396	586	
33	0.01189	8.83	0.003754	589	
34	0.01315	8.78	0.004088	594	
35	0.01453	8.74	0.004453	598	
36	0.01607	8.69	0.004851	603	
⋆	0.01755	8.65	0.005232	605	Jacket Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.22: Output Data for Shear Enhancement Rectangular Column RS-3

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00054	2.93	0.000060	242	
2	0.00060	3.22	0.000068	267	
3	0.00066	3.50	0.000078	294	
4	0.00073	3.74	0.000088	325	
5	0.00081	3.94	0.000100	358	
6	0.00089	4.37	0.000117	378	Begin Yield of Steel
8	0.00093	4.56	0.000125	386	
9	0.00103	4.99	0.000146	402	
10	0.00113	5.42	0.000173	415	
11	0.00125	5.86	0.000204	427	
12	0.00139	6.34	0.000245	434	
13	0.00153	6.72	0.000290	443	
14	0.00169	7.06	0.000343	452	
15	0.00187	7.44	0.000411	457	
16	0.00207	7.78	0.000490	461	
17	0.00229	8.06	0.000582	466	
18	0.00253	8.26	0.000676	468	
19	0.00280	8.40	0.000777	472	
20	0.00309	8.59	0.000908	475	
21	0.00342	8.74	0.001048	482	
22	0.00378	8.83	0.001193	494	
23	0.00418	8.93	0.001361	505	
24	0.00462	8.98	0.001528	518	
⋆	0.00500	9.01	0.001675	527	Ideal Yield of Steel
25	0.00511	9.02	0.001717	529	
26	0.00565	9.07	0.001929	540	
27	0.00624	9.07	0.002132	552	
⋆	0.00674	9.07	0.002304	560	Tranverse Steel Failure
28	0.00690	9.07	0.002357	562	
29	0.00763	9.12	0.002649	567	
30	0.00844	9.07	0.002881	578	
31	0.00933	9.07	0.003185	584	
32	0.01031	9.02	0.003464	591	
33	0.01140	9.02	0.003830	594	
34	0.01260	8.98	0.004166	599	
35	0.01393	8.93	0.004534	604	
36	0.01540	8.88	0.004935	606	
⋆	0.01633	8.85	0.005185	607	Jacket Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.23: Output Data for Shear Enhancement Rectangular Column RS-4

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00062	2.98	0.000069	264	
2	0.00069	3.26	0.000078	291	
3	0.00076	3.50	0.000089	321	
4	0.00084	3.70	0.000101	353	
5	0.00093	4.13	0.000118	374	Begin Yield of Steel
8	0.00097	4.32	0.000126	382	
9	0.00107	4.75	0.000148	398	
10	0.00118	5.23	0.000175	411	
11	0.00131	5.62	0.000205	424	
12	0.00145	6.10	0.000245	432	
13	0.00160	6.48	0.000290	441	
14	0.00177	6.86	0.000344	448	
15	0.00195	7.25	0.000411	454	
16	0.00216	7.58	0.000489	459	
17	0.00239	7.82	0.000572	460	
18	0.00264	7.97	0.000655	466	
19	0.00292	8.11	0.000751	469	
20	0.00323	8.30	0.000873	469	
21	0.00357	8.45	0.001005	474	
22	0.00395	8.54	0.001142	486	
23	0.00436	8.64	0.001298	497	
24	0.00482	8.69	0.001456	509	
⋆	0.00500	8.71	0.001518	513	Ideal Yield of Steel
25	0.00533	8.74	0.001633	520	
26	0.00589	8.78	0.001832	530	
27	0.00651	8.78	0.002026	542	
⋆	0.00708	8.78	0.002202	550	Tranverse Steel Failure
28	0.00720	8.78	0.002239	552	
29	0.00796	8.78	0.002476	561	
30	0.00880	8.78	0.002737	569	
31	0.00973	8.78	0.003026	575	
32	0.01076	8.78	0.003345	579	
33	0.01189	8.74	0.003643	586	
34	0.01315	8.69	0.003970	593	
35	0.01453	8.64	0.004326	597	
36	0.01607	8.59	0.004715	600	
⋆	0.01762	8.54	0.005105	601	Jacket Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.24: Output Data for Shear Enhancement Rectangular Column RS-5

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00061	3.31	0.000070	273	
2	0.00067	3.55	0.000080	301	
3	0.00075	3.79	0.000091	332	
4	0.00082	3.98	0.000103	365	
7	0.00089	4.37	0.000117	379	Begin Yield of Steel
8	0.00099	4.80	0.000137	397	
9	0.00109	5.28	0.000163	409	
10	0.00121	5.66	0.000191	424	
11	0.00134	6.14	0.000228	432	
12	0.00148	6.58	0.000272	439	
13	0.00163	6.91	0.000321	449	
14	0.00181	7.30	0.000384	455	
15	0.00200	7.68	0.000462	458	
16	0.00221	7.97	0.000547	464	
17	0.00244	8.21	0.000643	466	
18	0.00270	8.35	0.000739	470	
19	0.00298	8.54	0.000863	473	
20	0.00330	8.74	0.001010	477	
21	0.00364	8.83	0.001150	490	
22	0.00403	8.93	0.001311	501	
23	0.00445	8.98	0.001472	515	
24	0.00492	9.02	0.001654	528	
⋆	0.00500	9.03	0.001685	530	Ideal Yield of Steel
25	0.00544	9.07	0.001858	539	
26	0.00602	9.12	0.002089	549	
27	0.00665	9.12	0.002309	561	
⋆	0.00668	9.12	0.002321	561	Tranverse Steel Failure
28	0.00735	9.17	0.002596	567	
29	0.00813	9.17	0.002870	576	
30	0.00899	9.17	0.003173	583	
31	0.00993	9.12	0.003449	593	
32	0.01098	9.12	0.003813	597	
33	0.01214	9.07	0.004146	604	
34	0.01342	9.02	0.004510	608	
35	0.01484	9.02	0.004986	608	
⋆	0.01484	9.02	0.004987	608	Jacket Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.25: Output Data for Shear Enhancement Rectangular Column RS-6

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00065	3.46	0.000076	290	
2	0.00072	3.70	0.000087	320	
3	0.00079	3.94	0.000099	353	
4	0.00088	4.32	0.000114	375	Begin Yield of Steel
7	0.00097	4.70	0.000133	393	
8	0.00107	5.18	0.000157	406	
9	0.00118	5.62	0.000185	419	
10	0.00131	6.05	0.000220	430	
11	0.00145	6.48	0.000262	438	
12	0.00160	6.82	0.000308	448	
13	0.00177	7.25	0.000372	452	
14	0.00195	7.58	0.000442	459	
15	0.00216	7.92	0.000529	462	
16	0.00239	8.16	0.000621	466	
17	0.00264	8.30	0.000714	471	
18	0.00292	8.50	0.000832	473	
19	0.00322	8.69	0.000973	476	
20	0.00356	8.78	0.001108	488	
21	0.00394	8.88	0.001263	501	
22	0.00436	8.98	0.001441	511	
23	0.00482	9.02	0.001618	524	
$\star$	0.00500	9.04	0.001690	528	Ideal Yield of Steel
24	0.00532	9.07	0.001818	536	
25	0.00589	9.12	0.002044	546	
26	0.00651	9.12	0.002259	559	
$\star$	0.00664	9.13	0.002314	560	Tranverse Steel Failure
27	0.00719	9.17	0.002540	565	
28	0.00795	9.17	0.002808	574	
29	0.00879	9.17	0.003104	581	
30	0.00972	9.12	0.003375	592	
31	0.01074	9.12	0.003731	596	
32	0.01188	9.07	0.004057	603	
33	0.01313	9.07	0.004485	605	
$\star$	0.01448	9.02	0.004867	608	Jacket Failure

$\star$ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Table B.26: Output Data for Shear Enhancement Rectangular Column RS-7

Step	ϵ_c	$y_{N.A.}(in)$	Curvature ϕ	Moment(K-ft)	Comments
1	0.00065	3.46	0.000076	290	
2	0.00072	3.70	0.000087	320	
3	0.00079	3.94	0.000099	353	
4	0.00088	4.32	0.000114	375	Begin Yield of Steel
7	0.00097	4.70	0.000133	393	
8	0.00107	5.18	0.000157	406	
9	0.00118	5.62	0.000185	419	
10	0.00131	6.05	0.000220	430	
11	0.00145	6.48	0.000262	438	
12	0.00160	6.82	0.000308	448	
13	0.00177	7.25	0.000372	452	
14	0.00195	7.58	0.000442	459	
15	0.00216	7.92	0.000529	462	
16	0.00239	8.16	0.000621	466	
17	0.00264	8.30	0.000714	471	
18	0.00292	8.50	0.000832	473	
19	0.00322	8.69	0.000973	476	
20	0.00356	8.78	0.001108	488	
21	0.00394	8.88	0.001263	501	
22	0.00436	8.98	0.001441	511	
23	0.00482	9.02	0.001618	524	
24	0.00532	9.07	0.001818	536	
⋆	0.00500	9.04	0.001691	530	Ideal Yield of Steel
25	0.00589	9.12	0.002044	546	
26	0.00651	9.12	0.002259	559	
⋆	0.00660	9.13	0.002297	560	Tranverse Steel Failure
27	0.00719	9.17	0.002540	565	
28	0.00795	9.17	0.002808	574	
29	0.00879	9.17	0.003104	581	
⋆	0.00949	9.13	0.003308	589	Jacket Failure

⋆ Values by linear interpolation based on concrete strains, ϵ_c, calculated in Section 4.4.3.

Appendix C

SHEAR STRENGTH CALCULATIONS

C.1 Shear Enhancement Circular Columns

Table C.1: Ductility and Shear Strength Calculations for As-built Shear Enhancement Circular Column CS-1

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	13.0	0.015	0.1	3.50	139.8	
2	14.8	0.017	0.1	3.50	137.2	
3	16.8	0.021	0.1	3.50	135.0	
4	18.8	0.024	0.1	3.50	133.1	
5	20.8	0.030	0.1	3.50	131.3	
6	22.8	0.034	0.1	3.50	129.8	
7	25.0	0.041	0.1	3.50	128.5	
8	27.3	0.047	0.2	3.50	127.3	
9	30.0	0.056	0.2	3.50	126.3	
10	32.8	0.063	0.2	3.50	125.4	
11	35.8	0.075	0.3	3.50	124.5	
12	39.3	0.086	0.3	3.50	123.9	
13	43.0	0.097	0.3	3.50	123.3	
14	47.3	0.112	0.4	3.50	122.7	
15	51.8	0.129	0.5	3.50	122.2	
16	57.0	0.145	0.5	3.50	121.8	
17	62.5	0.164	0.6	3.50	121.4	
18	68.8	0.186	0.7	3.50	121.1	
19	75.3	0.211	0.7	3.50	120.8	Begin Yield of Steel
20	80.0	0.224	0.8	3.50	120.4	
21	84.3	0.236	0.8	3.50	119.9	
22	87.3	0.244	0.9	3.50	119.4	
23	90.3	0.253	0.9	3.50	118.8	
24	92.5	0.259	0.9	3.50	118.3	
25	94.8	0.265	0.9	3.50	117.9	
26	96.5	0.270	1.0	3.50	117.4	
27	98.0	0.274	1.0	3.50	117.0	
28	98.8	0.276	1.0	3.50	116.7	
29	100.0	0.280	1.0	3.50	116.5	
30	100.5	0.281	1.0	3.50	116.3	
31	100.8	0.282	1.0	3.50	116.0	
32	100.5	0.281	1.0	3.50	115.8	
33	100.5	0.281	1.0	3.50	115.7	
⋆	100.5	0.281	1.0	3.50	115.7	Ideal Yield of Steel
34	100.5	0.347	1.2	3.50	115.6	
35	100.8	0.423	1.5	3.50	115.6	
36	100.3	0.499	1.8	3.50	115.6	
37	99.3	0.579	2.1	3.44	113.9	
⋆	99.9	0.651	2.3	3.14	106.6	Tranverse Steel Failure

Table C.2: Ductility and Shear Strength Calculations for Shear Enhancement Circular Column CS-2

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	26.0	0.043	0.1	3.50	307.1	
2	28.5	0.050	0.2	3.50	306.0	
3	31.0	0.058	0.2	3.50	305.0	
4	34.0	0.067	0.2	3.50	304.2	
5	37.3	0.078	0.3	3.50	303.4	
6	40.8	0.089	0.3	3.50	302.7	
7	44.8	0.103	0.3	3.50	302.2	
8	49.0	0.117	0.4	3.50	301.7	
9	53.8	0.134	0.4	3.50	301.2	
10	58.8	0.151	0.5	3.50	300.8	
11	64.8	0.172	0.6	3.50	300.5	
12	71.0	0.194	0.6	3.50	300.2	
13	76.8	0.220	0.7	3.50	299.8	Begin Yield of Steel
14	78.0	0.224	0.7	3.50	299.8	
15	82.3	0.236	0.8	3.50	299.3	
16	85.8	0.246	0.8	3.50	298.8	
17	89.0	0.255	0.9	3.50	298.3	
18	91.5	0.262	0.9	3.50	297.8	
19	93.5	0.268	0.9	3.50	297.2	
20	96.5	0.277	0.9	3.50	296.9	
21	97.3	0.279	0.9	3.50	296.3	
22	98.5	0.282	0.9	3.50	296.0	
23	99.8	0.286	1.0	3.50	295.7	
24	101.3	0.290	1.0	3.50	295.4	
25	102.3	0.293	1.0	3.50	295.1	
26	102.5	0.294	1.0	3.50	294.8	
27	103.3	0.296	1.0	3.50	294.6	
28	103.3	0.296	1.0	3.50	294.4	
29	104.0	0.298	1.0	3.50	294.2	
$\star$	104.2	0.299	1.0	3.50	294.1	Ideal Yield of Steel
30	104.3	0.326	1.1	3.50	294.1	
$\star$	104.7	0.394	1.3	3.50	294.0	Tranverse Steel Failure
31	105.0	0.438	1.5	3.50	294.0	
32	107.0	0.563	1.9	3.50	294.0	
33	108.5	0.694	2.3	3.13	284.3	
34	110.0	0.838	2.8	2.57	269.8	
35	111.3	0.992	3.3	1.98	254.3	
36	113.3	1.153	3.9	1.36	238.3	
37	114.8	1.322	4.4	1.14	232.5	
38	115.8	1.502	5.0	1.05	230.2	
39	116.8	1.697	5.7	0.95	227.7	
40	118.0	1.891	6.3	0.85	225.3	Maximum Concrete Strain

Table C.3: Ductility and Shear Strength Calculations for Shear Enhancement Circular Column CS-3

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	25.5	0.041	0.1	3.50	309.1	
2	28.0	0.048	0.2	3.50	307.9	
3	30.5	0.056	0.2	3.50	306.9	
4	33.5	0.065	0.2	3.50	306.0	
5	36.5	0.075	0.3	3.50	305.3	
6	40.0	0.086	0.3	3.50	304.6	
7	43.8	0.099	0.3	3.50	304.0	
8	48.0	0.112	0.4	3.50	303.5	
9	52.5	0.129	0.4	3.50	303.0	
10	57.8	0.145	0.5	3.50	302.6	
11	63.5	0.166	0.6	3.50	302.3	
12	69.5	0.188	0.6	3.50	301.9	
13	75.8	0.213	0.7	3.50	301.6	Begin Yield of Steel
14	77.0	0.216	0.7	3.50	301.5	
15	81.3	0.228	0.8	3.50	301.1	
16	85.3	0.239	0.8	3.50	300.6	
17	88.3	0.248	0.8	3.50	300.1	
18	91.5	0.257	0.9	3.50	299.6	
19	93.5	0.262	0.9	3.50	299.1	
20	96.0	0.269	0.9	3.50	298.6	
21	97.8	0.274	0.9	3.50	298.2	
22	98.8	0.277	0.9	3.50	297.7	
23	100.0	0.281	1.0	3.50	297.4	
24	101.0	0.283	1.0	3.50	297.1	
25	102.0	0.286	1.0	3.50	296.8	
26	102.3	0.287	1.0	3.50	296.5	
27	103.0	0.289	1.0	3.50	296.3	
28	103.3	0.290	1.0	3.50	296.1	
29	104.0	0.292	1.0	3.50	295.9	
30	104.5	0.293	1.0	3.50	295.8	
⋆	104.6	0.293	1.0	3.50	295.7	Ideal Yield of Steel
⋆	105.4	0.385	1.3	3.50	295.7	Tranverse Steel Failure
31	105.5	0.395	1.3	3.50	295.7	
32	106.5	0.518	1.8	3.50	295.6	
33	108.0	0.647	2.2	3.26	289.3	
34	110.0	0.793	2.7	2.69	274.1	
35	112.3	0.940	3.2	2.12	258.9	
36	113.5	1.106	3.8	1.47	241.6	
37	115.0	1.273	4.3	1.15	233.3	
38	116.3	1.451	4.9	1.06	230.9	
39	117.0	1.641	5.6	0.96	228.4	
40	118.5	1.833	6.2	0.86	226.0	Maximum Concrete Strain

Table C.4: Ductility and Shear Strength Calculations for As-built Shear Enhancement Circular Column CS-4

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	4.0	0.009	0.0	3.50	161.4	
2	5.3	0.011	0.0	3.50	150.5	
3	7.0	0.015	0.1	3.50	141.3	
4	9.5	0.021	0.1	3.50	133.7	
5	10.5	0.023	0.1	3.50	132.9	
6	12.8	0.028	0.1	3.50	129.6	
7	14.8	0.032	0.1	3.50	126.9	
8	16.8	0.037	0.1	3.50	124.5	
9	18.8	0.041	0.2	3.50	122.5	
10	20.8	0.045	0.2	3.50	120.7	
11	23.0	0.050	0.2	3.50	119.1	
12	25.3	0.055	0.2	3.50	117.7	
13	27.8	0.061	0.2	3.50	116.4	
14	30.3	0.066	0.2	3.50	115.3	
15	33.3	0.073	0.3	3.50	114.4	
16	36.3	0.079	0.3	3.50	113.5	
17	40.0	0.087	0.3	3.50	112.8	
18	43.8	0.096	0.4	3.50	112.2	
19	48.0	0.105	0.4	3.50	111.5	
20	52.8	0.115	0.4	3.50	111.1	
21	57.8	0.126	0.5	3.50	110.6	
22	63.5	0.139	0.5	3.50	110.3	
23	69.8	0.153	0.6	3.50	110.0	
24	76.8	0.168	0.6	3.50	109.6	
25	84.3	0.184	0.7	3.50	109.3	
26	92.3	0.202	0.8	3.50	109.2	
27	99.3	0.217	0.8	3.50	108.9	Begin Yield of Steel
28	104.5	0.228	0.9	3.50	108.5	
29	109.0	0.238	0.9	3.50	108.1	
30	112.5	0.246	0.9	3.50	107.7	
31	115.8	0.253	0.9	3.50	107.3	
32	118.0	0.258	1.0	3.50	106.9	
33	120.5	0.263	1.0	3.50	106.6	
34	122.3	0.267	1.0	3.50	106.3	
35	122.5	0.268	1.0	3.50	106.0	
36	123.0	0.269	1.0	3.50	105.8	
37	123.5	0.270	1.0	3.50	105.8	
⋆	123.5	0.276	1.0	3.50	105.7	Ideal Yield of Steel
38	123.5	0.292	1.1	3.50	105.7	
39	123.5	0.363	1.4	3.50	105.7	
40	122.8	0.418	1.6	3.50	105.9	
⋆	122.0	0.466	1.7	3.50	106.1	Transverse Steel Failure

Table C.5: Ductility and Shear Strength Calculations for Shear Enhancement Circular Column CS-5

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	26.5	0.044	0.1	3.50	338.0	
2	28.8	0.052	0.1	3.50	336.8	
3	31.5	0.060	0.1	3.50	335.8	
4	34.5	0.070	0.2	3.50	334.9	
5	37.5	0.080	0.2	3.50	334.1	
6	41.3	0.092	0.2	3.50	333.4	
7	45.0	0.106	0.3	3.50	332.8	
8	49.3	0.122	0.3	3.50	332.3	
9	54.0	0.138	0.3	3.50	331.8	
10	59.3	0.158	0.4	3.50	331.4	
11	65.3	0.178	0.4	3.50	331.1	
12	71.5	0.202	0.5	3.50	330.7	
13	78.5	0.228	0.5	3.50	330.5	
14	86.3	0.256	0.6	3.50	330.2	
15	94.5	0.288	0.7	3.50	330.0	Begin Yield of Steel
16	101.5	0.309	0.7	3.50	329.7	
17	107.0	0.326	0.8	3.50	329.3	
18	111.3	0.339	0.8	3.50	328.9	
19	115.0	0.350	0.8	3.50	328.4	
20	118.3	0.360	0.9	3.50	327.9	
21	121.5	0.370	0.9	3.50	327.6	
22	124.3	0.378	0.9	3.50	327.2	
23	125.8	0.383	0.9	3.50	326.7	
24	126.8	0.386	0.9	3.50	326.3	
25	128.8	0.392	0.9	3.50	326.1	
26	129.5	0.394	1.0	3.50	325.9	
27	131.8	0.401	1.0	3.50	325.7	
28	133.5	0.407	1.0	3.50	325.6	
29	135.3	0.412	1.0	3.50	325.4	
⋆	136.1	0.414	1.0	3.50	325.4	Ideal Yield of Steel
30	137.5	0.493	1.2	3.50	325.4	
⋆	137.6	0.500	1.2	3.50	325.4	Tranverse Steel Failure
31	140.3	0.624	1.5	3.50	325.4	
32	141.8	0.759	1.8	3.50	325.4	
33	143.5	0.895	2.2	3.32	320.1	
34	144.0	1.048	2.5	2.89	307.8	
35	146.0	1.197	2.9	2.48	296.0	
36	146.5	1.363	3.3	2.02	282.7	
37	147.8	1.532	3.7	1.55	269.2	
38	148.3	1.712	4.1	1.18	258.7	
39	148.0	1.920	4.6	1.10	256.6	
40	149.0	2.116	5.1	1.03	254.7	Maximum Concrete Strain

C.2 Lap Splice Enhancement Circular Columns

Table C.6: Ductility and Shear Strength Calculations for As-built Lap Splice Enhancement Circular Column CF-1

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	4.4	0.059	0.1	3.50	123.4	
2	5.1	0.066	0.1	3.50	122.6	
3	5.8	0.081	0.1	3.50	121.9	
4	6.3	0.096	0.1	3.50	121.3	
5	7.0	0.118	0.1	3.50	120.8	
6	7.8	0.140	0.1	3.50	120.3	
7	8.5	0.163	0.1	3.50	119.9	
8	9.3	0.192	0.2	3.50	119.6	
9	10.2	0.222	0.2	3.50	119.2	
10	11.1	0.259	0.2	3.50	119.0	
11	12.2	0.296	0.3	3.50	118.7	
12	13.3	0.340	0.3	3.50	118.5	
13	14.6	0.392	0.3	3.50	118.3	
14	16.0	0.451	0.4	3.50	118.1	
15	17.5	0.510	0.5	3.50	118.0	
16	19.3	0.584	0.5	3.50	117.8	
17	21.2	0.658	0.6	3.50	117.7	
18	23.3	0.746	0.7	3.50	117.6	
19	25.3	0.842	0.7	3.50	117.5	Begin Yield of Steel
20	26.9	0.895	0.8	3.50	117.4	
21	28.3	0.939	0.8	3.50	117.2	
22	29.3	0.975	0.9	3.50	117.0	
23	30.4	1.011	0.9	3.50	116.9	
24	31.1	1.034	0.9	3.50	116.7	
25	31.9	1.061	0.9	3.50	116.6	
26	32.4	1.078	1.0	3.50	116.4	
27	32.8	1.089	1.0	3.50	116.3	
28	33.1	1.100	1.0	3.50	116.2	
29	33.4	1.111	1.0	3.50	116.1	
30	33.6	1.117	1.0	3.50	116.1	
31	33.7	1.119	1.0	3.50	116.0	
32	33.8	1.125	1.0	3.50	115.9	
33	33.8	1.125	1.0	3.50	115.9	
⋆	33.8	1.125	1.0	3.50	115.9	Ideal Yield of Steel
34	33.8	1.307	1.2	3.50	115.9	
35	33.5	1.521	1.4	3.50	115.8	
36	33.6	1.728	1.5	3.50	115.9	
37	33.3	1.970	1.8	3.50	115.9	
⋆	33.4	2.115	1.9	3.50	115.9	Tranverse Steel Failure

Table C.7: Ductility and Shear Strength Calculations for As-built Lap Splice Enhancement Circular Column CF-2

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	4.3	0.059	0.1	3.50	120.0	
2	4.8	0.066	0.1	3.50	119.2	
3	5.5	0.081	0.1	3.50	118.5	
4	6.2	0.096	0.1	3.50	117.8	
5	6.8	0.118	0.1	3.50	117.3	
6	7.5	0.133	0.1	3.50	116.8	
7	8.3	0.163	0.1	3.50	116.3	
8	9.0	0.185	0.2	3.50	116.0	
9	9.9	0.214	0.2	3.50	115.6	
10	10.8	0.251	0.2	3.50	115.4	
11	11.8	0.288	0.3	3.50	115.1	
12	13.0	0.332	0.3	3.50	114.9	
13	14.3	0.384	0.3	3.50	114.7	
14	15.6	0.443	0.4	3.50	114.5	
15	17.2	0.502	0.4	3.50	114.3	
16	18.8	0.569	0.5	3.50	114.2	
17	20.7	0.650	0.6	3.50	114.1	
18	22.7	0.731	0.7	3.50	114.0	
19	24.8	0.828	0.7	3.50	113.9	Begin Yield of Steel
20	26.4	0.880	0.8	3.50	113.7	
21	27.8	0.928	0.8	3.50	113.6	
22	28.9	0.964	0.9	3.50	113.4	
23	30.0	1.000	0.9	3.50	113.3	
24	30.8	1.025	0.9	3.50	113.1	
25	31.5	1.050	0.9	3.50	113.0	
26	32.1	1.069	1.0	3.50	112.8	
27	32.3	1.077	1.0	3.50	112.7	
28	32.7	1.089	1.0	3.50	112.6	
29	33.0	1.100	1.0	3.50	112.5	
30	33.3	1.108	1.0	3.50	112.4	
31	33.3	1.111	1.0	3.50	112.4	
32	33.6	1.119	1.0	3.50	112.3	
33	33.6	1.119	1.0	3.50	112.3	
$\star$	33.6	1.119	1.0	3.50	112.3	Ideal Yield of Steel
34	33.5	1.292	1.2	3.50	112.2	
35	33.3	1.502	1.3	3.50	112.2	
36	33.2	1.716	1.5	3.50	112.2	
37	33.2	1.937	1.7	3.50	112.2	
38	33.2	2.177	1.9	3.50	112.3	
$\star$	33.2	2.160	1.9	3.50	112.3	Tranverse Steel Failure

Table C.8: Ductility and Shear Strength Calculations for Lap Splice Enhancement Circular Column CF-3

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	8.5	0.170	0.1	3.50	176.5	
2	9.3	0.192	0.2	3.50	176.2	
3	10.2	0.229	0.2	3.50	175.9	
4	11.2	0.259	0.2	3.50	175.6	
5	12.2	0.303	0.3	3.50	175.4	
6	13.3	0.347	0.3	3.50	175.1	
7	14.6	0.399	0.3	3.50	174.9	
8	16.0	0.458	0.4	3.50	174.8	
9	17.6	0.517	0.4	3.50	174.6	
10	19.3	0.591	0.5	3.50	174.5	
11	21.1	0.672	0.6	3.50	174.4	
12	23.2	0.754	0.6	3.50	174.3	
13	25.2	0.857	0.7	3.50	174.2	Begin Yield of Steel
14	25.6	0.871	0.7	3.50	174.2	
15	27.1	0.922	0.8	3.50	174.0	
16	28.3	0.965	0.8	3.50	173.9	
17	29.3	0.999	0.9	3.50	173.7	
18	30.3	1.030	0.9	3.50	173.5	
19	30.9	1.053	0.9	3.50	173.4	
20	31.7	1.078	0.9	3.50	173.2	
21	32.3	1.098	0.9	3.50	173.1	
22	32.6	1.110	1.0	3.50	173.0	
23	33.1	1.127	1.0	3.50	172.9	
24	33.3	1.135	1.0	3.50	172.8	
25	33.8	1.152	1.0	3.50	172.7	
26	34.0	1.158	1.0	3.50	172.6	
27	33.9	1.155	1.0	3.50	172.5	
28	34.0	1.158	1.0	3.50	172.4	
29	34.3	1.169	1.0	3.50	172.4	
⋆	34.3	1.167	1.0	3.50	172.3	Ideal Yield of Steel
30	34.3	1.238	1.1	3.50	172.3	
31	34.6	1.525	1.3	3.50	172.3	
32	35.2	1.826	1.6	3.50	172.3	
⋆	35.3	1.896	1.6	3.50	172.3	Tranverse Steel Failure
33	35.7	2.152	1.8	3.50	172.3	
34	36.2	2.510	2.2	3.33	167.7	
35	36.8	2.874	2.5	2.97	158.3	
36	37.4	3.267	2.8	2.58	148.0	
37	37.8	3.733	3.2	2.12	135.8	
38	38.3	4.154	3.6	1.71	124.9	
39	38.7	4.660	4.0	1.21	111.7	
40	38.9	5.210	4.5	1.13	109.6	Maximum Concrete Strain

Table C.9: Ductility and Shear Strength Calculations for Lap Splice Enhancement Circular Column CF-4

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	8.7	0.177	0.1	3.50	175.4	
2	9.5	0.199	0.2	3.50	175.0	
3	10.4	0.236	0.2	3.50	174.7	
4	11.3	0.273	0.2	3.50	174.5	
5	12.4	0.318	0.3	3.50	174.2	
6	13.6	0.362	0.3	3.50	174.0	
7	14.9	0.414	0.3	3.50	173.8	
8	16.3	0.473	0.4	3.50	173.7	
9	17.9	0.539	0.5	3.50	173.5	
10	19.7	0.613	0.5	3.50	173.4	
11	21.6	0.695	0.6	3.50	173.3	
12	23.7	0.783	0.7	3.50	173.2	
13	25.6	0.887	0.7	3.50	173.1	Begin Yield of Steel
14	26.0	0.901	0.8	3.50	173.1	
15	27.4	0.950	0.8	3.50	172.9	
16	28.5	0.988	0.8	3.50	172.7	
17	29.6	1.025	0.9	3.50	172.6	
18	30.4	1.054	0.9	3.50	172.4	
19	31.1	1.077	0.9	3.50	172.3	
20	31.9	1.106	0.9	3.50	172.1	
21	32.4	1.123	0.9	3.50	172.0	
22	32.8	1.135	1.0	3.50	171.9	
23	33.1	1.147	1.0	3.50	171.8	
24	33.3	1.155	1.0	3.50	171.7	
25	33.6	1.164	1.0	3.50	171.6	
26	33.9	1.175	1.0	3.50	171.5	
27	33.9	1.175	1.0	3.50	171.4	
28	34.3	1.187	1.0	3.50	171.4	
29	34.3	1.190	1.0	3.50	171.3	
⋆	34.3	1.190	1.0	3.50	171.3	Ideal Yield of Steel
30	34.3	1.364	1.1	3.50	171.3	
31	34.6	1.657	1.4	3.50	171.2	
⋆	35.2	1.958	1.6	3.50	171.2	Tranverse Steel Failure
32	35.3	1.967	1.7	3.50	171.2	
33	35.8	2.300	1.9	3.50	171.2	
34	36.2	2.668	2.2	3.22	164.0	
35	36.8	3.038	2.6	2.86	154.6	
36	37.4	3.440	2.9	2.47	144.5	
37	37.9	3.877	3.3	2.05	133.4	
38	38.3	4.351	3.7	1.60	121.5	
39	38.6	4.868	4.1	1.19	110.8	
40	38.8	5.432	4.6	1.12	109.0	Maximum Concrete Strain

Table C.10: Ductility and Shear Strength Calculations for Lap Splice Enhancement Circular Column CF-5

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	12.3	0.303	0.3	3.50	262.2	
2	13.4	0.355	0.3	3.50	262.0	
3	14.7	0.406	0.3	3.50	261.8	
4	16.1	0.458	0.4	3.50	261.7	
5	17.6	0.525	0.4	3.50	261.5	
6	19.3	0.591	0.5	3.50	261.4	
7	21.2	0.672	0.6	3.50	261.3	
8	23.3	0.761	0.6	3.50	261.2	
9	25.3	0.857	0.7	3.50	261.1	Begin Yield of Steel
10	26.8	0.908	0.8	3.50	261.0	
11	28.0	0.950	0.8	3.50	260.8	
12	29.0	0.984	0.8	3.50	260.6	
13	30.1	1.021	0.9	3.50	260.5	
14	30.8	1.047	0.9	3.50	260.3	
15	31.8	1.078	0.9	3.50	260.2	
16	32.2	1.092	0.9	3.50	260.0	
17	32.8	1.112	0.9	3.50	259.9	
18	33.1	1.123	0.9	3.50	259.8	
19	33.6	1.140	1.0	3.50	259.7	
20	33.9	1.151	1.0	3.50	259.6	
21	34.0	1.154	1.0	3.50	259.5	
22	34.2	1.160	1.0	3.50	259.4	
23	34.5	1.171	1.0	3.50	259.3	
24	34.6	1.174	1.0	3.50	259.2	
25	35.0	1.188	1.0	3.50	259.2	Ideal Yield of Steel
26	35.3	1.505	1.3	3.50	259.1	
27	36.0	1.842	1.6	3.50	259.1	
⋆	36.3	2.000	1.7	3.50	259.1	Tranverse Steel Failure
28	36.8	2.219	1.9	3.50	259.1	
29	37.6	2.637	2.2	3.25	252.3	
30	38.3	3.102	2.6	2.80	240.2	
31	39.2	3.571	3.0	2.34	228.1	
32	39.7	4.132	3.5	1.80	213.5	
33	40.4	4.705	4.0	1.25	198.7	
34	41.0	5.329	4.5	1.13	195.5	
35	41.5	6.015	5.1	1.04	193.2	
36	42.3	6.698	5.6	0.95	190.9	
37	42.6	7.520	6.3	0.85	188.1	
38	43.2	8.335	7.0	0.75	185.4	
⋆	43.3	9.145	7.7	0.65	182.6	Maximum Concrete Strain

Table C.11: Ductility and Shear Strength Calculations for Lap Splice Enhancement Circular Column CF-6

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	12.4	0.325	0.3	3.50	261.1	
2	13.6	0.369	0.3	3.50	260.9	
3	14.8	0.421	0.3	3.50	260.8	
4	16.3	0.488	0.4	3.50	260.6	
5	17.8	0.547	0.4	3.50	260.5	
6	19.6	0.621	0.5	3.50	260.3	
7	21.4	0.709	0.6	3.50	260.2	
8	23.5	0.791	0.6	3.50	260.2	
9	25.3	0.901	0.7	3.50	260.0	Begin Yield of Steel
10	26.0	0.925	0.8	3.50	260.0	
11	27.4	0.976	0.8	3.50	259.8	
12	28.5	1.014	0.8	3.50	259.7	
13	29.5	1.050	0.9	3.50	259.5	
14	30.3	1.079	0.9	3.50	259.3	
15	31.0	1.103	0.9	3.50	259.2	
16	31.9	1.136	0.9	3.50	259.0	
17	32.3	1.148	0.9	3.50	258.9	
18	32.7	1.162	0.9	3.50	258.8	
19	32.9	1.171	1.0	3.50	258.7	
20	33.5	1.192	1.0	3.50	258.6	
21	33.6	1.195	1.0	3.50	258.5	
22	33.9	1.207	1.0	3.50	258.4	
23	34.0	1.210	1.0	3.50	258.3	
24	34.2	1.216	1.0	3.50	258.2	
⋆	34.5	1.227	1.0	3.50	258.2	Ideal Yield of Steel
25	34.5	1.238	1.0	3.50	258.1	
26	34.8	1.536	1.3	3.50	258.1	
27	35.3	1.856	1.5	3.50	258.1	
⋆	35.9	2.172	1.8	3.50	258.1	Tranverse Steel Failure
28	36.0	2.212	1.8	3.50	258.1	
29	36.8	2.575	2.1	3.39	255.2	
30	37.5	3.012	2.5	2.98	245.0	
31	38.2	3.495	2.8	2.52	233.6	
32	39.0	3.990	3.3	2.06	222.0	
33	39.8	4.531	3.7	1.55	209.4	
34	40.1	5.176	4.2	1.17	199.7	
35	40.7	5.834	4.8	1.09	197.7	
36	41.5	6.493	5.3	1.01	195.7	
37	41.9	7.280	5.9	0.91	193.3	
38	42.3	8.148	6.6	0.80	190.7	
⋆	42.6	8.809	7.2	0.72	188.7	Maximum Concrete Strain

Table C.12: Ductility and Shear Strength Calculations for Lap Splice Enhancement Circular Column CF-7

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	12.4	0.325	0.3	3.50	261.6	
2	13.6	0.369	0.3	3.50	261.4	
3	14.9	0.421	0.3	3.50	261.3	
4	16.3	0.488	0.4	3.50	261.1	
5	17.9	0.554	0.5	3.50	260.9	
6	19.6	0.628	0.5	3.50	260.8	
7	21.5	0.709	0.6	3.50	260.7	
8	23.6	0.798	0.7	3.50	260.6	
9	25.4	0.901	0.7	3.50	260.5	Begin Yield of Steel
10	27.1	0.961	0.8	3.50	260.3	
11	28.3	1.005	0.8	3.50	260.2	
12	29.3	1.040	0.8	3.50	260.0	
13	30.3	1.073	0.9	3.50	259.9	
14	30.9	1.096	0.9	3.50	259.7	
15	31.7	1.123	0.9	3.50	259.5	
16	32.1	1.138	0.9	3.50	259.4	
17	32.5	1.153	0.9	3.50	259.3	
18	33.0	1.170	1.0	3.50	259.2	
19	33.3	1.182	1.0	3.50	259.1	
20	33.8	1.197	1.0	3.50	259.0	
21	33.8	1.197	1.0	3.50	258.9	
22	34.2	1.212	1.0	3.50	258.8	
23	34.4	1.221	1.0	3.50	258.7	
24	34.5	1.224	1.0	3.50	258.6	
⋆	34.5	1.224	1.0	3.50	258.6	Ideal Yield of Steel
25	34.7	1.471	1.2	3.50	258.6	
26	35.3	1.785	1.5	3.50	258.6	
27	35.9	2.132	1.7	3.50	258.5	
⋆	36.0	2.156	1.8	3.50	258.5	Tranverse Steel Failure
28	36.5	2.518	2.1	3.43	256.9	
29	37.5	2.919	2.4	3.06	247.4	
30	38.2	3.395	2.8	2.61	236.2	
31	38.8	3.922	3.2	2.12	223.7	
32	39.5	4.456	3.6	1.62	211.2	
33	40.2	5.045	4.1	1.18	200.3	
34	40.8	5.690	4.6	1.10	198.3	
35	41.3	6.399	5.2	1.02	196.1	
36	42.0	7.108	5.8	0.93	194.0	
37	42.3	7.958	6.5	0.83	191.4	
⋆	42.6	8.871	7.2	0.71	188.6	Maximum Concrete Strain

Table C.13: Ductility and Shear Strength Calculations for Lap Splice Enhancement Circular Column CF-8

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	13.4	0.347	0.3	3.50	299.2	
2	14.7	0.399	0.3	3.50	299.0	
3	16.1	0.458	0.4	3.50	298.9	
4	17.6	0.517	0.4	3.50	298.7	
5	19.3	0.591	0.5	3.50	298.6	
6	21.2	0.665	0.6	3.50	298.5	
7	23.3	0.754	0.6	3.50	298.4	
8	25.3	0.850	0.7	3.50	298.3	Begin Yield of Steel
9	27.0	0.909	0.8	3.50	298.1	
10	28.3	0.953	0.8	3.50	298.0	
11	29.4	0.990	0.8	3.50	297.8	
12	30.3	1.021	0.9	3.50	297.7	
13	31.1	1.046	0.9	3.50	297.5	
14	31.9	1.074	0.9	3.50	297.3	
15	32.3	1.088	0.9	3.50	297.2	
16	32.9	1.108	0.9	3.50	297.0	
17	33.3	1.119	0.9	3.50	296.9	
18	33.7	1.133	1.0	3.50	296.8	
19	34.2	1.150	1.0	3.50	296.7	
20	34.2	1.150	1.0	3.50	296.6	
21	34.7	1.167	1.0	3.50	296.5	
22	34.6	1.164	1.0	3.50	296.4	
23	34.8	1.169	1.0	3.50	296.4	
$\star$	35.1	1.183	1.0	3.50	296.3	Ideal Yield of Steel
24	35.2	1.195	1.0	3.50	296.3	
25	35.7	1.530	1.3	3.50	296.3	
26	36.8	1.889	1.6	3.50	296.2	
$\star$	36.9	1.970	1.7	3.50	296.2	Tranverse Steel Failure
27	37.4	2.316	2.0	3.50	296.2	
28	38.3	2.757	2.3	3.12	285.7	
29	39.0	3.245	2.7	2.65	272.7	
30	39.7	3.785	3.2	2.12	258.2	
31	40.6	4.335	3.7	1.58	243.6	
32	41.4	4.936	4.2	1.17	232.3	
33	42.1	5.594	4.7	1.09	230.0	
34	42.7	6.317	5.3	1.00	227.5	
35	43.2	7.111	6.0	0.90	224.7	
36	43.6	7.986	6.8	0.79	221.7	
37	43.8	8.946	7.6	0.67	218.3	
$\star$	44.3	9.673	8.2	0.60	216.5	Maximum Concrete Strain

Table C.14: Ductility and Shear Strength Calculations for Lap Splice Enhancement Circular Column CF-9

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	13.4	0.347	0.3	3.50	299.3	
2	14.7	0.399	0.3	3.50	299.1	
3	16.1	0.458	0.4	3.50	299.0	
4	17.6	0.517	0.4	3.50	298.8	
5	19.3	0.591	0.5	3.50	298.7	
6	21.2	0.665	0.6	3.50	298.6	
7	23.3	0.754	0.6	3.50	298.5	
8	25.3	0.850	0.7	3.50	298.4	Begin Yield of Steel
9	27.1	0.911	0.8	3.50	298.2	
10	28.4	0.956	0.8	3.50	298.1	
11	29.4	0.990	0.8	3.50	297.9	
12	30.3	1.021	0.9	3.50	297.8	
13	31.1	1.046	0.9	3.50	297.6	
14	32.0	1.077	0.9	3.50	297.4	
15	32.4	1.091	0.9	3.50	297.3	
16	33.0	1.111	0.9	3.50	297.1	
17	33.3	1.122	0.9	3.50	297.0	
18	33.8	1.136	1.0	3.50	296.9	
19	34.2	1.150	1.0	3.50	296.8	
20	34.3	1.153	1.0	3.50	296.7	
21	34.7	1.167	1.0	3.50	296.6	
22	34.7	1.167	1.0	3.50	296.5	
23	34.8	1.172	1.0	3.50	296.5	
⋆	35.2	1.183	1.0	3.50	296.4	Ideal Yield of Steel
24	35.2	1.195	1.0	3.50	296.4	
25	35.7	1.530	1.3	3.50	296.4	
26	36.8	1.889	1.6	3.50	296.3	
⋆	36.9	1.967	1.7	3.50	296.3	Tranverse Steel Failure
27	37.4	2.316	2.0	3.50	296.3	
28	38.3	2.758	2.3	3.12	285.8	
29	39.1	3.247	2.7	2.64	272.7	
30	39.8	3.788	3.2	2.12	258.2	
31	40.7	4.338	3.7	1.58	243.6	
32	41.4	4.936	4.2	1.17	232.3	
33	41.8	5.661	4.8	1.08	229.8	
34	42.3	6.391	5.4	0.99	227.2	
35	43.2	7.111	6.0	0.90	224.7	
36	43.6	7.986	6.8	0.79	221.7	
37	43.9	8.949	7.6	0.67	218.3	
38	44.4	9.895	8.4	0.60	216.6	
⋆	44.4	9.648	8.2	0.60	216.6	Maximum Concrete Strain

C.3 Lap Splice Enhancement Rectangular Columns

Table C.15: Ductility and Shear Strength Calculations for As-built Lap Splice Enhancement Rectangular Column RF-1

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	15.6	0.185	0.1	3.50	132.8	
2	17.3	0.222	0.1	3.50	132.3	
3	19.0	0.259	0.2	3.50	131.9	
4	21.0	0.296	0.2	3.50	131.6	
5	23.3	0.347	0.2	3.50	131.3	
6	25.8	0.399	0.2	3.50	131.0	
7	28.4	0.458	0.3	3.50	130.8	
8	31.4	0.517	0.3	3.50	130.6	
9	34.8	0.591	0.4	3.50	130.5	
10	38.4	0.672	0.4	3.50	130.3	
11	42.5	0.761	0.5	3.50	130.2	
12	46.9	0.857	0.5	3.50	130.1	
13	51.8	0.968	0.6	3.50	130.0	
14	57.0	1.086	0.6	3.50	130.0	
15	59.7	1.263	0.8	3.50	129.7	Begin Yield of Steel
16	62.0	1.313	0.8	3.50	129.5	
17	64.0	1.355	0.8	3.50	129.2	
18	65.3	1.383	0.8	3.50	128.9	
19	66.8	1.415	0.8	3.50	128.7	
20	67.7	1.433	0.9	3.50	128.5	
21	69.4	1.470	0.9	3.50	128.3	
22	71.5	1.514	0.9	3.50	128.1	
23	73.2	1.549	0.9	3.50	128.0	
24	75.2	1.592	1.0	3.50	127.9	
25	77.2	1.634	1.0	3.50	127.8	
26	78.2	1.655	1.0	3.50	127.7	
⋆	79.0	1.673	1.0	3.50	127.7	Ideal Yield of Steel
27	79.2	1.714	1.0	3.50	127.7	
28	80.2	1.939	1.2	3.50	127.8	
29	81.0	2.180	1.3	3.50	127.8	
30	81.6	2.441	1.5	3.50	127.8	
31	82.3	2.690	1.6	3.50	127.9	
32	82.6	2.957	1.8	3.50	128.0	
33	82.8	3.245	1.9	3.50	128.0	
34	83.0	3.518	2.1	3.38	123.9	
⋆	83.0	3.610	2.2	3.32	121.6	Tranverse Steel Failure

Table C.16: Ductility and Shear Strength Calculations for Lap Splice Enhancement Rectangular Column RF-2

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	46.5	0.857	0.5	3.50	630.9	
2	51.3	0.961	0.5	3.50	630.8	
3	56.6	1.086	0.6	3.50	630.7	
4	59.4	1.263	0.7	3.50	630.4	First Yield of Steel
5	61.1	1.299	0.7	3.50	630.3	
6	63.1	1.341	0.7	3.50	630.0	
⋆	63.7	1.354	0.7	3.50	629.9	Unconfined Lap Splice Failure
7	65.0	1.382	0.8	3.50	629.7	
8	66.4	1.412	0.8	3.50	629.5	
9	67.8	1.442	0.8	3.50	629.2	
10	69.3	1.474	0.8	3.50	629.0	
11	71.5	1.520	0.8	3.50	628.8	
12	73.9	1.572	0.9	3.50	628.6	
13	76.0	1.616	0.9	3.50	628.4	
14	78.3	1.666	0.9	3.50	628.3	
15	80.6	1.714	0.9	3.50	628.1	
16	82.4	1.753	1.0	3.50	628.1	
17	84.1	1.788	1.0	3.50	628.0	
18	86.1	1.831	1.0	3.50	628.0	
⋆	86.6	1.842	1.0	3.50	628.0	Ideal Yield of Steel
19	87.8	2.159	1.2	3.50	627.9	
20	89.9	2.632	1.4	3.50	627.9	
21	91.3	3.218	1.7	3.50	627.8	
⋆	92.6	3.856	2.1	3.39	623.9	Tranverse Steel Failure
22	93.9	4.428	2.4	3.03	611.0	
23	94.3	4.565	2.5	2.95	608.0	
24	95.6	5.319	2.9	2.48	591.0	
25	96.8	6.166	3.3	1.95	572.0	
26	97.8	7.115	3.9	1.36	550.6	
27	98.6	8.178	4.4	1.13	542.6	Longitudinal Steel Failure

Table C.17: Ductility and Shear Strength Calculations for Lap Splice Enhancement Rectangular Column RF-3

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	47.9	0.909	0.5	3.50	619.1	
2	52.8	1.020	0.6	3.50	619.0	
3	57.4	1.160	0.7	3.50	618.9	First Yield of Steel
4	58.8	1.189	0.7	3.50	618.8	
5	61.3	1.237	0.7	3.50	618.5	
⋆	62.3	1.259	0.7	3.50	618.3	Unconfined Lap Splice Failure
6	63.3	1.278	0.7	3.50	618.2	
7	64.9	1.312	0.8	3.50	617.9	
8	66.5	1.344	0.8	3.50	617.7	
9	67.7	1.367	0.8	3.50	617.4	
10	69.7	1.408	0.8	3.50	617.2	
11	71.8	1.451	0.8	3.50	617.0	
12	74.3	1.502	0.9	3.50	616.8	
13	76.5	1.546	0.9	3.50	616.6	
14	78.6	1.588	0.9	3.50	616.5	
15	80.5	1.626	1.0	3.50	616.4	
16	82.3	1.662	1.0	3.50	616.4	
17	83.9	1.695	1.0	3.50	616.3	
⋆	84.7	1.712	1.0	3.50	616.3	Ideal Yield of Steel
18	85.4	1.900	1.1	3.50	616.3	
19	87.2	2.318	1.4	3.50	616.2	
20	89.1	2.788	1.6	3.50	616.2	
21	90.4	3.369	2.0	3.50	616.1	
⋆	91.8	3.817	2.2	3.24	607.4	Tranverse Steel Failure
22	92.3	3.961	2.3	3.14	604.2	
⋆	93.2	4.536	2.7	2.75	591.4	Lap Splice Failure
24	94.6	5.449	3.2	2.14	571.0	
25	95.8	6.285	3.7	1.58	552.5	
26	96.8	7.222	4.2	1.17	538.9	
27	97.8	8.277	4.8	1.07	535.8	Longitudinal Steel Failure

Table C.18: Ductility and Shear Strength Calculations for Lap Splice Enhancement Rectangular Column RF-5

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	35.4	0.613	0.4	3.50	457.2	
2	39.1	0.687	0.4	3.50	457.0	
3	43.2	0.783	0.5	3.50	456.9	
4	47.6	0.879	0.5	3.50	456.8	
5	52.5	0.990	0.6	3.50	456.7	
6	57.3	1.116	0.7	3.50	456.6	First Yield of Steel
7	60.0	1.168	0.7	3.50	456.4	
8	62.2	1.210	0.7	3.50	456.1	
⋆	63.7	1.239	0.7	3.50	455.9	Unconfined Lap Splice Failure
9	64.3	1.250	0.7	3.50	455.9	
10	65.7	1.278	0.8	3.50	455.6	
11	67.2	1.307	0.8	3.50	455.3	
12	68.5	1.333	0.8	3.50	455.1	
13	70.7	1.375	0.8	3.50	454.9	
14	72.7	1.414	0.8	3.50	454.7	
15	74.8	1.455	0.9	3.50	454.5	
16	77.1	1.500	0.9	3.50	454.4	
17	79.7	1.550	0.9	3.50	454.2	
18	81.2	1.580	0.9	3.50	454.1	
19	83.3	1.620	1.0	3.50	454.1	
20	84.8	1.649	1.0	3.50	454.1	
⋆	86.1	1.675	1.0	3.50	454.0	Ideal Yield of Steel
21	86.6	1.778	1.1	3.50	454.0	
22	88.4	2.208	1.3	3.50	454.0	
23	89.8	2.743	1.6	3.50	453.9	
24	91.6	3.287	2.0	3.50	453.9	
⋆	92.2	3.766	2.2	3.21	443.6	Tranverse Steel Failure
25	92.5	3.967	2.4	3.08	438.6	
26	93.9	4.655	2.8	2.60	421.5	
27	95.0	5.425	3.2	2.08	402.5	
28	95.9	6.285	3.8	1.49	381.2	
29	97.2	7.121	4.3	1.16	369.5	
30	97.6	8.183	4.9	1.07	366.0	Longitudinal Steel Failure

Table C.19: Ductility and Shear Strength Calculations for Lap Splice Enhancement Rectangular Column RF-6

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	43.0	0.776	0.5	3.50	562.1	
2	47.5	0.879	0.5	3.50	562.0	
3	52.3	0.990	0.6	3.50	561.9	
4	57.3	1.116	0.7	3.50	561.8	First Yield of Steel
5	60.0	1.168	0.7	3.50	561.6	
6	62.2	1.210	0.7	3.50	561.3	
⋆	63.9	1.243	0.7	3.50	561.1	Unconfined Lap Splice Failure
7	64.3	1.252	0.7	3.50	561.1	
8	64.1	1.247	0.7	3.50	561.1	
9	67.3	1.310	0.8	3.50	560.5	
10	68.7	1.336	0.8	3.50	560.3	
11	70.6	1.374	0.8	3.50	560.1	
12	73.0	1.421	0.8	3.50	559.9	
13	75.2	1.463	0.9	3.50	559.7	
14	77.5	1.508	0.9	3.50	559.6	
15	79.7	1.550	0.9	3.50	559.4	
16	81.4	1.584	0.9	3.50	559.3	
17	83.2	1.618	1.0	3.50	559.2	
18	85.3	1.659	1.0	3.50	559.2	
⋆	86.7	1.688	1.0	3.50	559.2	Ideal Yield of Steel
19	87.2	1.776	1.1	3.50	559.2	
20	88.7	2.267	1.3	3.50	559.1	
21	90.3	2.814	1.7	3.50	559.1	
22	92.2	3.375	2.0	3.50	559.0	
⋆	92.7	3.718	2.2	3.27	550.6	Tranverse Steel Failure
23	93.3	4.078	2.4	3.02	541.7	
24	94.6	4.796	2.8	2.53	524.1	
25	96.0	5.584	3.3	2.00	504.7	
26	97.1	6.473	3.8	1.39	482.8	
27	97.9	7.473	4.4	1.14	473.6	Longitudinal Steel Failure

C.4 Shear Enhancement Rectangular Columns

Table C.20: Ductility and Shear Strength Calculations for As-built Shear Enhancement Rectangular Column RS-1

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	38.0	0.056	0.2	3.50	143.3	
2	41.8	0.065	0.3	3.50	142.2	
3	46.3	0.076	0.3	3.50	141.3	
4	51.0	0.088	0.3	3.50	140.5	
5	56.3	0.103	0.4	3.50	139.8	
6	62.0	0.117	0.5	3.50	139.3	
7	68.5	0.134	0.5	3.50	138.7	
8	75.5	0.153	0.6	3.50	138.3	
9	83.3	0.173	0.7	3.50	137.9	
10	91.3	0.198	0.8	3.50	137.5	Begin Yield of Steel
11	95.8	0.207	0.8	3.50	136.8	
12	99.5	0.215	0.8	3.50	136.1	
13	103.0	0.223	0.9	3.50	135.4	
14	105.8	0.229	0.9	3.50	134.7	
15	108.0	0.234	0.9	3.50	134.0	
16	110.3	0.239	0.9	3.50	133.4	
17	112.3	0.243	1.0	3.50	132.9	
18	113.5	0.246	1.0	3.50	132.3	
19	114.3	0.247	1.0	3.50	131.7	
20	115.3	0.250	1.0	3.50	131.4	
21	115.8	0.251	1.0	3.50	131.2	
22	115.5	0.250	1.0	3.50	131.0	
23	116.5	0.252	1.0	3.50	130.9	
24	116.5	0.252	1.0	3.50	130.7	
25	117.5	0.254	1.0	3.50	130.7	
⋆	118.0	0.256	1.0	3.50	130.7	Ideal Yield of Steel
26	119.5	0.335	1.3	3.50	130.7	
27	121.0	0.449	1.8	3.50	130.7	
28	122.5	0.559	2.2	3.28	125.3	Shear Failure
29	123.8	0.676	2.6	2.76	112.1	
30	125.0	0.786	3.1	2.26	99.6	
31	126.0	0.903	3.5	1.74	86.5	
32	126.8	1.009	3.9	1.26	74.6	
⋆	127.1	1.078	4.2	1.17	72.4	Tranverse Steel Failure

Table C.21: Ductility and Shear Strength Calculations for Shear Enhancement Rectangular Column RS-2

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	65.8	0.127	0.4	3.50	594.0	
2	72.3	0.145	0.5	3.50	593.6	
3	79.8	0.164	0.6	3.50	593.2	
4	88.0	0.186	0.6	3.50	592.9	
5	93.5	0.216	0.7	3.50	592.3	Begin Yield of Steel
8	96.3	0.223	0.7	3.50	591.8	
9	100.0	0.231	0.8	3.50	591.1	
10	103.0	0.238	0.8	3.50	590.4	
11	106.0	0.245	0.8	3.50	589.7	
12	108.3	0.250	0.8	3.50	589.0	
13	110.3	0.255	0.9	3.50	588.4	
14	112.3	0.260	0.9	3.50	587.8	
15	113.5	0.263	0.9	3.50	587.2	
16	114.5	0.265	0.9	3.50	586.7	
17	116.0	0.268	0.9	3.50	586.4	
18	116.3	0.269	0.9	3.50	586.1	
19	117.3	0.271	0.9	3.50	585.8	
20	117.5	0.272	0.9	3.50	585.5	
21	119.0	0.275	0.9	3.50	585.3	
22	122.0	0.282	0.9	3.50	585.1	
23	125.5	0.290	1.0	3.50	585.1	
24	127.8	0.296	1.0	3.50	584.9	
⋆	128.8	0.298	1.0	3.50	584.9	Ideal Yield of Steel
25	130.8	0.414	1.4	3.50	584.8	
26	134.0	0.589	2.0	3.50	584.8	
27	136.3	0.799	2.7	2.71	564.3	
⋆	138.0	0.943	3.2	2.16	549.8	Tranverse Steel Failure
28	138.8	1.005	3.4	1.92	543.5	
29	141.0	1.229	4.1	1.18	524.2	
30	143.0	1.472	4.9	1.06	521.0	
31	144.5	1.736	5.8	0.93	517.6	
32	146.5	1.986	6.7	0.80	514.3	
33	147.3	2.295	7.7	0.64	510.3	
⋆	148.3	2.586	8.7	0.62	509.8	
35	149.5	2.904	9.7	0.60	509.3	
36	150.8	3.251	10.9	0.60	509.3	
⋆	151.2	3.577	12.0	0.60	509.4	Jacket Failure

Table C.22: Ductility and Shear Strength Calculations for Shear Enhancement Rectangular Column RS-3

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	60.5	0.112	0.4	3.50	596.0	
2	66.8	0.127	0.4	3.50	595.5	
3	73.5	0.145	0.5	3.50	595.1	
4	81.3	0.164	0.5	3.50	594.7	
5	89.5	0.186	0.6	3.50	594.4	
6	94.5	0.218	0.7	3.50	593.7	Begin Yield of Steel
8	96.5	0.223	0.7	3.50	593.4	
9	100.5	0.232	0.8	3.50	592.7	
10	103.8	0.239	0.8	3.50	592.1	
11	106.8	0.246	0.8	3.50	591.4	
12	108.5	0.250	0.8	3.50	590.6	
13	110.8	0.256	0.8	3.50	590.0	
14	113.0	0.261	0.9	3.50	589.5	
15	114.3	0.264	0.9	3.50	588.9	
16	115.3	0.266	0.9	3.50	588.3	
17	116.5	0.269	0.9	3.50	587.9	
18	117.0	0.270	0.9	3.50	587.6	
19	118.0	0.272	0.9	3.50	587.3	
20	118.8	0.274	0.9	3.50	587.0	
21	120.5	0.278	0.9	3.50	586.8	
22	123.5	0.285	0.9	3.50	586.7	
23	126.3	0.291	1.0	3.50	586.5	
24	129.5	0.299	1.0	3.50	586.4	
⋆	131.6	0.304	1.0	3.50	586.4	Ideal Yield of Steel
25	132.3	0.344	1.1	3.50	586.4	
26	135.0	0.545	1.8	3.50	586.3	
27	138.0	0.739	2.4	3.00	572.5	
⋆	139.9	0.899	3.0	2.40	555.8	Tranverse Steel Failure
28	140.5	0.949	3.1	2.21	550.6	
29	141.8	1.206	4.0	1.24	523.7	
30	144.5	1.423	4.7	1.10	520.0	
31	146.0	1.692	5.6	0.96	516.3	
32	147.8	1.941	6.4	0.84	513.0	
33	148.5	2.257	7.4	0.69	508.7	
⋆	149.7	2.548	8.4	0.65	507.6	
35	151.0	2.872	9.5	0.60	506.5	
36	151.5	3.215	10.6	0.60	506.5	
⋆	151.6	3.428	11.3	0.60	506.6	Jacket Failure

Table C.23: Ductility and Shear Strength Calculations for Shear Enhancement Rectangular Column RS-4

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	66.0	0.129	0.4	3.50	581.2	
2	72.8	0.145	0.5	3.50	580.8	
3	80.3	0.166	0.5	3.50	580.4	
4	88.3	0.188	0.6	3.50	580.1	
5	93.5	0.220	0.7	3.50	579.4	Begin Yield of Steel
8	95.5	0.225	0.7	3.50	579.1	
9	99.5	0.234	0.8	3.50	578.4	
10	102.8	0.242	0.8	3.50	577.6	
11	106.0	0.249	0.8	3.50	577.0	
12	108.0	0.254	0.8	3.50	576.3	
13	110.3	0.259	0.9	3.50	575.7	
14	112.0	0.264	0.9	3.50	575.1	
15	113.5	0.267	0.9	3.50	574.4	
16	114.8	0.270	0.9	3.50	573.9	
17	115.0	0.271	0.9	3.50	573.5	
18	116.5	0.274	0.9	3.50	573.3	
19	117.3	0.276	0.9	3.50	573.1	
20	117.3	0.276	0.9	3.50	572.8	
21	118.5	0.279	0.9	3.50	572.5	
22	121.5	0.286	0.9	3.50	572.4	
23	124.3	0.292	1.0	3.50	572.2	
24	127.3	0.299	1.0	3.50	572.2	
⋆	128.2	0.302	1.0	3.50	572.1	Ideal Yield of Steel
25	130.0	0.413	1.4	3.50	572.1	
26	132.5	0.601	2.0	3.50	572.0	
27	135.5	0.788	2.6	2.80	554.2	
⋆	137.6	0.953	3.2	2.17	538.3	Tranverse Steel Failure
28	138.0	0.988	3.3	2.03	534.9	
29	140.3	1.206	4.0	1.20	513.8	
30	142.3	1.443	4.8	1.08	510.8	
31	143.8	1.699	5.6	0.96	507.5	
32	144.8	1.977	6.6	0.82	504.0	
⋆	146.4	2.240	7.4	0.71	501.5	
34	148.3	2.533	8.4	0.60	498.7	
35	149.3	2.842	9.4	0.60	498.8	
36	150.0	3.178	10.5	0.60	498.8	
⋆	150.2	3.510	11.6	0.60	498.9	Jacket Failure

Table C.24: Ductility and Shear Strength Calculations for Shear Enhancement Rectangular Column RS-5

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	68.3	0.131	0.4	3.50	595.4	
2	75.3	0.149	0.5	3.50	595.0	
3	83.0	0.170	0.6	3.50	594.6	
4	91.3	0.192	0.6	3.50	594.3	
7	94.8	0.218	0.7	3.50	593.7	Begin Yield of Steel
8	99.3	0.229	0.7	3.50	593.0	
9	102.3	0.235	0.8	3.50	592.3	
10	106.0.	0.244	0.8	3.50	591.7	
11	108.0	0.249	0.8	3.50	590.9	
12	109.8	0.253	0.8	3.50	590.2	
13	112.3	0.258	0.8	3.50	589.7	
14	113.8	0.262	0.9	3.50	589.1	
15	114.5	0.264	0.9	3.50	588.5	
16	116.0	0.267	0.9	3.50	588.0	
17	116.5	0.268	0.9	3.50	587.6	
18	117.5	0.271	0.9	3.50	587.4	
19	118.3	0.272	0.9	3.50	587.1	
20	119.3	0.275	0.9	3.50	586.8	
21	122.5	0.282	0.9	3.50	586.7	
22	125.3	0.288	0.9	3.50	586.5	
23	128.8	0.296	1.0	3.50	586.4	
24	132.0	0.304	1.0	3.50	586.4	
⋆	132.4	0.305	1.0	3.50	586.3	Ideal Yield of Steel
25	134.8	0.469	1.5	3.50	586.3	
26	137.3	0.683	2.2	3.22	578.6	
27	140.3	0.892	2.9	2.44	556.8	
⋆	140.3	0.903	3.0	2.39	555.7	Tranverse Steel Failure
28	141.8	1.146	3.8	1.48	530.3	
29	144.0	1.395	4.6	1.11	520.3	
30	145.8	1.665	5.5	0.98	516.6	
31	148.3	1.917	6.3	0.86	513.2	
32	149.3	2.233	7.3	0.70	509.0	
33	151.0	2.528	8.3	0.60	506.2	
34	152.0	2.844	9.3	0.60	506.3	
35	152.0	3.247	10.7	0.60	506.3	
⋆	152.0	3.248	10.7	0.60	506.3	Jacket Failure

Table C.25: Ductility and Shear Strength Calculations for Shear Enhancement Rectangular Column RS-6

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	72.5	0.142	0.5	3.50	691.5	
2	80.0	0.162	0.5	3.50	691.1	
3	88.3	0.185	0.6	3.50	690.7	
4	93.8	0.213	0.7	3.50	690.1	Begin Yield of Steel
7	98.3	0.223	0.7	3.50	689.5	
8	101.5	0.230	0.8	3.50	688.8	
9	104.8	0.237	0.8	3.50	688.1	
10	107.5	0.244	0.8	3.50	687.4	
11	109.5	0.248	0.8	3.50	686.7	
12	112.0	0.254	0.8	3.50	686.2	
13	113.0	0.256	0.9	3.50	685.5	
14	114.8	0.260	0.9	3.50	685.0	
15	115.5	0.262	0.9	3.50	684.4	
16	116.5	0.264	0.9	3.50	684.0	
17	117.8	0.267	0.9	3.50	683.8	
18	118.3	0.268	0.9	3.50	683.5	
19	119.0	0.270	0.9	3.50	683.2	
20	122.0	0.277	0.9	3.50	683.1	
21	125.3	0.284	0.9	3.50	682.9	
22	127.8	0.290	1.0	3.50	682.7	
23	131.0	0.297	1.0	3.50	682.7	
⋆	132.1	0.299	1.0	3.50	682.7	Ideal Yield of Steel
24	134.0	0.422	1.4	3.50	682.6	
25	136.5	0.633	2.1	3.37	679.0	
26	139.8	0.839	2.8	2.58	657.0	
⋆	140.0	0.888	3.0	2.39	651.9	Tranverse Steel Failure
27	141.3	1.088	3.6	1.62	630.6	
28	143.5	1.332	4.4	1.13	617.1	
29	145.3	1.596	5.3	1.00	613.5	
30	148.0	1.846	6.2	0.88	610.1	
31	149.0	2.155	7.2	0.72	605.8	
32	150.8	2.445	8.2	0.60	602.6	
33	151.3	2.811	9.4	0.60	602.6	
⋆	152.0	3.140	10.5	0.60	602.6	Jacket Failure

Table C.26: Ductility and Shear Strength Calculations for Shear Enhancement Rectangular Column RS-7

Step	H (kips)	Δ (in)	μ_Δ	k	V'(kips)	Comments
1	72.5	0.142	0.5	3.50	691.7	
2	80.0	0.162	0.5	3.50	691.3	
3	88.3	0.185	0.6	3.50	690.9	
4	93.8	0.213	0.7	3.50	690.3	Begin Yield of Steel
7	98.3	0.223	0.7	3.50	689.7	
8	101.5	0.230	0.8	3.50	688.9	
9	104.8	0.237	0.8	3.50	688.2	
10	107.5	0.244	0.8	3.50	687.6	
11	109.5	0.248	0.8	3.50	686.9	
12	112.0	0.254	0.8	3.50	686.3	
13	113.0	0.256	0.9	3.50	685.7	
14	114.8	0.260	0.9	3.50	685.1	
15	115.5	0.262	0.9	3.50	684.6	
16	116.5	0.264	0.9	3.50	684.2	
17	117.8	0.267	0.9	3.50	684.0	
18	118.3	0.268	0.9	3.50	683.7	
19	119.0	0.270	0.9	3.50	683.4	
20	122.0	0.277	0.9	3.50	683.2	
21	125.3	0.284	0.9	3.50	683.1	
22	127.8	0.290	1.0	3.50	682.9	
23	131.0	0.297	1.0	3.50	682.8	
24	134.0	0.419	1.4	3.50	682.8	
$\star$	132.6	0.301	1.0	3.50	682.8	Ideal Yield of Steel
25	136.5	0.629	2.1	3.39	679.8	
26	139.8	0.835	2.8	2.60	657.9	
$\star$	140.0	0.869	2.9	2.48	654.4	Tranverse Steel Failure
27	141.3	1.085	3.6	1.65	631.5	
28	143.5	1.328	4.4	1.14	617.3	
29	145.3	1.592	5.3	1.01	613.6	
$\star$	147.3	1.780	5.9	0.91	611.1	Jacket Failure

Appendix D

LAP SPLICE STRENGTH CALCULATIONS

D.1 Lap Splice Enhancement Circular Columns

Table D.1: Lap Splice Strength Calculations for As-built Column CF-1

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00002	0.68	3.42	
2	0.00004	1.28	6.39	
3	0.00007	2.00	10.00	
4	0.00010	2.84	14.19	
5	0.00013	3.81	19.03	
6	0.00017	4.88	24.37	
7	0.00022	6.29	31.39	
8	0.00027	7.87	39.27	
9	0.00034	9.87	49.25	
10	0.00041	11.80	58.86	
11	0.00050	14.46	72.13	
12	0.00059	17.14	85.51	
13	0.00070	20.26	101.07	
14	0.00082	23.90	119.25	
15	0.00096	27.72	138.32	
16	0.00111	32.06	159.95	
17	0.00128	37.20	185.61	
18	0.00146	42.37	211.38	
19	0.00167	43.41	216.58	Begin Yield of Steel
20	0.00196	43.41	216.58	
21	0.00230	43.41	216.58	
22	0.00273	43.41	216.58	
23	0.00317	43.41	216.58	
24	0.00377	43.41	216.58	
25	0.00442	43.41	216.58	
26	0.00518	43.41	216.58	
27	0.00610	43.41	216.58	
28	0.00706	43.41	216.58	
29	0.00805	43.42	216.62	
30	0.00919	43.64	217.73	
31	0.01053	43.90	219.03	
32	0.01192	44.17	220.37	
33	0.01348	44.47	221.88	
⋆	0.01363	44.50	222.02	Ideal Yield of Steel
34	0.01509	44.78	223.44	
35	0.01688	45.13	225.17	
36	0.01847	45.44	226.70	
37	0.02040	45.81	228.57	
⋆	0.02144	46.01	229.57	Tranverse Steel Failure

Table D.2: Lap Splice Strength Calculations for As-built Column CF-2

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00002	0.53	2.63	
2	0.00004	1.10	5.49	
3	0.00006	1.79	8.95	
4	0.00009	2.60	12.99	
5	0.00012	3.54	17.67	
6	0.00016	4.59	22.91	
7	0.00021	5.99	29.88	
8	0.00026	7.50	37.41	
9	0.00033	9.47	47.26	
10	0.00039	11.32	56.48	
11	0.00048	13.99	69.80	
12	0.00057	16.44	82.02	
13	0.00068	19.60	97.77	
14	0.00080	23.11	115.32	
15	0.00092	26.80	133.72	
16	0.00108	31.26	155.98	
17	0.00125	36.27	180.96	
18	0.00142	41.30	206.04	
19	0.00163	43.41	216.58	Begin Yield of Steel
20	0.00191	43.41	216.58	
21	0.00222	43.41	216.58	
22	0.00262	43.41	216.58	
23	0.00305	43.41	216.58	
24	0.00363	43.41	216.58	
25	0.00425	43.41	216.58	
26	0.00497	43.41	216.58	
27	0.00585	43.41	216.58	
28	0.00675	43.41	216.58	
29	0.00771	43.41	216.58	
30	0.00880	43.56	217.35	
31	0.01007	43.81	218.58	
32	0.01140	44.07	219.86	
33	0.01287	44.35	221.29	
⋆	0.01302	44.38	221.43	Ideal Yield of Steel
34	0.01441	44.65	222.78	
35	0.01608	44.98	224.39	
36	0.01780	45.31	226.06	
37	0.01947	45.63	227.67	
38	0.02129	45.99	229.43	
⋆	0.02116	45.96	229.31	Tranverse Steel Failure

Table D.3: Lap Splice Strength Calculations for Column CF-3

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00022	6.51	32.47	
2	0.00028	8.12	40.50	
3	0.00035	10.15	50.62	
4	0.00042	12.32	61.45	
5	0.00051	14.68	73.26	
6	0.00061	17.58	87.69	
7	0.00071	20.66	103.07	
8	0.00084	24.32	121.34	
9	0.00097	28.12	140.31	
10	0.00112	32.42	161.76	
11	0.00129	37.52	187.17	
12	0.00147	42.62	212.65	
13	0.00169	43.41	216.58	Begin Yield of Steel
14	0.00176	43.41	216.58	
15	0.00205	43.41	216.58	
16	0.00239	43.41	216.58	
17	0.00282	43.41	216.58	
18	0.00334	43.41	216.58	
19	0.00394	43.41	216.58	
20	0.00462	43.41	216.58	
21	0.00544	43.41	216.58	
22	0.00634	43.41	216.58	
23	0.00730	43.41	216.58	
24	0.00843	43.49	217.00	
25	0.00967	43.73	218.19	
26	0.01118	44.03	219.66	
27	0.01293	44.37	221.35	
28	0.01480	44.73	223.15	
29	0.01676	45.11	225.05	
$\star$	0.01841	45.43	226.64	Ideal Yield of Steel
30	0.01901	45.54	227.23	
31	0.02127	45.98	229.41	
32	0.02352	46.42	231.58	
$\star$	0.02405	46.52	232.10	Tranverse Steel Failure
33	0.02599	46.90	233.97	
34	0.02872	47.43	236.62	
35	0.03143	47.95	239.23	
36	0.03429	48.50	242.00	
37	0.03791	49.21	245.50	
38	0.04089	49.78	248.38	
39	0.04461	50.50	251.97	
40	0.04884	51.32	256.06	Maximum Concrete Strain

Table D.4: Lap Splice Strength Calculations for Column CF-4

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00024	6.90	34.45	
2	0.00029	8.51	42.45	
3	0.00036	10.58	52.80	
4	0.00044	12.81	63.93	
5	0.00053	15.25	76.06	
6	0.00063	18.21	90.86	
7	0.00074	21.60	107.75	
8	0.00087	25.34	126.43	
9	0.00101	29.17	145.53	
10	0.00116	33.54	167.33	
11	0.00134	38.89	194.02	
12	0.00152	43.41	216.58	
13	0.00174	43.41	216.58	Begin Yield of Steel
14	0.00184	43.41	216.58	
15	0.00214	43.41	216.58	
16	0.00254	43.41	216.58	
17	0.00295	43.41	216.58	
18	0.00350	43.41	216.58	
19	0.00412	43.41	216.58	
20	0.00480	43.41	216.58	
21	0.00565	43.41	216.58	
22	0.00656	43.41	216.58	
23	0.00759	43.41	216.58	
24	0.00874	43.55	217.29	
25	0.01010	43.82	218.61	
26	0.01157	44.10	220.03	
27	0.01341	44.46	221.81	
28	0.01517	44.80	223.52	
29	0.01716	45.19	225.44	
$\star$	0.01801	45.35	226.26	Ideal Yield of Steel
30	0.01947	45.63	227.67	
31	0.02179	46.08	229.92	
$\star$	0.02402	46.52	232.07	Tranverse Steel Failure
32	0.02409	46.53	232.14	
33	0.02661	47.02	234.58	
34	0.02943	47.56	237.30	
35	0.03213	48.09	239.91	
36	0.03508	48.66	242.77	
37	0.03828	49.28	245.86	
38	0.04179	49.96	249.25	
39	0.04577	50.73	253.10	
40	0.04996	51.54	257.15	Maximum Concrete Strain

Table D.5: Lap Splice Strength Calculations for Column CF-5

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00051	14.79	73.77	
2	0.00061	17.73	88.46	
3	0.00072	20.84	103.97	
4	0.00084	24.32	121.34	
5	0.00097	28.12	140.31	
6	0.00112	32.42	161.76	
7	0.00129	37.52	187.17	
8	0.00149	43.10	215.02	
9	0.00169	43.41	216.58	Begin Yield of Steel
10	0.00196	43.41	216.58	
11	0.00232	43.41	216.58	
12	0.00273	43.41	216.58	
13	0.00319	43.41	216.58	
14	0.00378	43.41	216.58	
15	0.00441	43.41	216.58	
16	0.00525	43.41	216.58	
17	0.00611	43.41	216.58	
18	0.00713	43.41	216.58	
19	0.00822	43.45	216.80	
20	0.00951	43.70	218.03	
21	0.01113	44.02	219.60	
22	0.01291	44.36	221.32	
23	0.01478	44.72	223.13	
24	0.01693	45.14	225.21	
25	0.01922	45.58	227.43	Ideal Yield of Steel
26	0.02179	46.08	229.91	
27	0.02437	46.58	232.41	
⋆	0.02559	46.82	233.58	Tranverse Steel Failure
28	0.02729	47.15	235.23	
29	0.03058	47.79	238.41	
30	0.03428	48.50	241.99	
31	0.03790	49.20	245.48	
32	0.04247	50.09	249.90	
33	0.04698	50.96	254.26	
34	0.05195	51.93	259.07	
35	0.05742	52.99	264.37	
36	0.06258	53.99	269.35	
37	0.06918	55.27	275.74	
38	0.07546	56.48	281.80	
⋆	0.08197	57.75	288.10	Maximum Concrete Strain

Table D.6: Lap Splice Strength Calculations for Column CF-6

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00002	0.68	3.42	
2	0.00004	1.28	6.39	
3	0.00007	2.00	10.00	
4	0.00010	2.84	14.19	
5	0.00013	3.81	19.03	
6	0.00017	4.88	24.37	
7	0.00022	6.29	31.39	
8	0.00027	7.87	39.27	
9	0.00034	9.87	49.25	
10	0.00041	11.80	58.86	
11	0.00050	14.46	72.13	
12	0.00059	17.14	85.51	
13	0.00070	20.26	101.07	
14	0.00082	23.90	119.25	
15	0.00096	27.72	138.32	
16	0.00111	32.06	159.95	
17	0.00128	37.20	185.61	
18	0.00146	42.37	211.38	
19	0.00167	43.41	216.58	Begin Yield of Steel
20	0.00196	43.41	216.58	
21	0.00230	43.41	216.58	
22	0.00273	43.41	216.58	
23	0.00317	43.41	216.58	
24	0.00377	43.41	216.58	
25	0.00442	43.41	216.58	
26	0.00518	43.41	216.58	
27	0.00610	43.41	216.58	
28	0.00706	43.41	216.58	
29	0.00805	43.42	216.62	
30	0.00919	43.64	217.73	
31	0.01053	43.90	219.03	
32	0.01192	44.17	220.37	
33	0.01348	44.47	221.88	
⋆	0.01363	44.50	222.02	Ideal Yield of Steel
34	0.01509	44.78	223.44	
35	0.01688	45.13	225.17	
36	0.01847	45.44	226.70	
37	0.02040	45.81	228.57	
⋆	0.02144	46.01	229.57	Tranverse Steel Failure

Table D.7: Lap Splice Strength Calculations for Column CF-7

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00054	15.66	78.15	
2	0.00064	18.47	92.15	
3	0.00075	21.81	108.84	
4	0.00088	25.46	127.04	
5	0.00102	29.69	148.12	
6	0.00117	34.00	169.62	
7	0.00135	39.18	195.50	
8	0.00154	43.41	216.58	
9	0.00176	43.41	216.58	Begin Yield of Steel
10	0.00214	43.41	216.58	
11	0.00250	43.41	216.58	
12	0.00294	43.41	216.58	
13	0.00346	43.41	216.58	
14	0.00412	43.41	216.58	
15	0.00482	43.41	216.58	
16	0.00566	43.41	216.58	
17	0.00658	43.41	216.58	
18	0.00759	43.41	216.58	
19	0.00876	43.56	217.32	
20	0.01014	43.82	218.65	
21	0.01183	44.15	220.28	
22	0.01355	44.49	221.94	
23	0.01552	44.87	223.85	
24	0.01778	45.30	226.03	
⋆	0.01814	45.37	226.38	Ideal Yield of Steel
25	0.02016	45.77	228.34	
26	0.02254	46.23	230.64	
27	0.02523	46.75	233.24	
⋆	0.02541	46.78	233.41	Tranverse Steel Failure
28	0.02825	47.33	236.16	
29	0.03125	47.92	239.06	
30	0.03501	48.65	242.70	
31	0.03919	49.45	246.74	
32	0.04334	50.26	250.74	
33	0.04791	51.15	255.17	
34	0.05297	52.12	260.06	
35	0.05857	53.21	265.47	
36	0.06387	54.24	270.60	
37	0.07061	55.54	277.12	
⋆	0.07789	56.96	284.16	Maximum Concrete Strain

Table D.8: Lap Splice Strength Calculations for Column CF-8

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00060	17.50	87.29	
2	0.00071	20.64	102.98	
3	0.00084	24.31	121.27	
4	0.00096	27.90	139.20	
5	0.00112	32.51	162.17	
6	0.00129	37.33	186.23	
7	0.00147	42.54	212.22	
8	0.00169	43.41	216.58	Begin Yield of Steel
9	0.00203	43.41	216.58	
10	0.00236	43.41	216.58	
11	0.00278	43.41	216.58	
12	0.00330	43.41	216.58	
13	0.00391	43.41	216.58	
14	0.00457	43.41	216.58	
15	0.00544	43.41	216.58	
16	0.00633	43.41	216.58	
17	0.00739	43.41	216.58	
18	0.00855	43.52	217.11	
19	0.00988	43.77	218.40	
20	0.01158	44.10	220.04	
21	0.01327	44.43	221.68	
22	0.01539	44.84	223.73	
23	0.01768	45.29	225.94	
⋆	0.01993	45.72	228.11	Ideal Yield of Steel
24	0.02003	45.74	228.21	
25	0.02275	46.27	230.84	
26	0.02551	46.80	233.51	
⋆	0.02615	46.93	234.13	Tranverse Steel Failure
27	0.02893	47.47	236.81	
28	0.03240	48.14	240.17	
29	0.03633	48.90	243.97	
30	0.04076	49.76	248.25	
31	0.04507	50.59	252.42	
32	0.04983	51.52	257.02	
33	0.05507	52.53	262.09	
34	0.06085	53.65	267.68	
35	0.06730	54.90	273.91	
36	0.07441	56.28	280.79	
37	0.08223	57.80	288.35	
⋆	0.08793	58.90	293.86	Maximum Concrete Strain

Table D.9: Lap Splice Strength Calculations for Column CF-9

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00060	17.50	87.29	
2	0.00071	20.64	102.98	
3	0.00084	24.31	121.27	
4	0.00097	28.15	140.45	
5	0.00112	32.51	162.17	
6	0.00129	37.33	186.23	
7	0.00147	42.54	212.22	
8	0.00169	43.41	216.58	Begin Yield of Steel
9	0.00203	43.41	216.58	
10	0.00236	43.41	216.58	
11	0.00278	43.41	216.58	
12	0.00330	43.41	216.58	
13	0.00391	43.41	216.58	
14	0.00457	43.41	216.58	
15	0.00544	43.41	216.58	
16	0.00633	43.41	216.58	
17	0.00739	43.41	216.58	
18	0.00855	43.52	217.11	
19	0.00988	43.77	218.40	
20	0.01158	44.10	220.04	
21	0.01327	44.43	221.68	
22	0.01539	44.84	223.73	
23	0.01768	45.29	225.94	
$\star$	0.01993	45.72	228.11	Ideal Yield of Steel
24	0.02003	45.74	228.21	
25	0.02275	46.27	230.84	
26	0.02551	46.80	233.51	
$\star$	0.02613	46.92	234.11	Tranverse Steel Failure
27	0.02893	47.47	236.81	
28	0.03240	48.14	240.17	
29	0.03633	48.90	243.97	
30	0.04076	49.76	248.25	
31	0.04507	50.59	252.42	
32	0.04983	51.52	257.02	
33	0.05587	52.69	262.87	
34	0.06173	53.82	268.53	
35	0.06730	54.90	273.91	
36	0.07441	56.28	280.79	
37	0.08223	57.80	288.35	
38	0.08965	59.23	295.53	
$\star$	0.08764	58.84	293.58	Maximum Concrete Strain

D.2 Lap Splice Enhancement Rectangular Columns

Table D.10: Lap Splice Strength Calculations for As-built Column RF-1

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00029	8.36	41.43	
2	0.00036	10.40	51.59	
3	0.00044	12.89	63.94	
4	0.00054	15.67	77.71	
5	0.00064	18.56	92.01	
6	0.00076	22.06	109.41	
7	0.00089	25.81	127.99	
8	0.00104	30.19	149.70	
9	0.00120	34.67	171.92	
10	0.00138	40.06	198.65	
11	0.00159	46.03	228.24	
12	0.00179	51.90	257.34	
13	0.00205	59.37	294.38	
14	0.00231	64.36	319.13	
15	0.00275	64.36	319.13	Begin Yield of Steel
16	0.00329	64.36	319.13	
17	0.00394	64.36	319.13	
18	0.00480	64.36	319.13	
19	0.00571	64.36	319.13	
20	0.00696	64.36	319.13	
21	0.00827	64.44	319.51	
22	0.00962	64.83	321.44	
23	0.01134	65.32	323.90	
24	0.01319	65.85	326.53	
25	0.01519	66.43	329.38	
26	0.01704	66.96	332.01	
⋆	0.01852	67.38	334.12	Ideal Yield of Steel
27	0.01884	67.48	334.58	
28	0.02053	67.96	336.99	
29	0.02246	68.51	339.73	
30	0.02445	69.09	342.57	
31	0.02627	69.61	345.16	
32	0.02831	70.20	348.07	
33	0.03045	70.81	351.12	
34	0.03244	71.38	353.96	
⋆	0.03309	71.57	354.87	Tranverse Steel Failure

Table D.11: Lap Splice Strength Calculations for Column RF-2

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00178	51.57	255.73	
2	0.00203	58.81	291.60	
3	0.00229	64.36	319.13	
4	0.00274	64.36	319.13	First Yield of Steel
5	0.00307	64.36	319.13	
6	0.00371	64.36	319.13	
⋆	0.00394	64.36	319.13	Unconfined Lap Splice Failure
7	0.00449	64.36	319.13	
8	0.00547	64.36	319.13	
9	0.00659	64.36	319.13	
10	0.00804	64.37	319.20	
11	0.00957	64.81	321.38	
12	0.01129	65.31	323.82	
13	0.01356	65.96	327.06	
14	0.01613	66.69	330.71	
15	0.01892	67.50	334.69	
16	0.02162	68.27	338.53	
17	0.02472	69.16	342.95	
18	0.02768	70.02	347.18	
⋆	0.02891	70.37	348.92	Ideal Yield of Steel
19	0.03167	71.16	352.86	
20	0.03566	72.31	358.55	
21	0.04068	73.75	365.70	
⋆	0.04635	75.38	373.77	Tranverse Steel Failure
22	0.05138	76.82	380.9	Lap Splice Failure
23	0.05259	77.17	382.66	
24	0.05922	79.08	392.10	
25	0.06646	81.16	402.42	
26	0.07490	83.58	414.45	
27	0.08445	86.33	428.05	Longitudinal Steel Failure

Table D.12: Lap Splice Strength Calculations for Column RF-3

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00187	54.11	268.30	
2	0.00211	61.18	303.39	
3	0.00243	64.36	319.13	First Yield of Steel
4	0.00269	64.36	319.13	
5	0.00326	64.36	319.13	
⋆	0.00361	64.36	319.13	Unconfined Lap Splice Failure
6	0.00394	64.36	319.13	
7	0.00477	64.36	319.13	
8	0.00576	64.36	319.13	
9	0.00704	64.36	319.13	
10	0.00845	64.49	319.78	
11	0.01009	64.96	322.11	
12	0.01188	65.48	324.67	
13	0.01430	66.17	328.10	
14	0.01669	66.86	331.52	
15	0.01897	67.51	334.76	
16	0.02163	68.28	338.56	
17	0.02467	69.15	342.89	
⋆	0.02649	69.67	345.48	Ideal Yield of Steel
18	0.02808	70.13	347.75	
19	0.03155	71.13	352.68	
20	0.03546	72.25	358.26	
21	0.04038	73.66	365.27	
⋆	0.04419	74.76	370.70	Tranverse Steel Failure
22	0.04544	75.12	372.47	
⋆	0.05049	76.57	379.67	Lap Splice Failure
24	0.05850	78.87	391.08	
25	0.06563	80.92	401.23	
26	0.07386	83.28	412.96	
27	0.08317	85.96	426.22	Longitudinal Steel Failure

Table D.13: Lap Splice Strength Calculations for Column RF-5

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00123	35.71	177.05	
2	0.00141	40.76	202.10	
3	0.00161	46.70	231.58	
4	0.00184	53.22	263.87	
5	0.00209	60.56	300.28	
6	0.00238	64.36	319.13	First Yield of Steel
7	0.00284	64.36	319.13	
8	0.00342	64.36	319.13	
⋆	0.00391	64.36	319.13	Unconfined Lap Splice Failure
9	0.00411	64.36	319.13	
10	0.00500	64.36	319.13	
11	0.00604	64.36	319.13	
12	0.00733	64.36	319.13	
13	0.00873	64.57	320.17	
14	0.01041	65.05	322.57	
15	0.01249	65.65	325.53	
16	0.01483	66.32	328.87	
17	0.01734	67.04	332.44	
18	0.02008	67.83	336.34	
19	0.02255	68.54	339.87	
20	0.02575	69.46	344.42	
⋆	0.02809	70.13	347.75	Ideal Yield of Steel
21	0.02895	70.38	348.98	
22	0.03243	71.38	353.94	
23	0.03712	72.73	360.62	
24	0.05049	76.57	379.67	
⋆	0.04587	75.24	373.08	Tranverse Steel Failure
25	0.04765	75.75	375.62	
26	0.05365	77.48	384.17	
27	0.06039	79.41	393.77	
28	0.06803	81.61	404.66	
29	0.07526	83.69	414.97	
30	0.08474	86.41	428.46	Longitudinal Steel Failure

Table D.14: Lap Splice Strength Calculations for Column RF-6

Step	ϵ_s	$f_s(ksi)$	$f_l(psi)$	Comments
1	0.00161	46.70	231.58	
2	0.00184	53.22	263.87	
3	0.00209	60.56	300.28	
4	0.00235	64.36	319.13	First Yield of Steel
5	0.00281	64.36	319.13	
6	0.00342	64.36	319.13	
$\star$	0.00393	64.36	319.13	Unconfined Lap Splice Failure
7	0.00408	64.36	319.13	
8	0.00394	64.36	319.13	
9	0.00601	64.36	319.13	
10	0.00729	64.36	319.13	
11	0.00880	64.59	320.28	
12	0.01037	65.04	322.51	
13	0.01245	65.64	325.47	
14	0.01474	66.30	328.73	
15	0.01756	67.11	332.75	
16	0.02030	67.89	336.66	
17	0.02320	68.73	340.78	
18	0.02607	69.55	344.88	
$\star$	0.02851	70.25	348.36	Ideal Yield of Steel
19	0.02923	70.46	349.38	
20	0.03338	71.65	355.30	
21	0.03832	73.07	362.34	
22	0.04292	74.39	368.89	
$\star$	0.04594	75.26	373.19	Tranverse Steel Failure
23	0.05049	76.57	379.67	
24	0.05543	77.99	386.71	
25	0.06250	80.02	396.78	
26	0.07013	82.21	407.65	
27	0.07906	84.78	420.37	Longitudinal Steel Failure

Appendix E

COMPARISON OF LOAD-DISPLACEMENT ENVELOPES

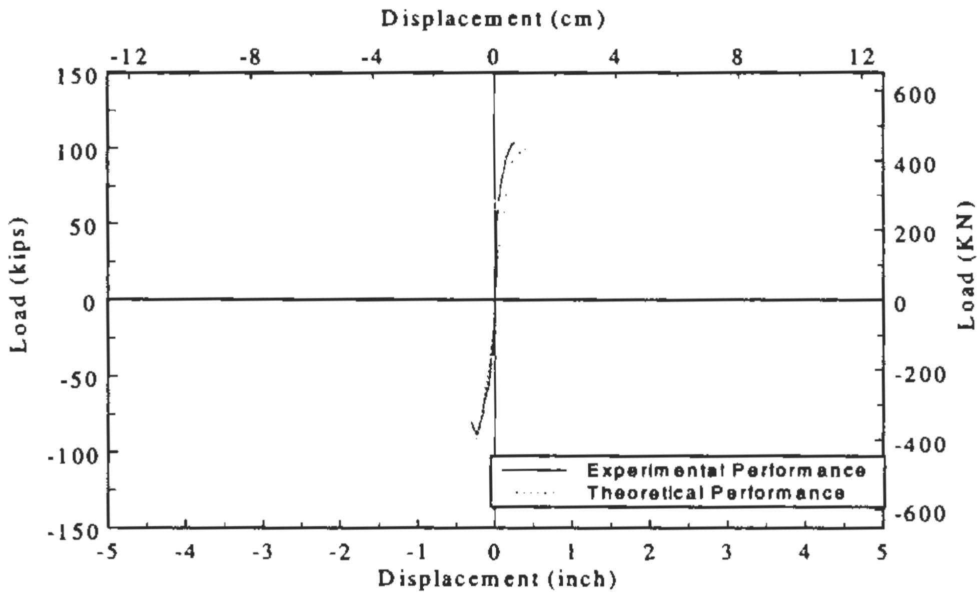

Figure E.1: Envelope Comparison for As-built Shear Enhancement Circular Column CS-1

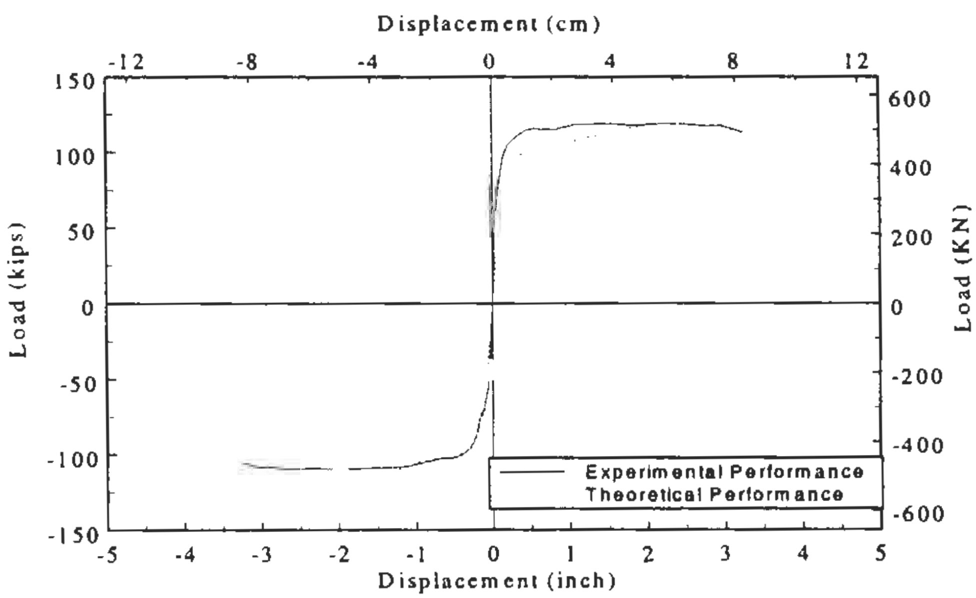

Figure E.2: Envelope Comparison for Shear Enhancement Circular Column CS-2

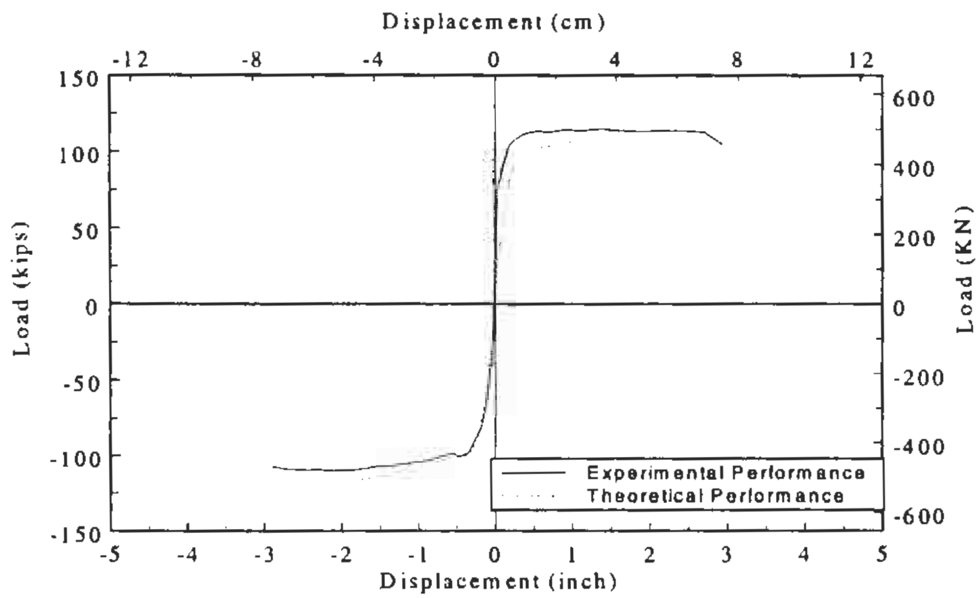

Figure E.3: Envelope Comparison for Shear Enhancement Circular Column CS-3

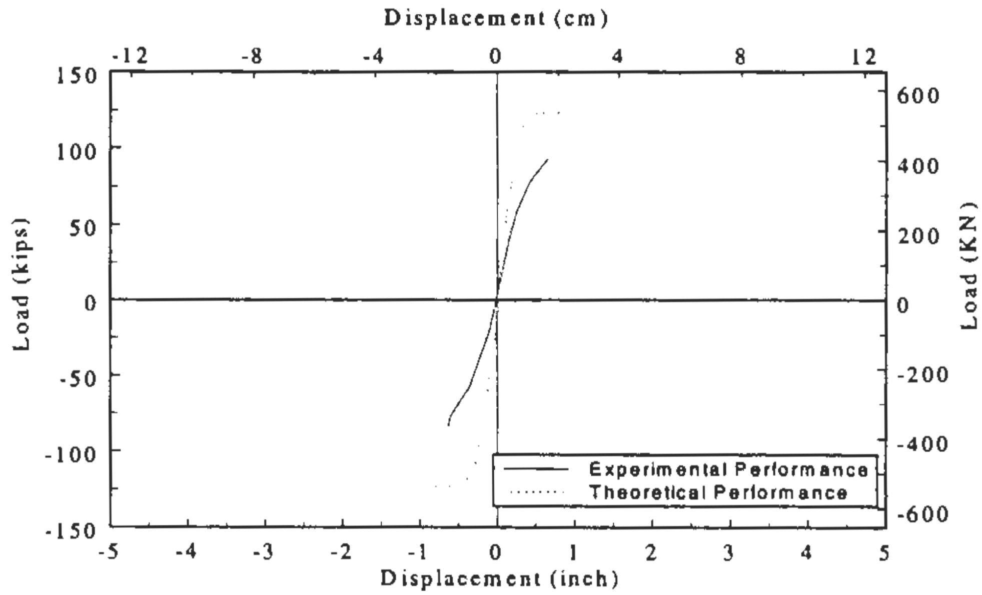

Figure E.4: Envelope Comparison for As-built Shear Enhancement Circular Column CS-4

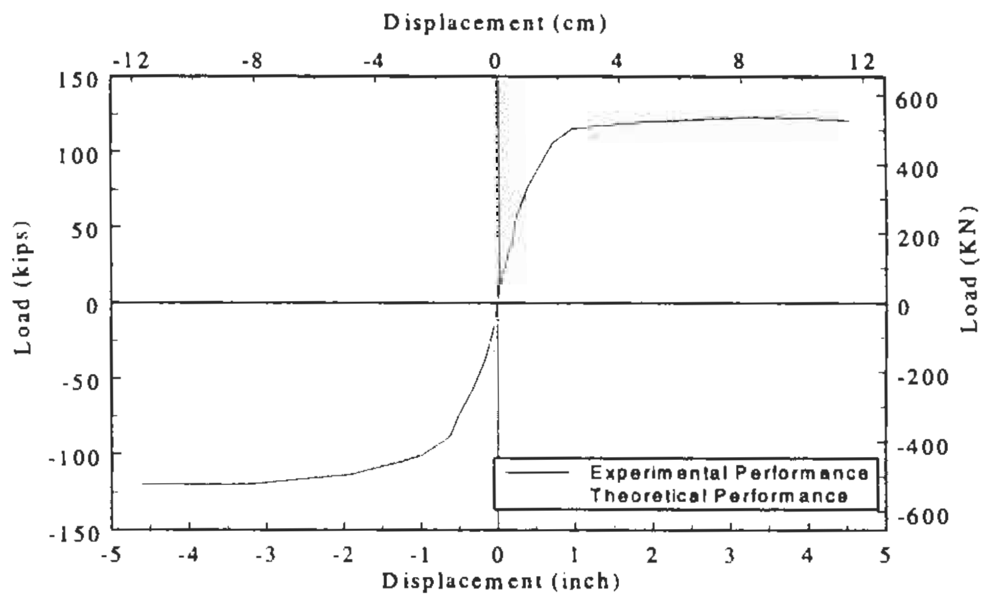

Figure E.5: Envelope Comparison for Shear Enhancement Circular Column CS-5

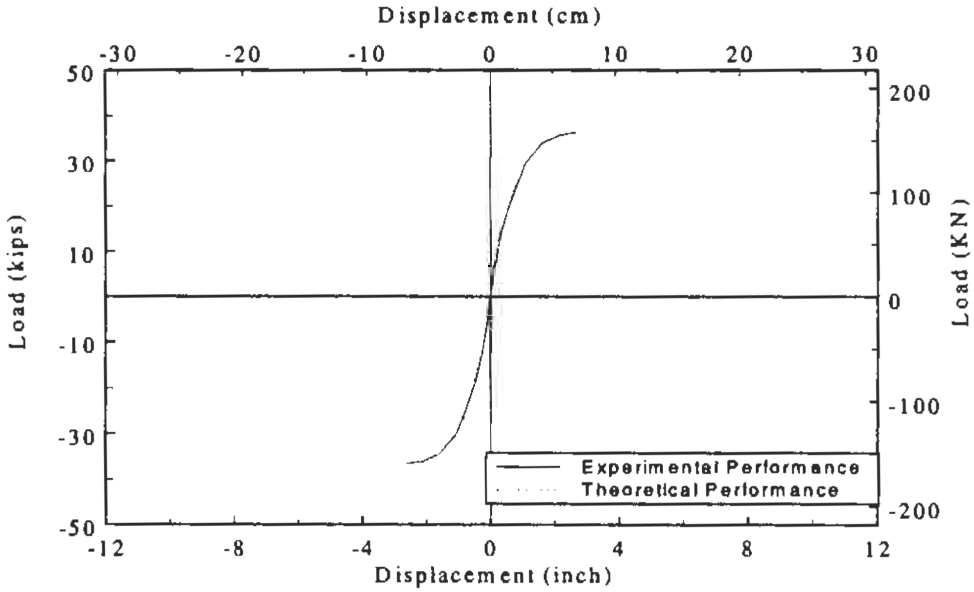

Figure E.6: Envelope Comparison for As-built Lap Splice Enhancement Circular Column CF-1

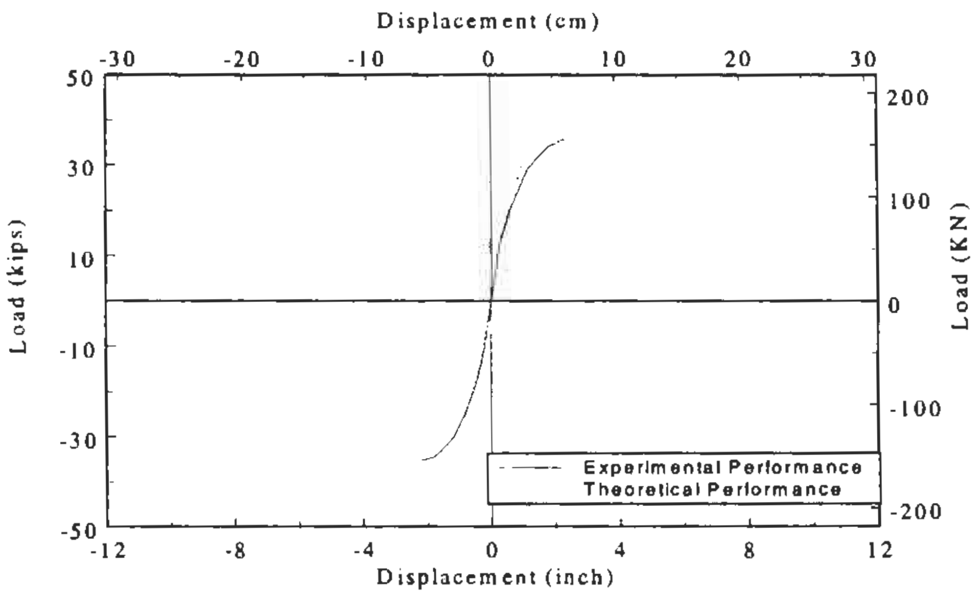

Figure E.7: Envelope Comparison for As-built Lap Splice Enhancement Circular Column CF-2

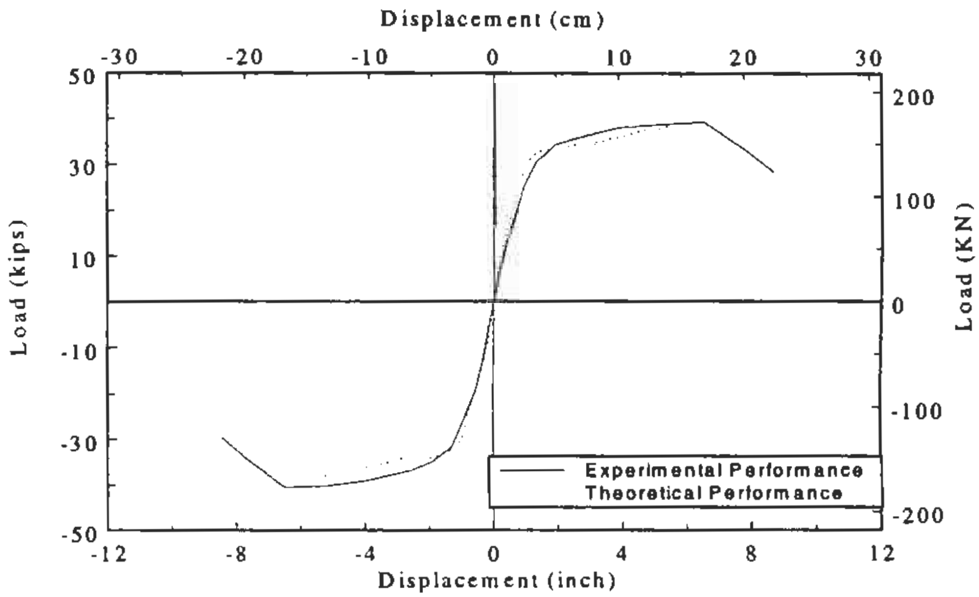

Figure E.8: Envelope Comparison for Lap Splice Enhancement Circular Column CF-3

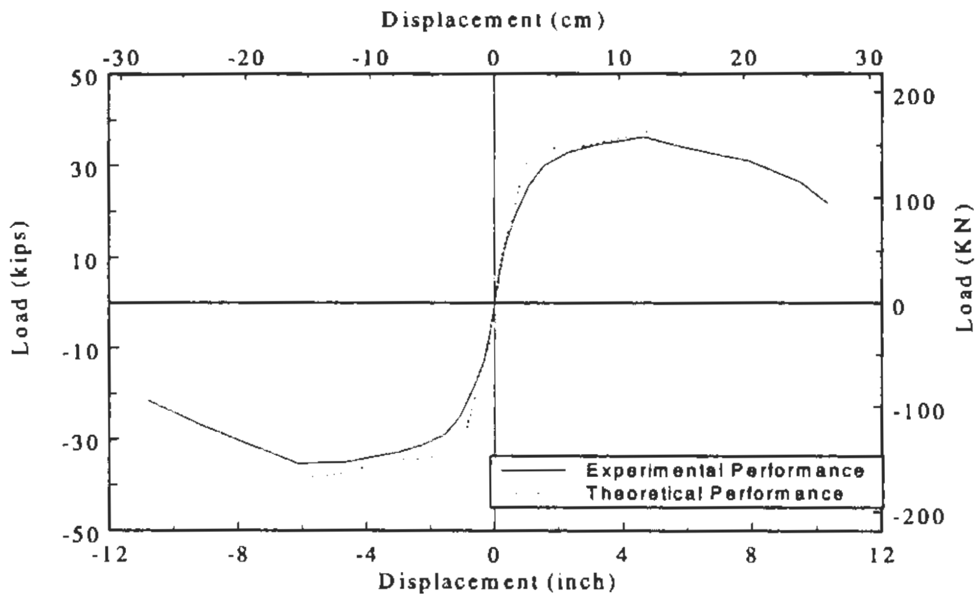

Figure E.9: Envelope Comparison for Lap Splice Enhancement Circular Column CF-4

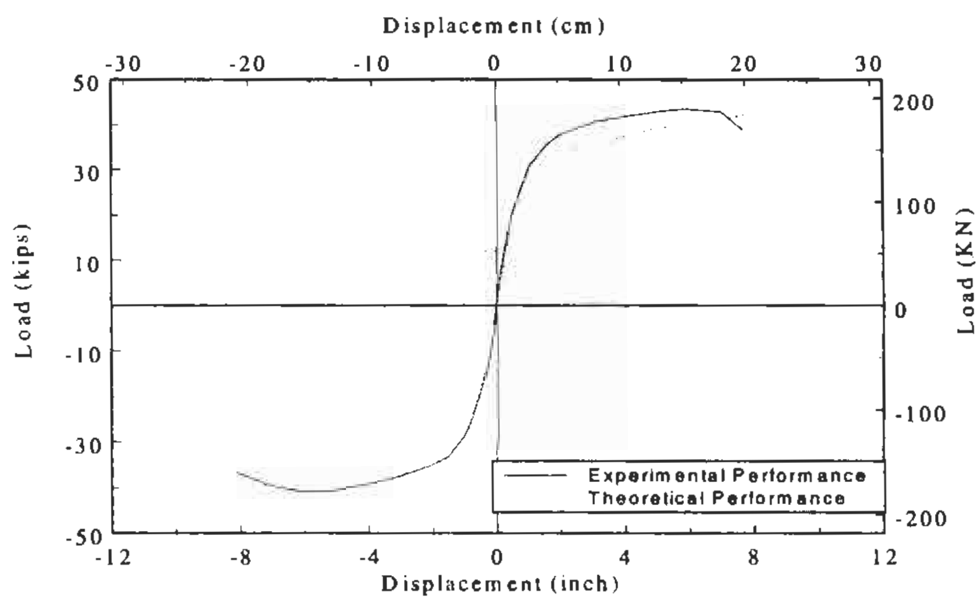

Figure E.10: Envelope Comparison for Lap Splice Enhancement Circular Column CF-5

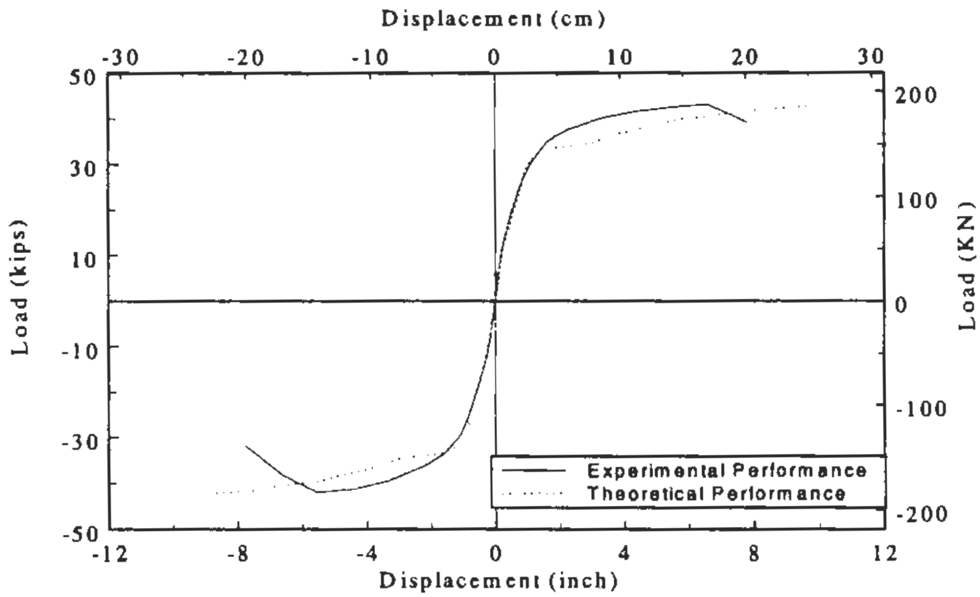

Figure E.11: Envelope Comparison for Lap Splice Enhancement Circular Column CF-6

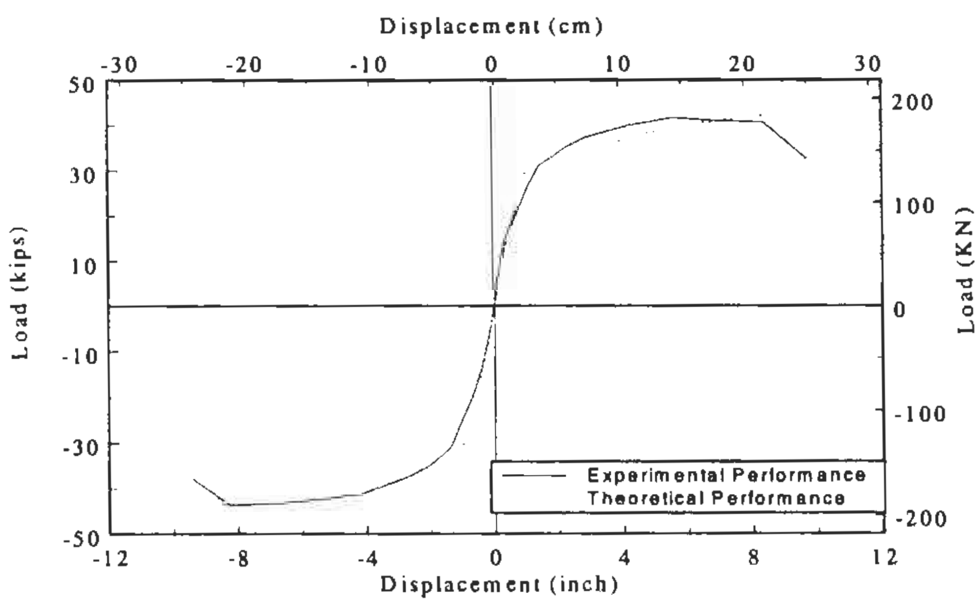

Figure E.12: Envelope Comparison for Lap Splice Enhancement Circular Column CF-7

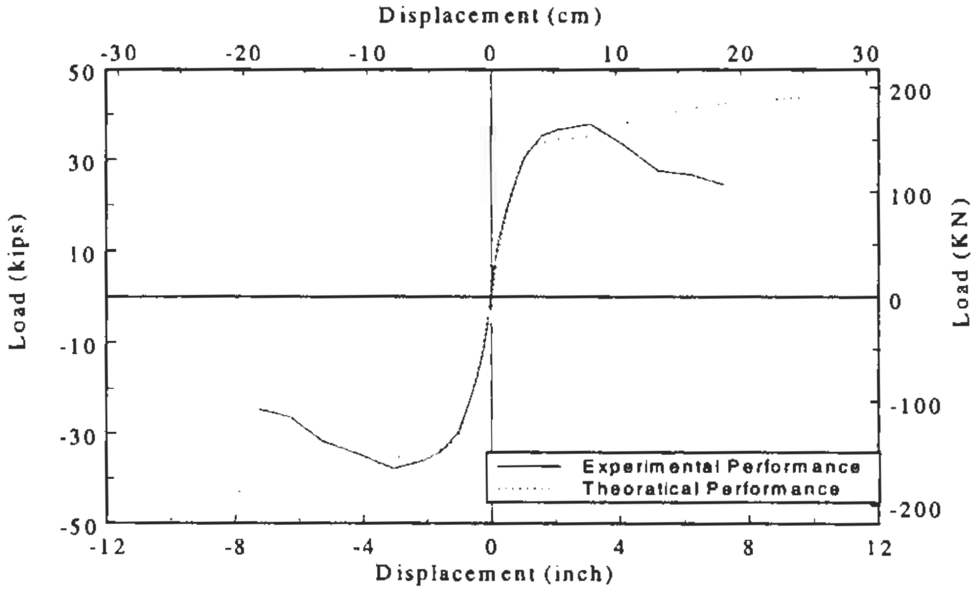

Figure E.13: Envelope Comparison for Lap Splice Enhancement Circular Column CF-8

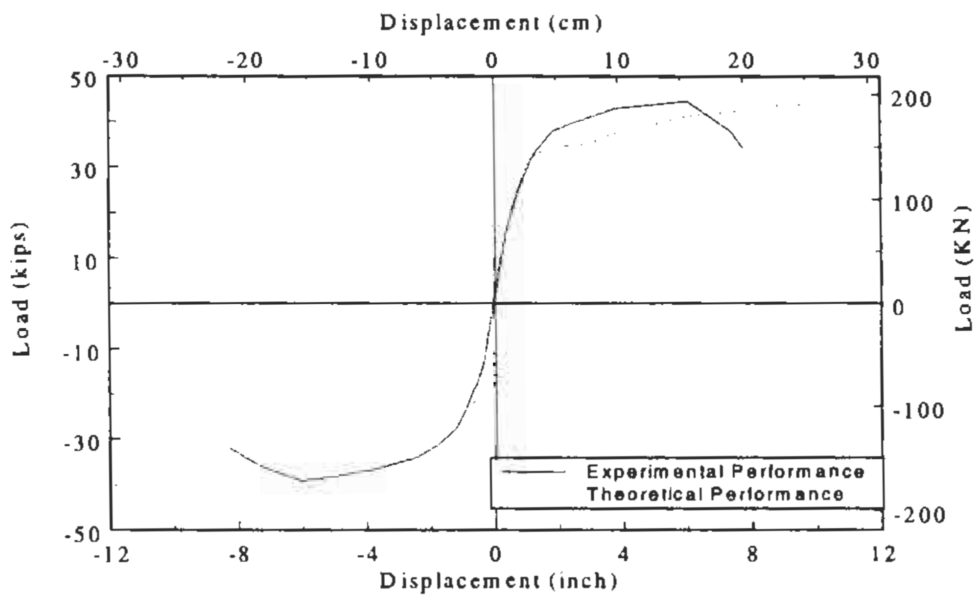

Figure E.14: Envelope Comparison for Lap Splice Enhancement Circular Column CF-9

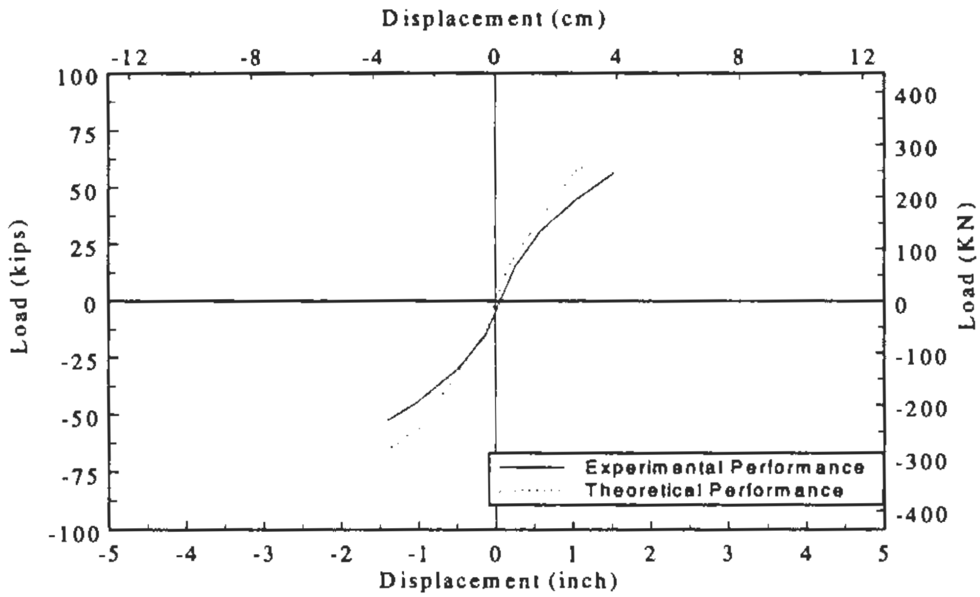

Figure E.15: Envelope Comparison for As-built Lap Splice Enhancement Rectangular Column RF-1

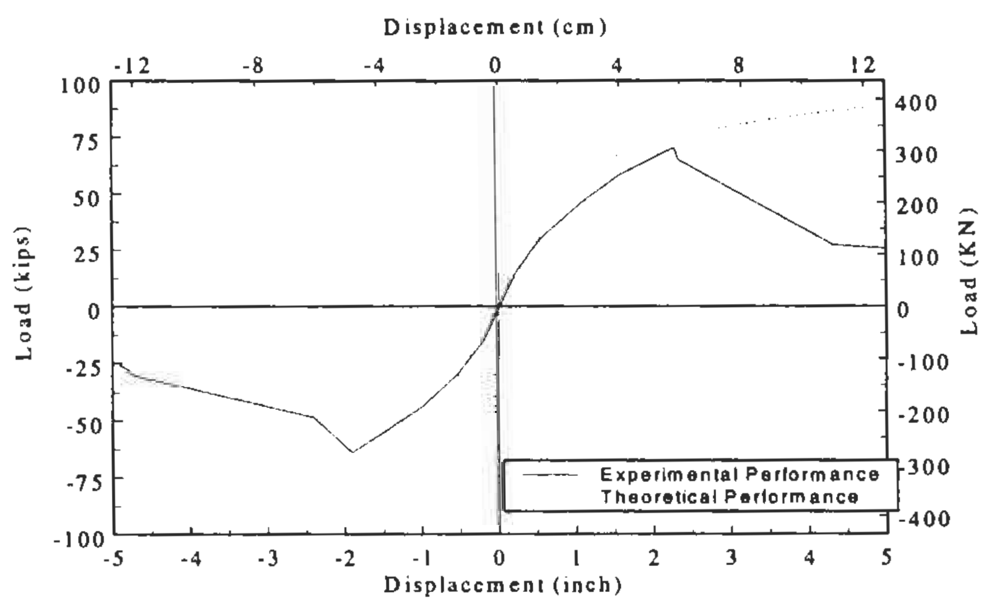

Figure E.16: Envelope Comparison for Lap Splice Enhancement Rectangular Column RF-2

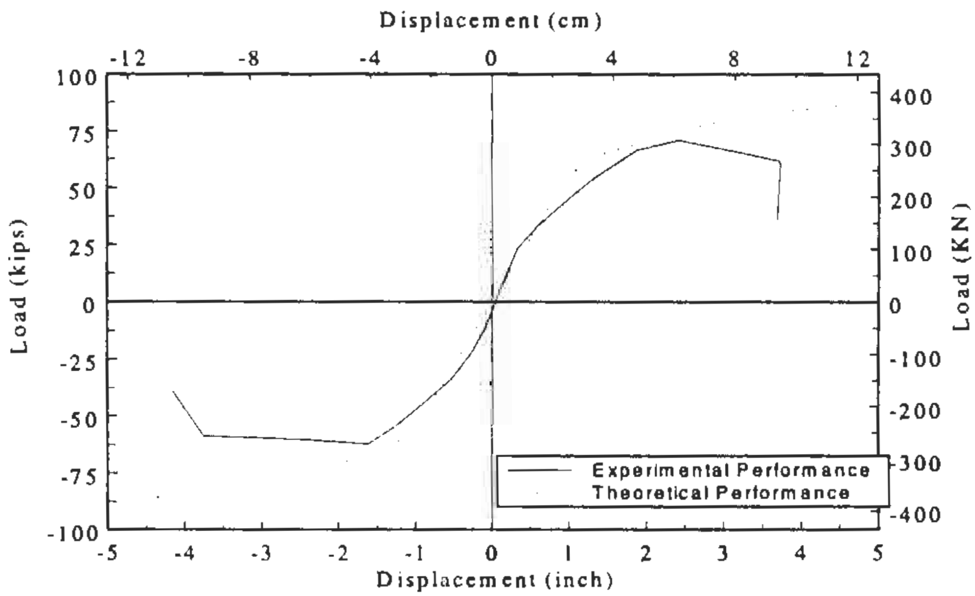

Figure E.17: Envelope Comparison for Lap Splice Enhancement Rectangular Column RF-3

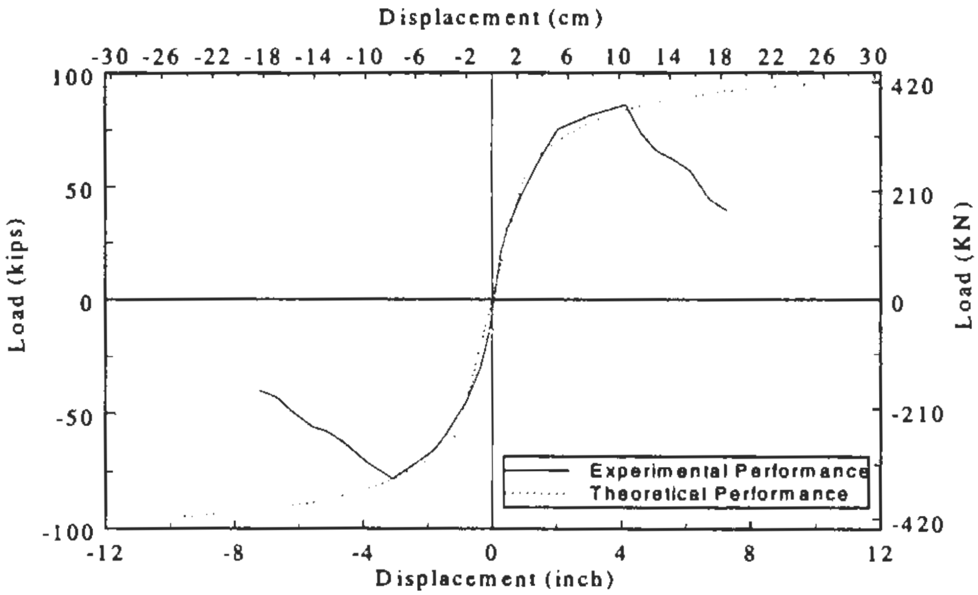

Figure E.18: Envelope Comparison for Lap Splice Enhancement Rectangular Column RF-5

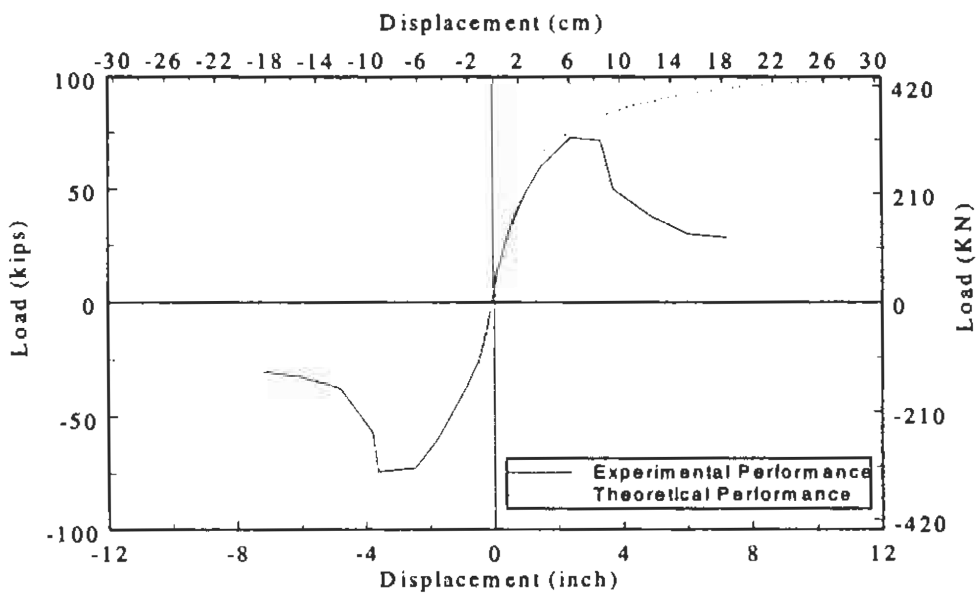

Figure E.19: Envelope Comparison for Lap Splice Enhancement Rectangular Column RF-6

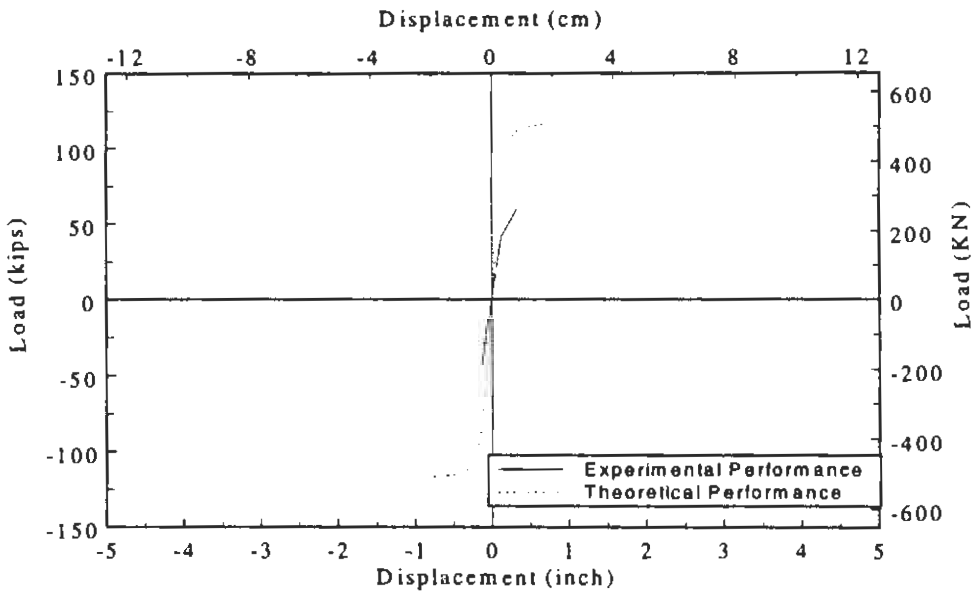

Figure E.20: Envelope Comparison for As-built Shear Enhancement Rectangular Column RS-1

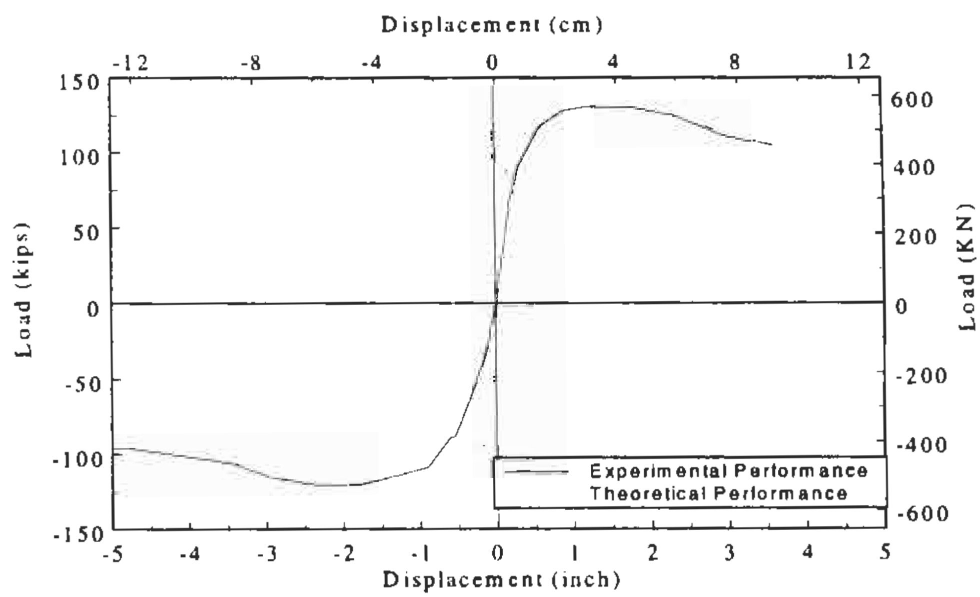

Figure E.21: Envelope Comparison for Shear Enhancement Rectangular Column RS-2

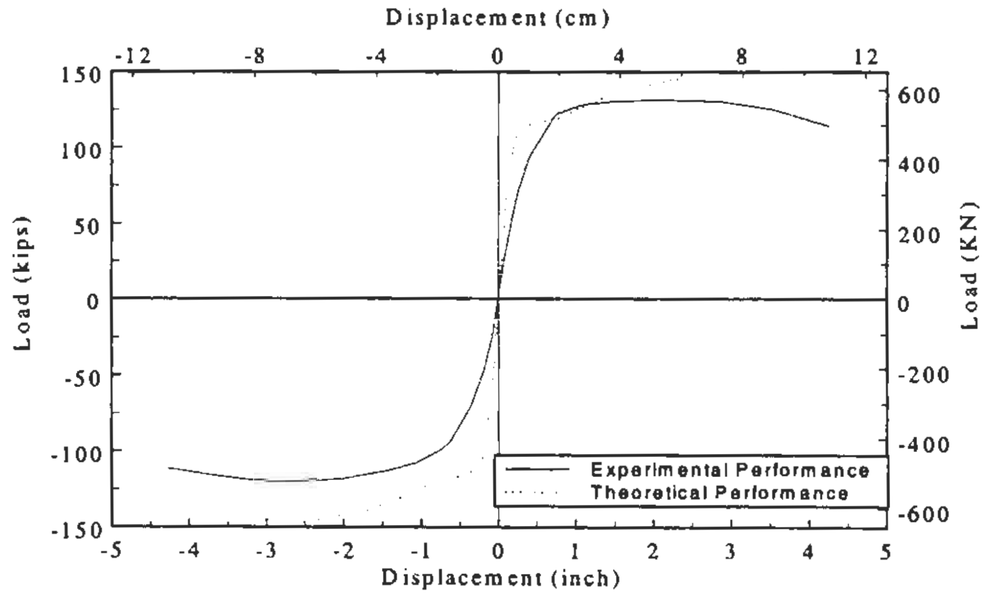

Figure E.22: Envelope Comparison for Shear Enhancement Rectangular Column RS-3

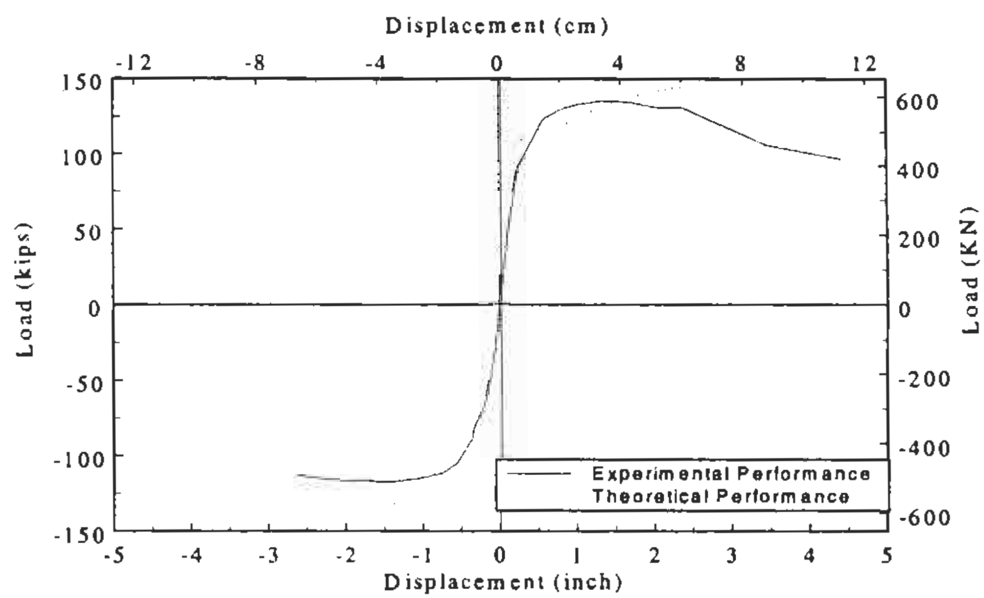

Figure E.23: Envelope Comparison for Shear Enhancement Rectangular Column RS-4

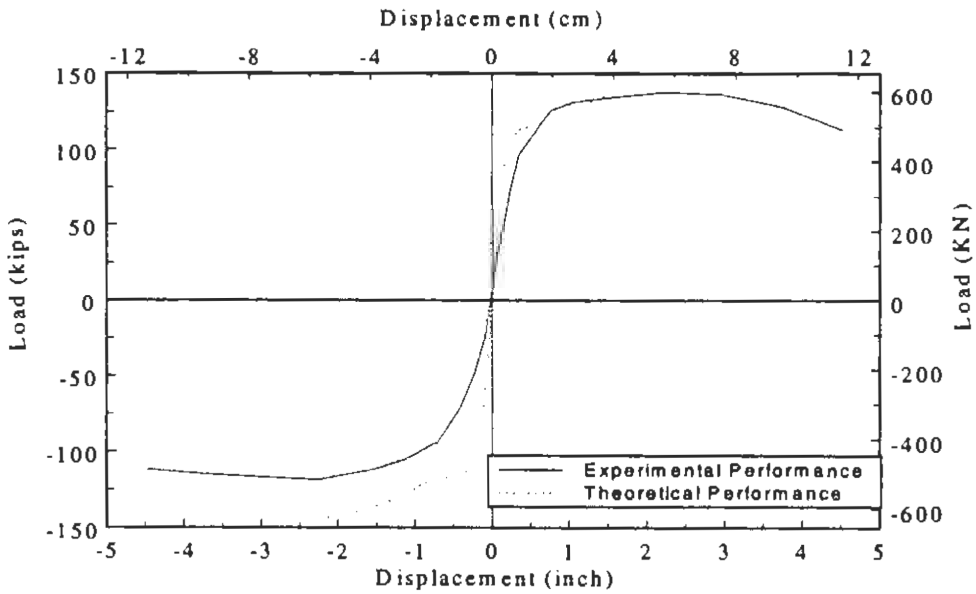

Figure E.24: Envelope Comparison for Shear Enhancement Rectangular Column RS-5

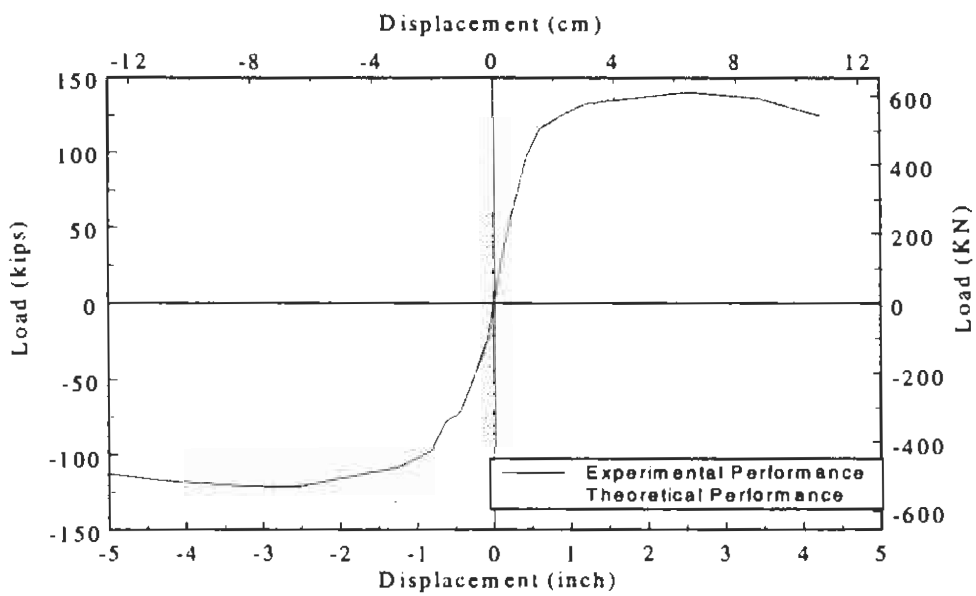

Figure E.25: Envelope Comparison for Shear Enhancement Rectangular Column RS-6

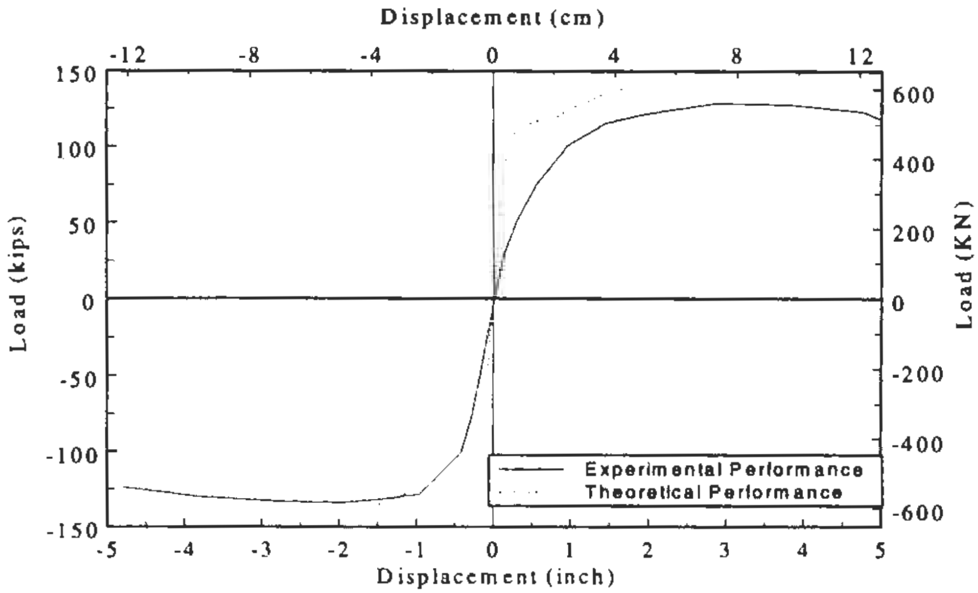

Figure E.26: Envelope Comparison for Shear Enhancement Rectangular Column RS-7

Appendix F

DISPLACEMENT PROFILES

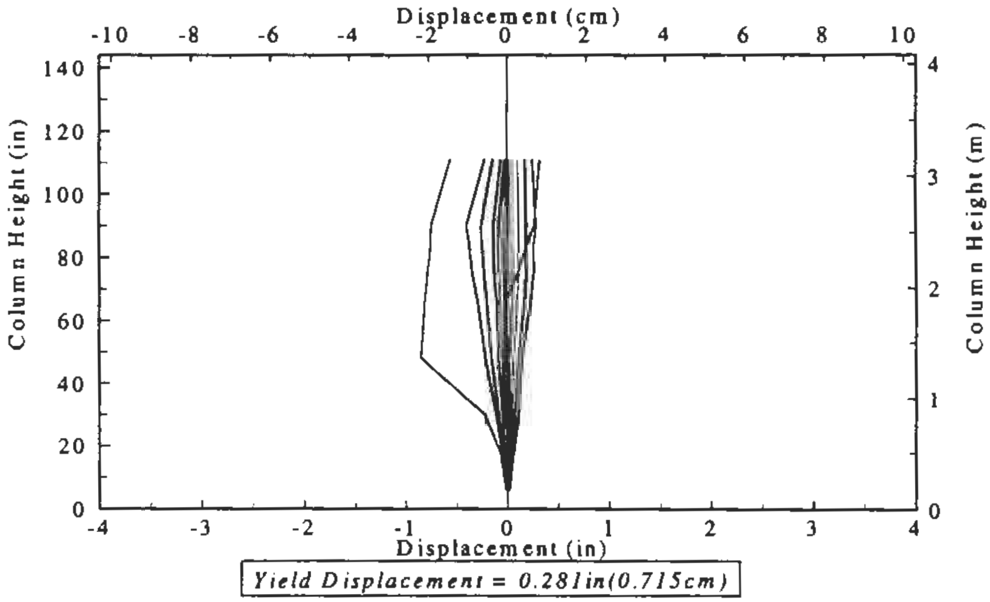

Figure F.1: Maximum Column Profile for Each Cycle for As-built Shear Enhancement Circular Column CS-1

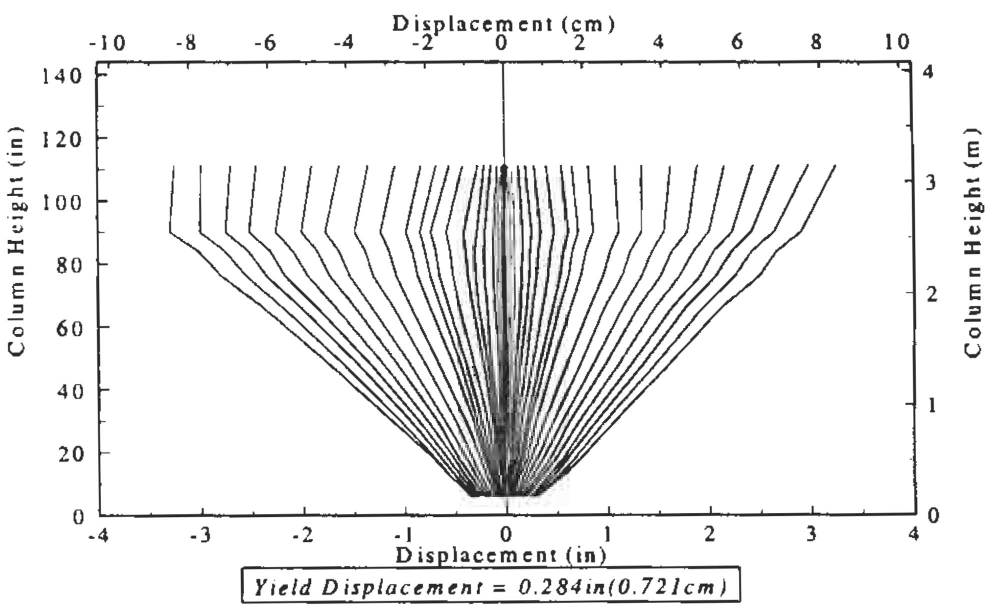

Figure F.2: Maximum Column Profile for Each Cycle for Shear Enhancement Circular Column CS-2

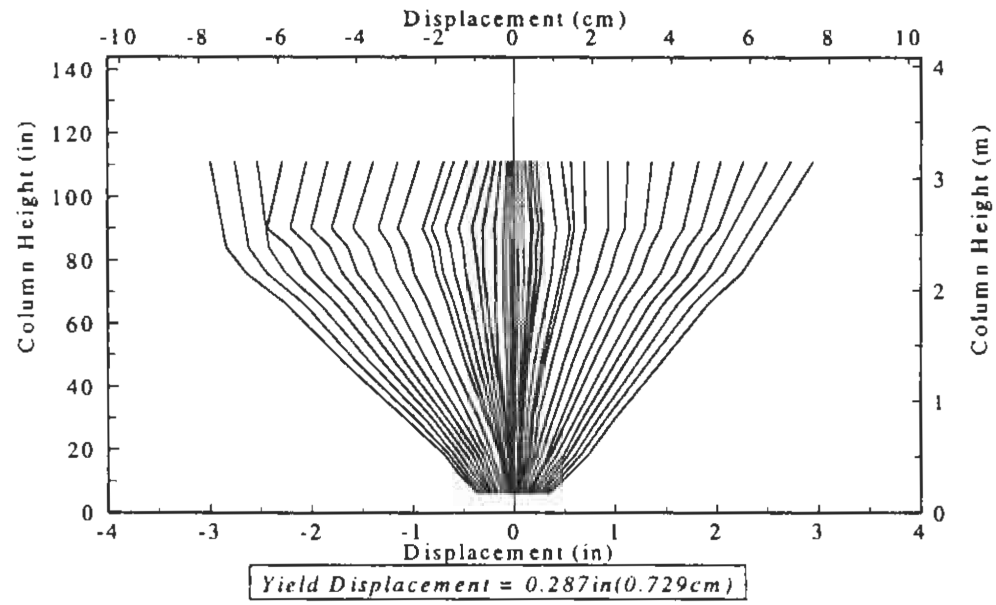

Figure F.3: Maximum Column Profile for Each Cycle for Shear Enhancement Circular Column CS-3

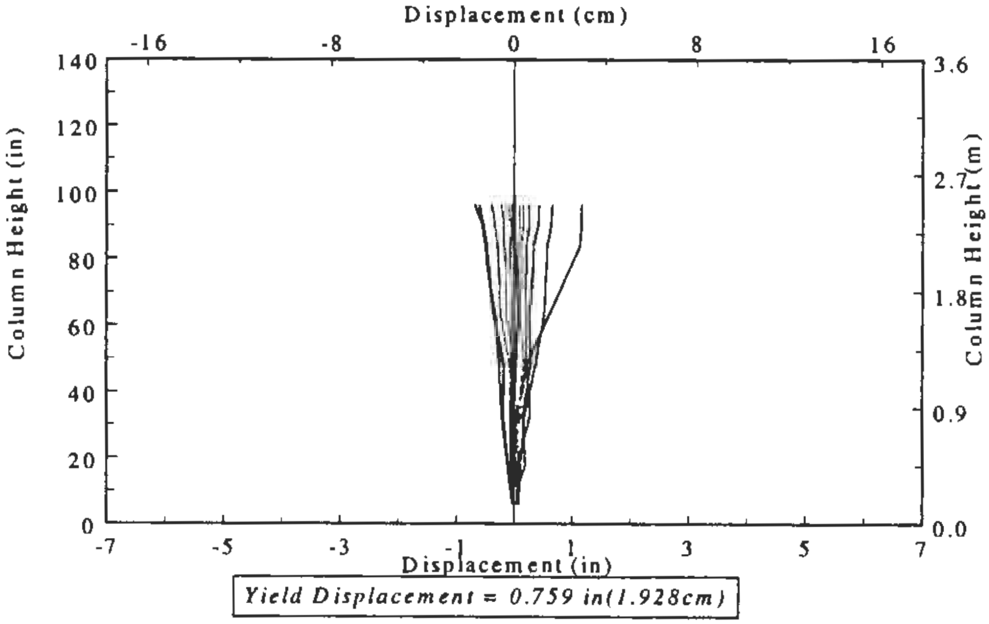

Figure F.4: Maximum Column Profile for Each Cycle for As-built Shear Enhancement Circular Column CS-4

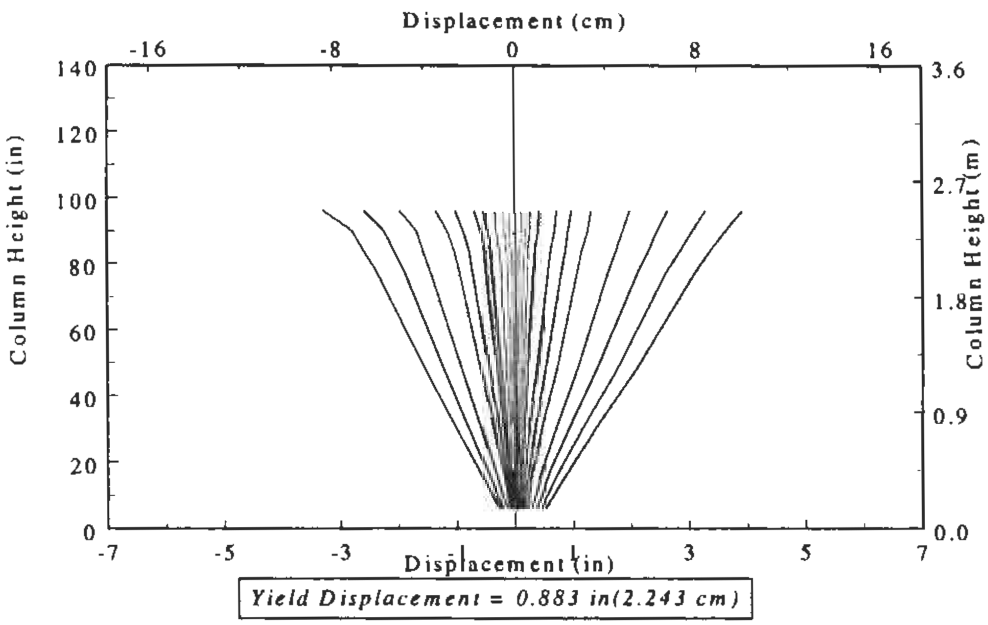

Figure F.5: Maximum Column Profile for Each Cycle for Shear Enhancement Circular Column CS-5

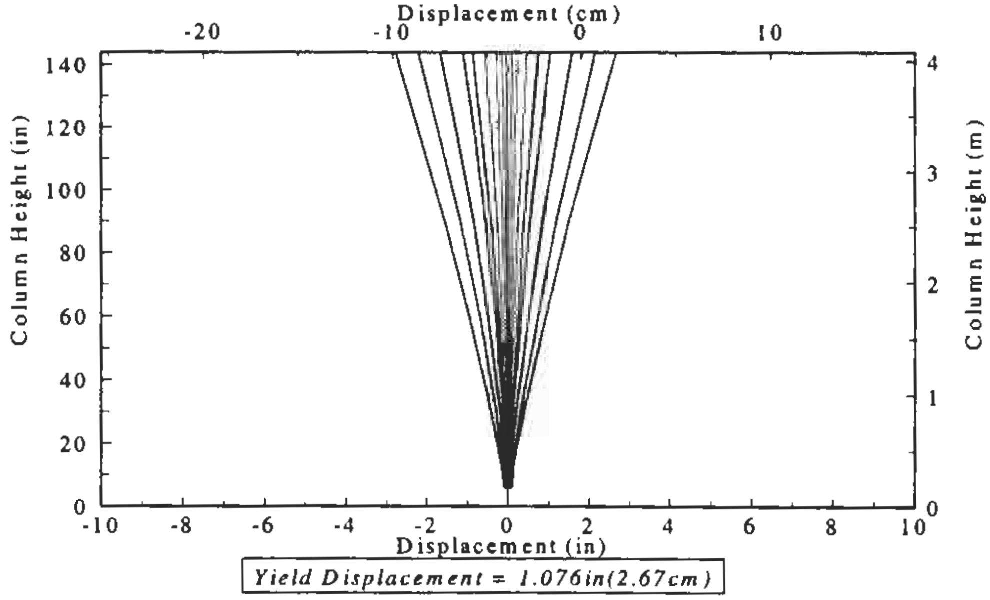

Figure F.6: Maximum Column Profile for Each Cycle for As-built Lap Splice Enhancement Circular Column CF-1

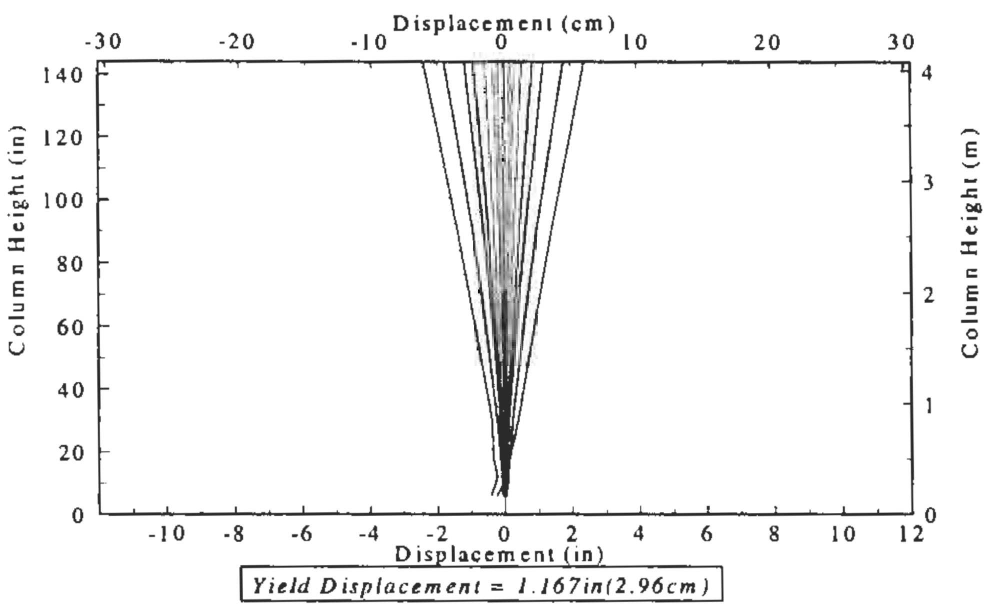

Figure F.7: Maximum Column Profile for Each Cycle for As-built Lap Splice Enhancement Circular Column CF-2

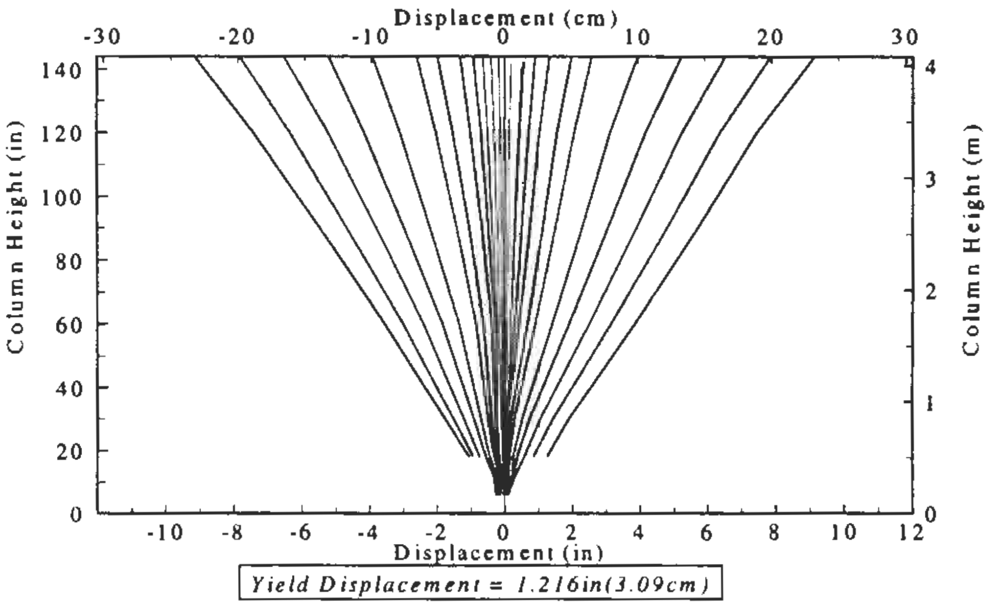

Figure F.8: Maximum Column Profile for Each Cycle for Lap Splice Enhancement Circular Column CF-3

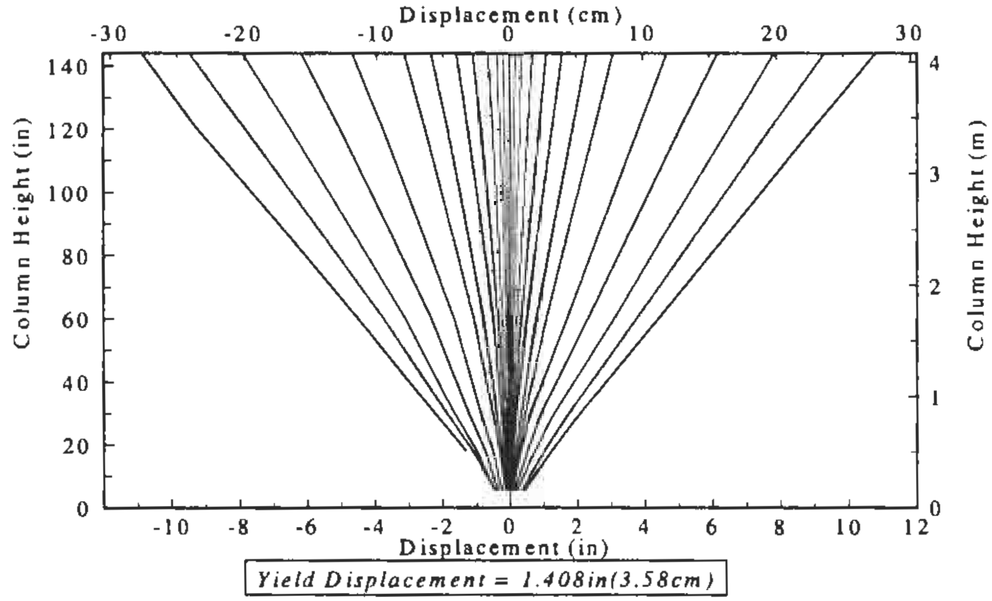

Figure F.9: Maximum Column Profile for Each Cycle for Lap Splice Enhancement Circular Column CF-4

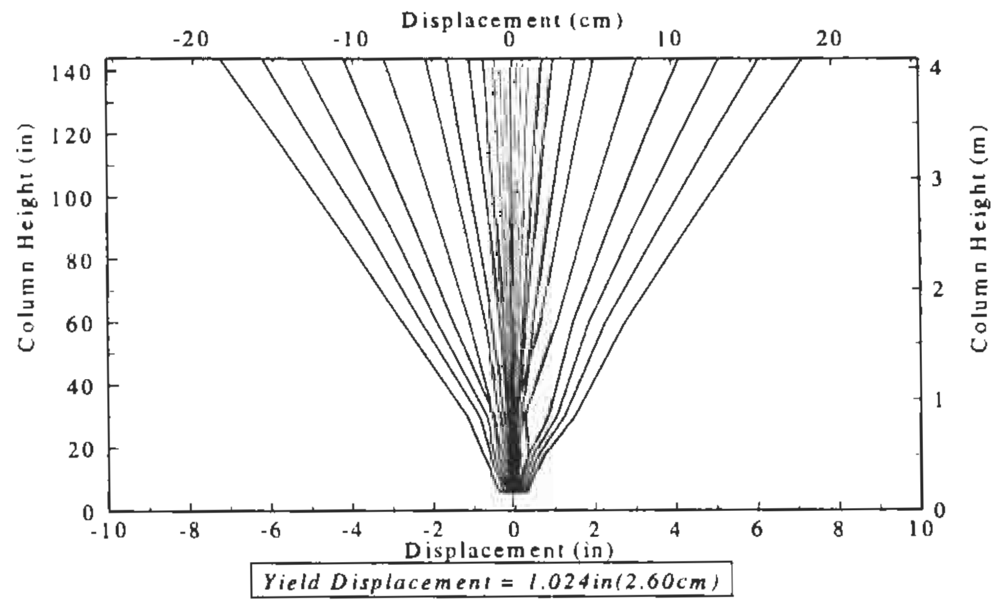

Figure F.10: Maximum Column Profile for Each Cycle for Lap Splice Enhancement Circular Column CF-5

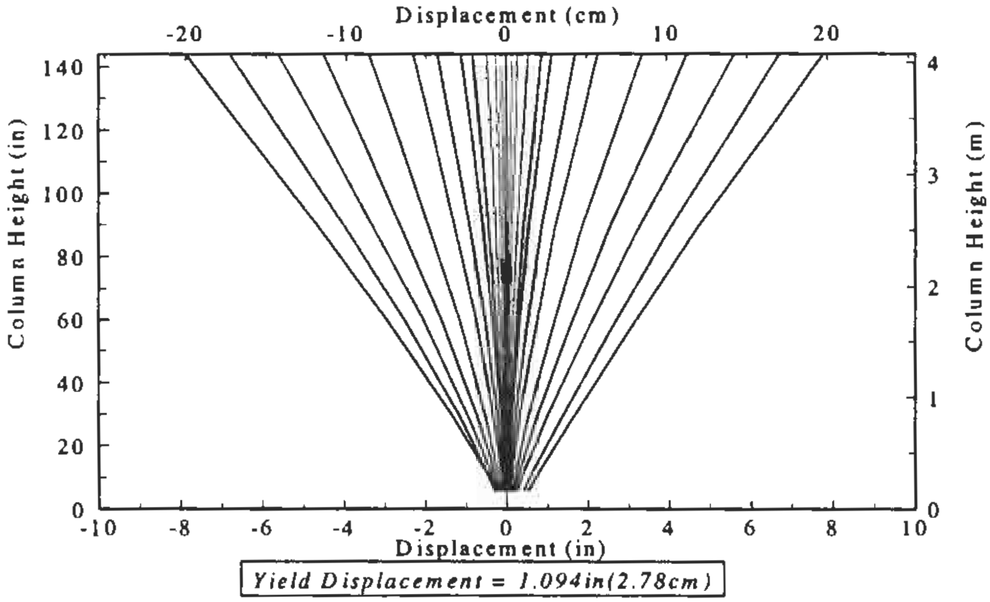

Figure F.11: Maximum Column Profile for Each Cycle for Lap Splice Enhancement Circular Column CF-6

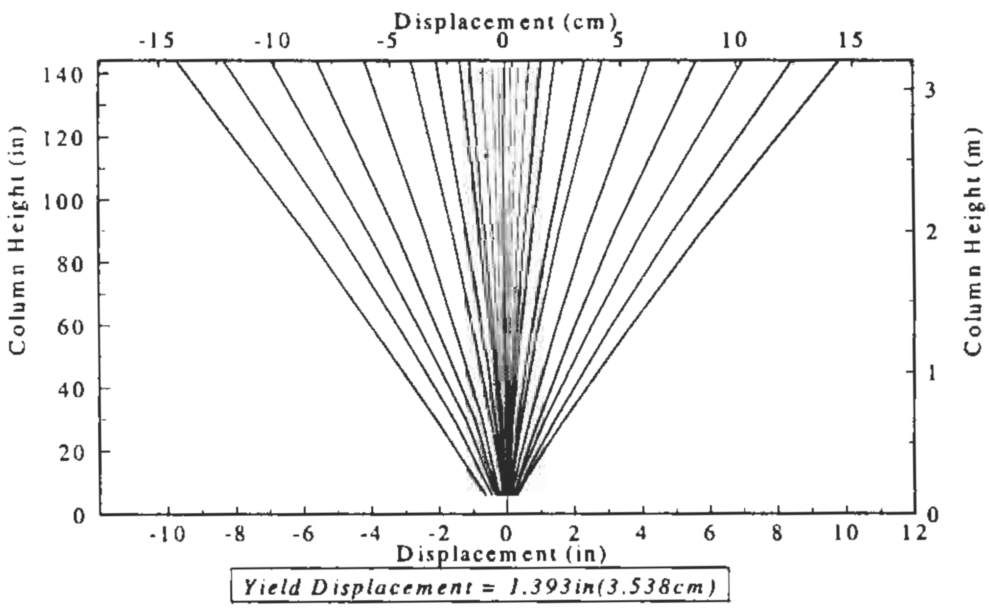

Figure F.12: Maximum Column Profile for Each Cycle for Lap Splice Enhancement Circular Column CF-7

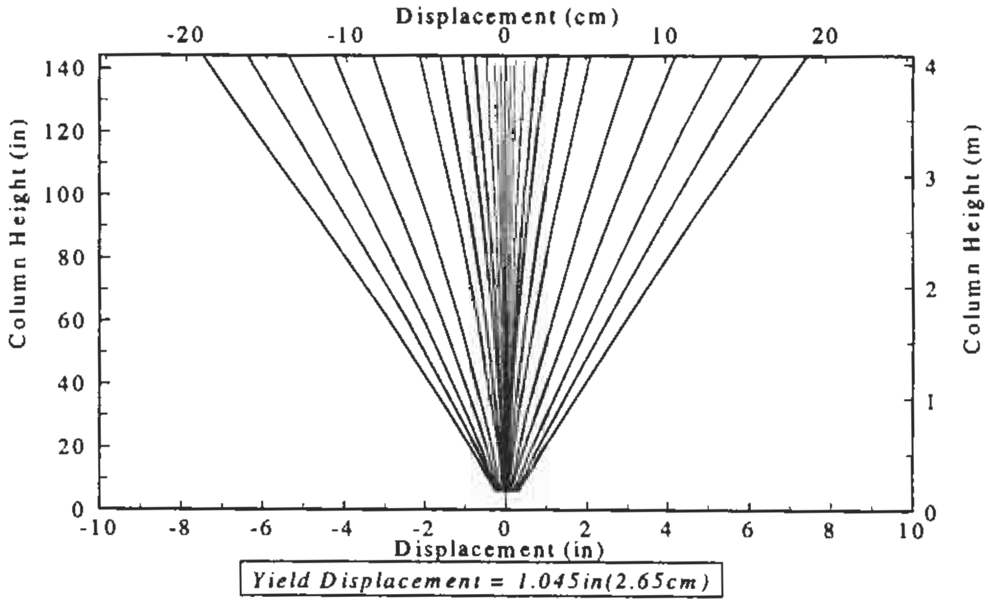

Figure F.13: Maximum Column Profile for Each Cycle for Lap Splice Enhancement Circular Column CF-8

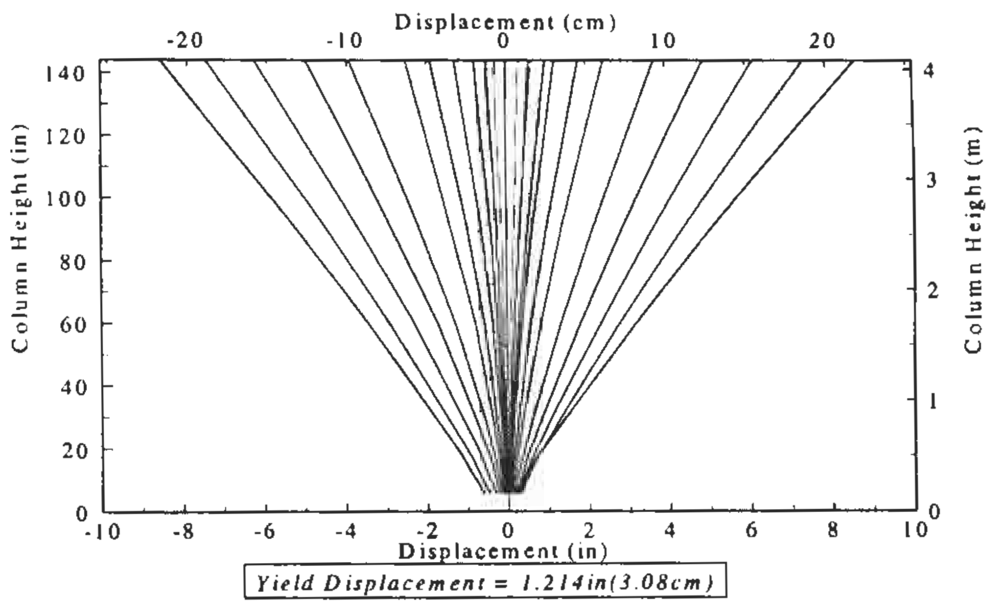

Figure F.14: Maximum Column Profile for Each Cycle for Lap Splice Enhancement Circular Column CF-9

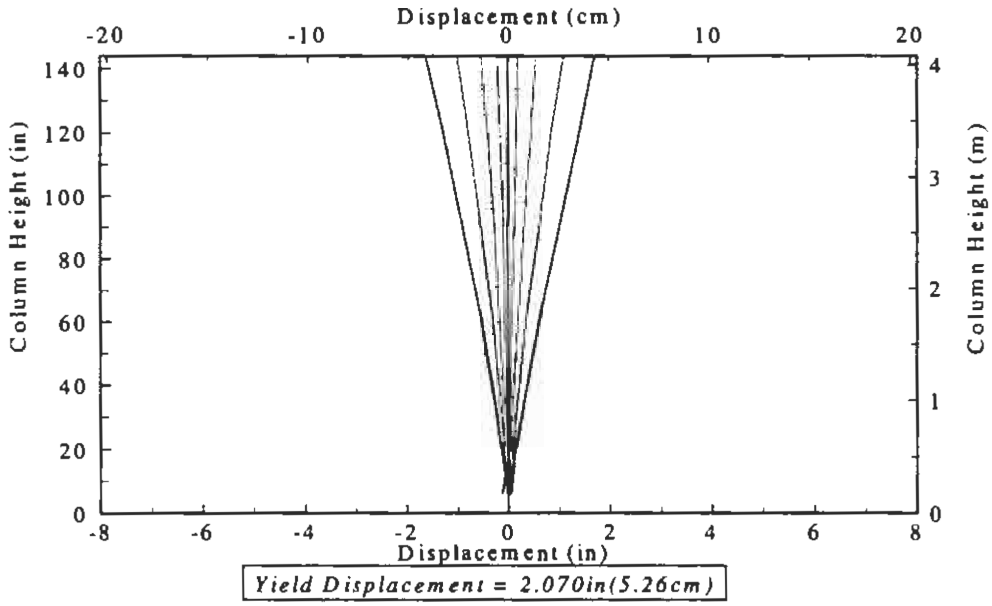

Figure F.15: Maximum Column Profile for Each Cycle for As-built Lap Splice Enhancement Rectangular Column RF-1

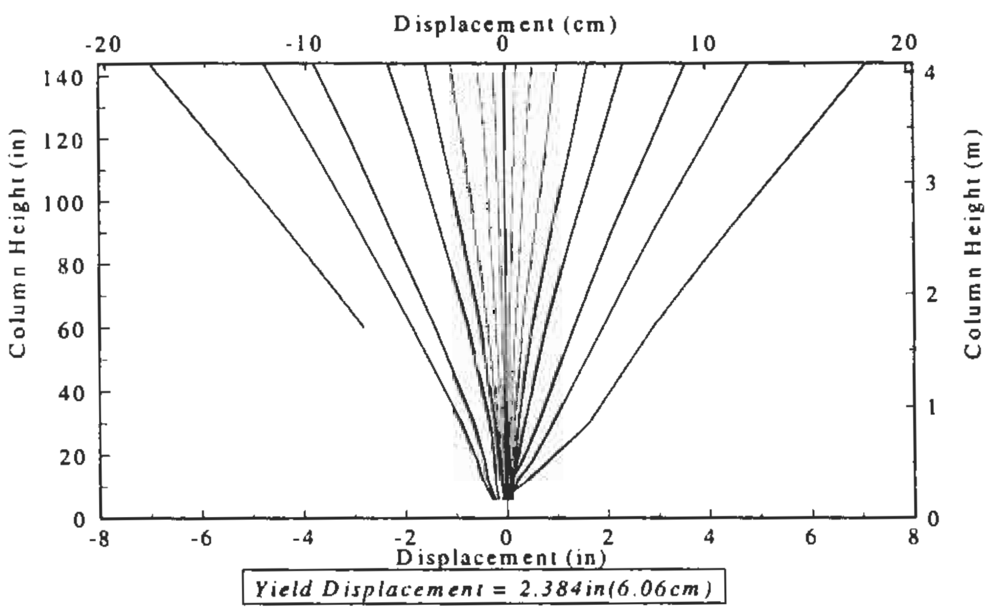

Figure F.16: Maximum Column Profile for Each Cycle for Lap Splice Enhancement Rectangular Column RF-2

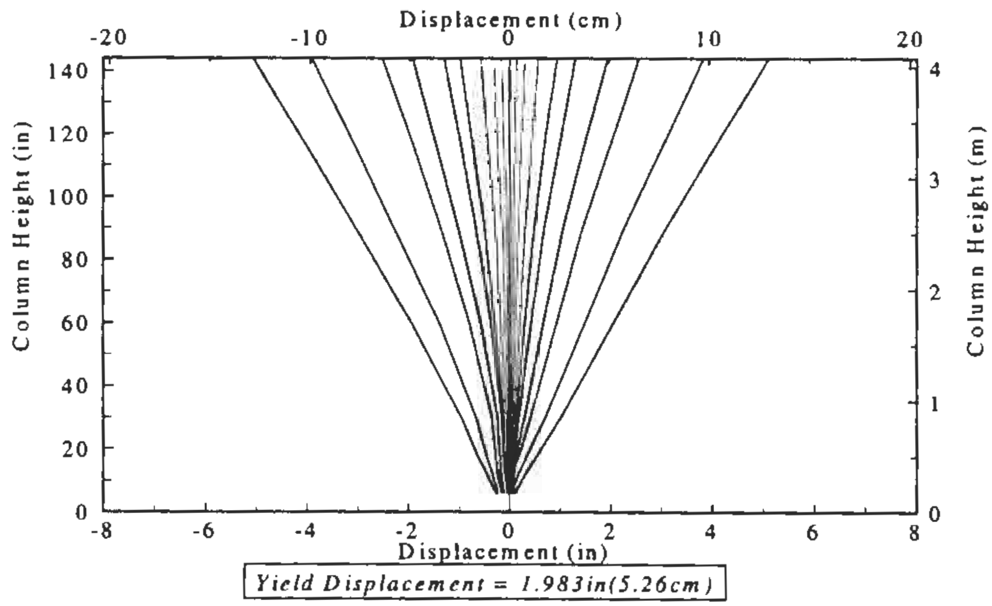

Figure F.17: Maximum Column Profile for Each Cycle for Lap Splice Enhancement Rectangular Column RF-3

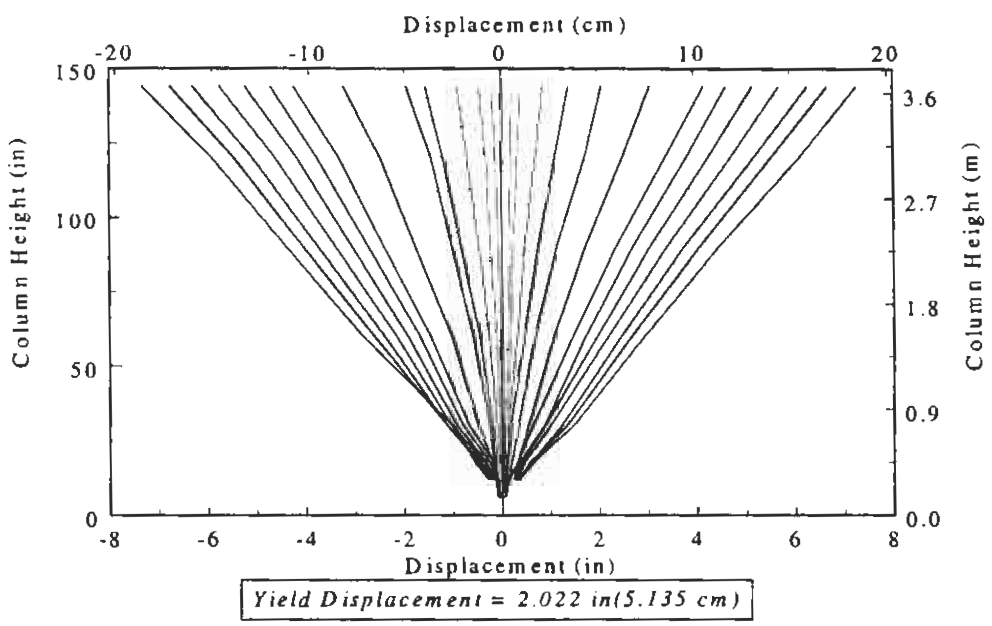

Figure F.18: Maximum Column Profile for Each Cycle for Lap Splice Enhancement Rectangular Column RF-5

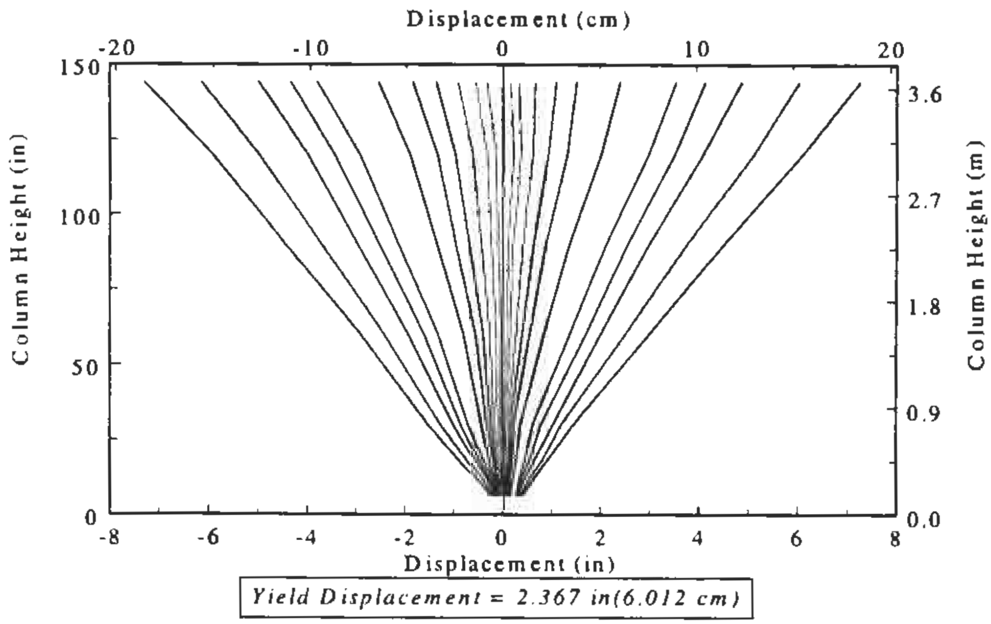

Figure F.19: Maximum Column Profile for Each Cycle for Lap Splice Enhancement Rectangular Column RF-6

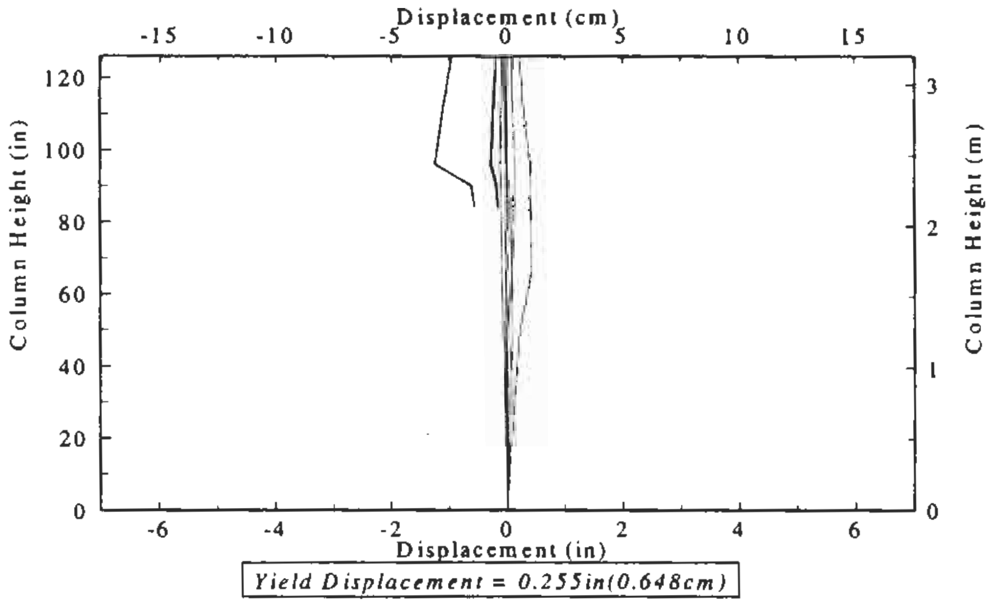

Figure F.20: Maximum Column Profile for Each Cycle for As-built Shear Enhancement Rectangular Column RS-1

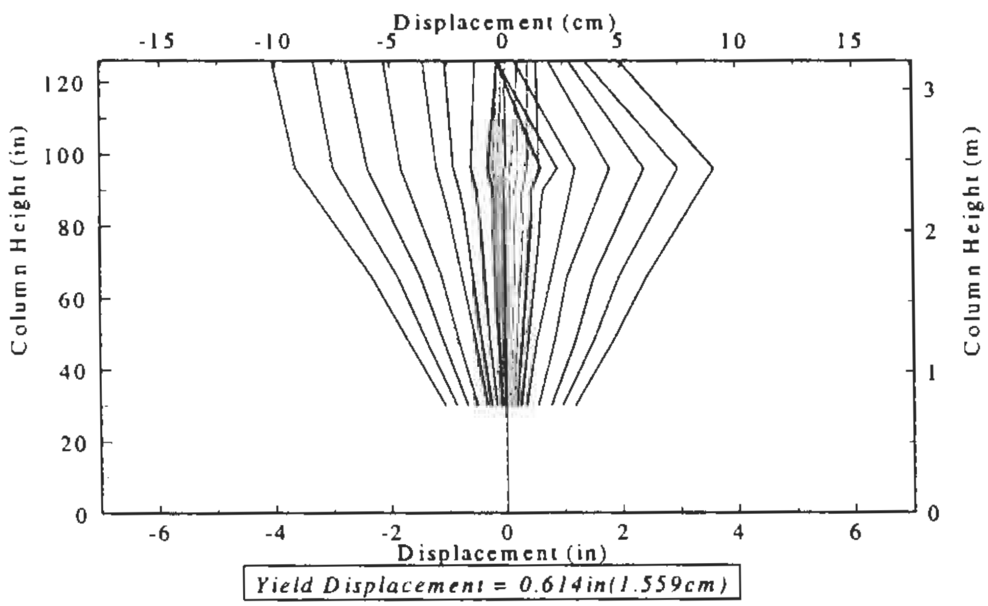

Figure F.21: Maximum Column Profile for Each Cycle for Shear Enhancement Rectangular Column RS-2

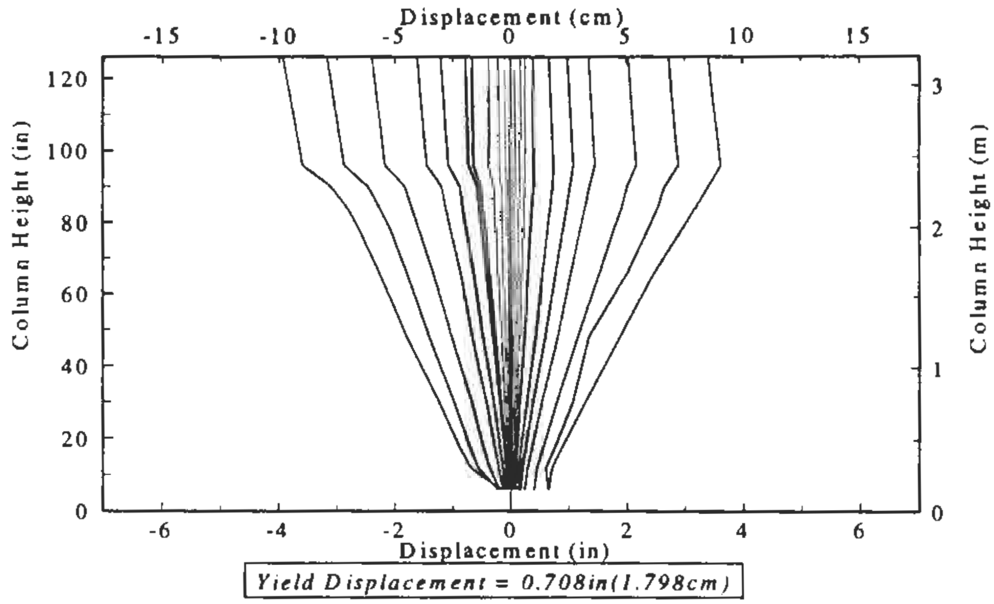

Figure F.22: Maximum Column Profile for Each Cycle for Shear Enhancement Rectangular Column RS-3

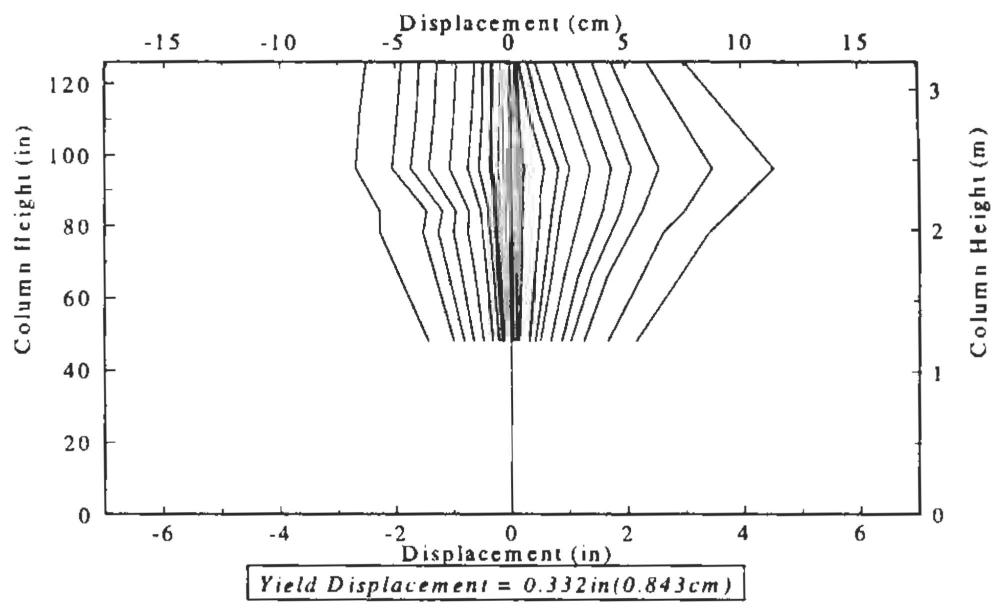

Figure F.23: Maximum Column Profile for Each Cycle for Shear Enhancement Rectangular Column RS-4

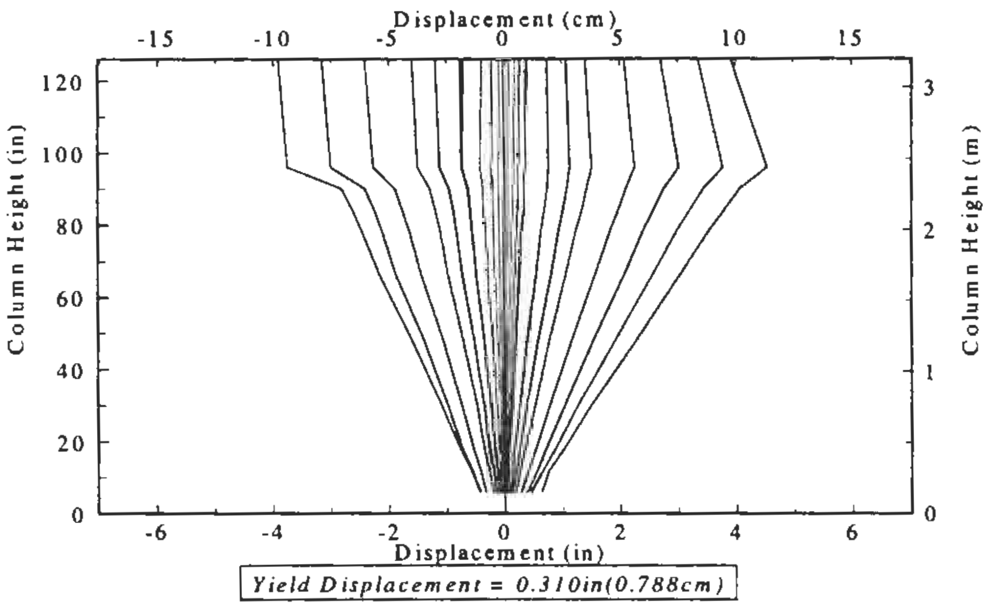

Figure F.24: Maximum Column Profile for Each Cycle for Shear Enhancement Rectangular Column RS-5

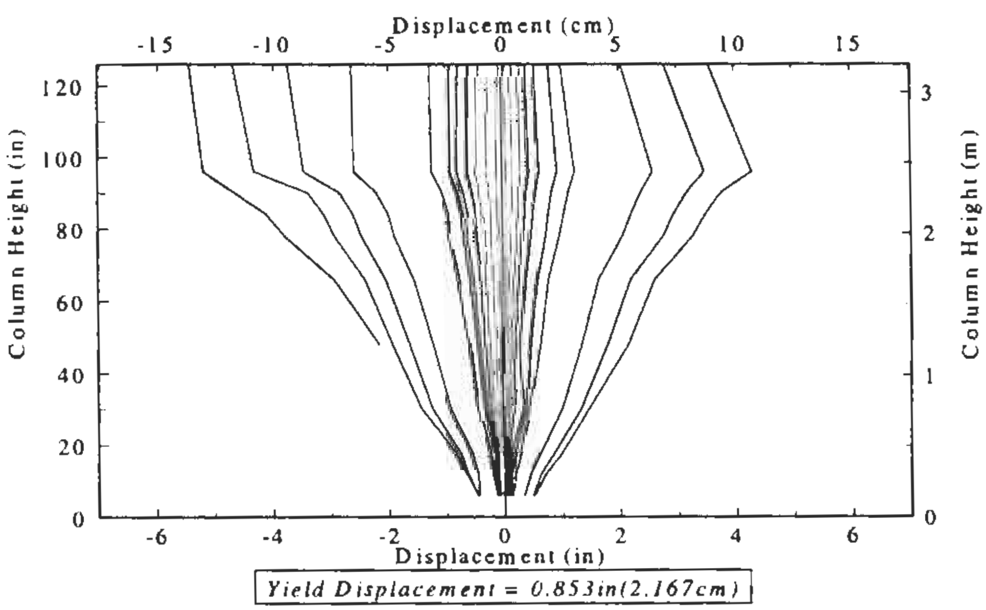

Figure F.25: Maximum Column Profile for Each Cycle for Shear Enhancement Rectangular Column RS-6

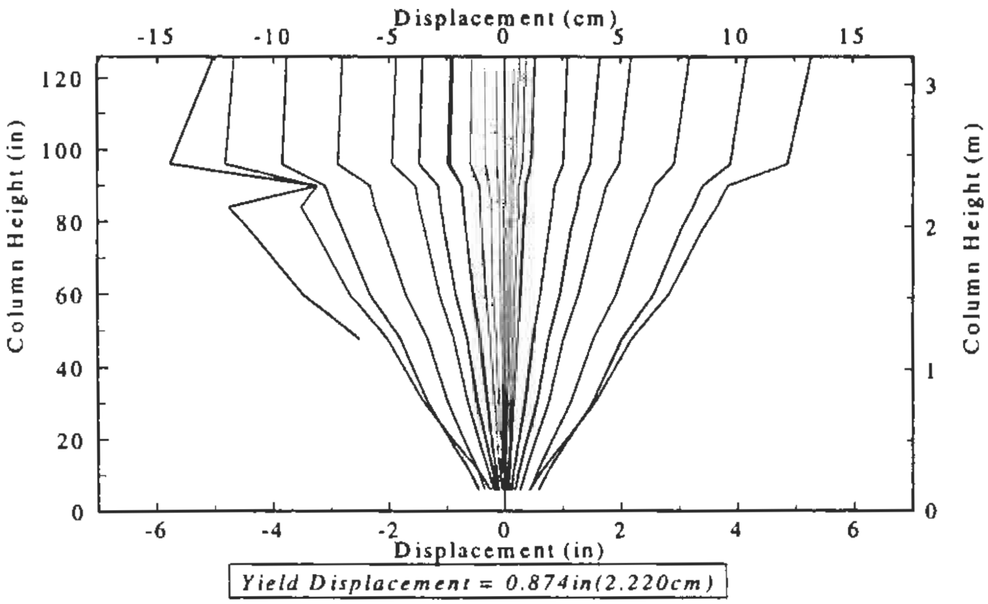

Figure F.26: Maximum Column Profile for Each Cycle for Shear Enhancement Rectangular Column RS-7

Appendix G

LOAD-DISPLACEMENT PLOTS

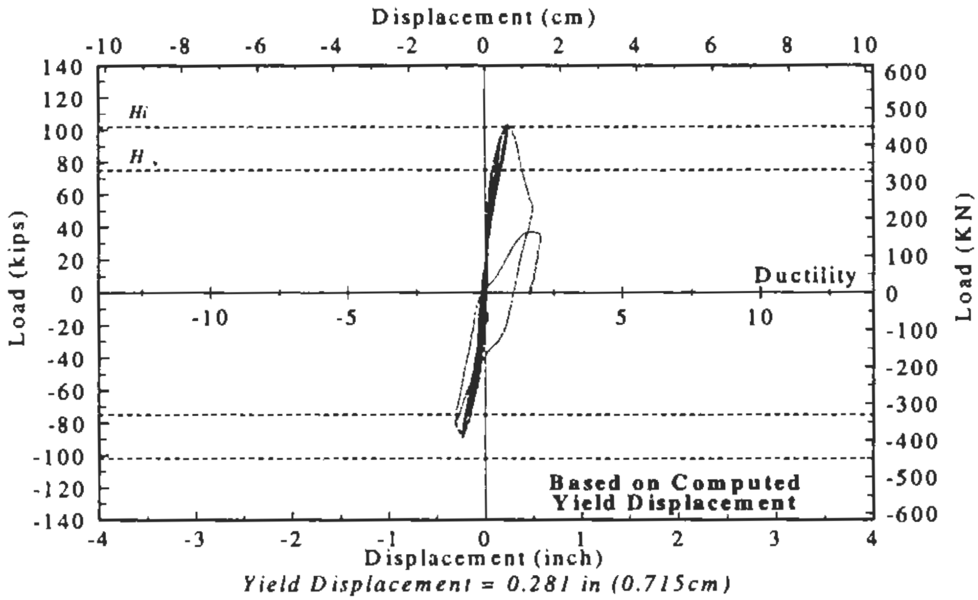

Figure G.1: Hysteresis for As-built Shear Enhancement Circular Column CS-1

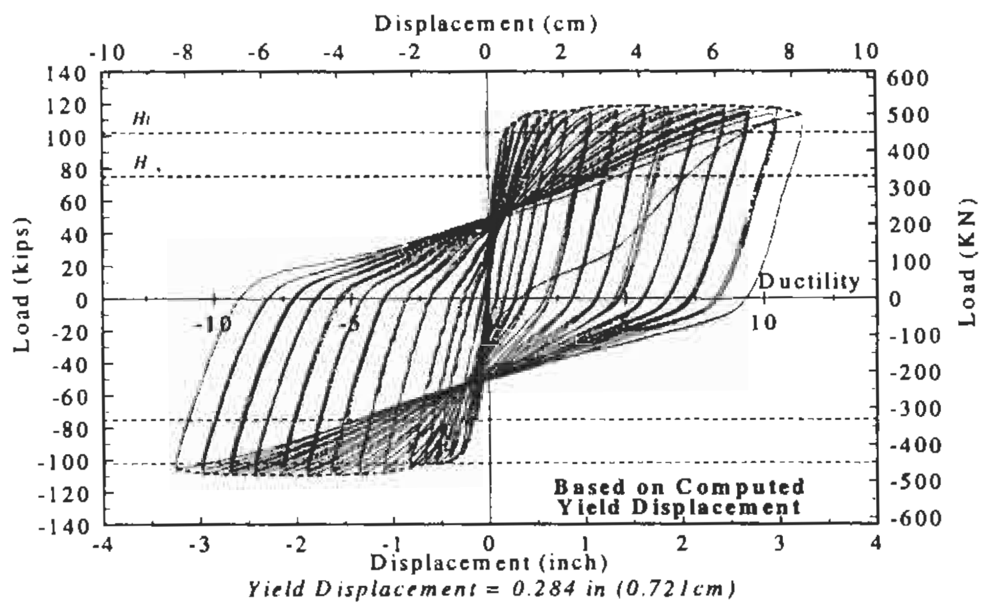

Figure G.2: Hysteresis for Shear Enhancement Circular Column CS-2

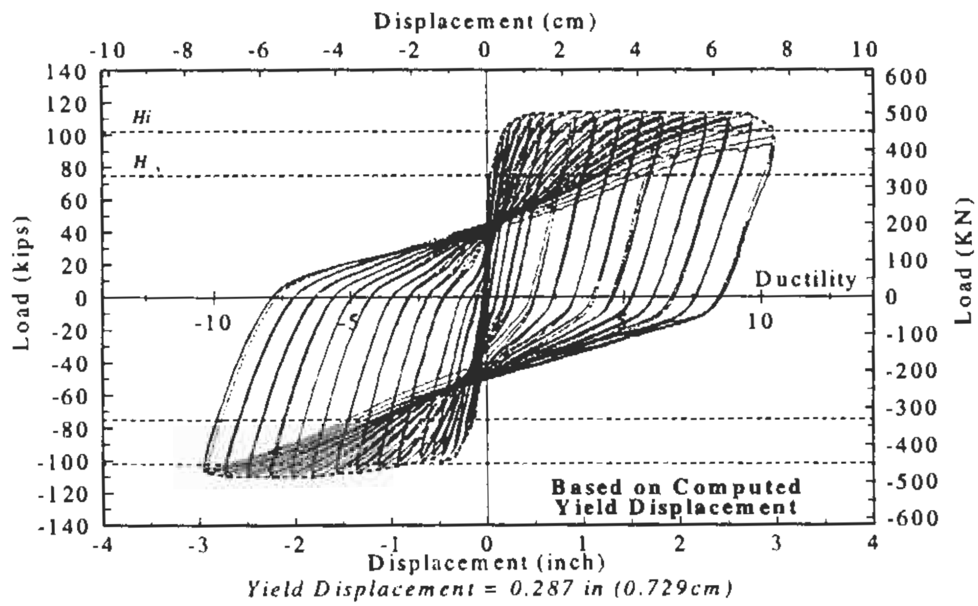

Figure G.3: Hysteresis for Shear Enhancement Circular Column CS-3

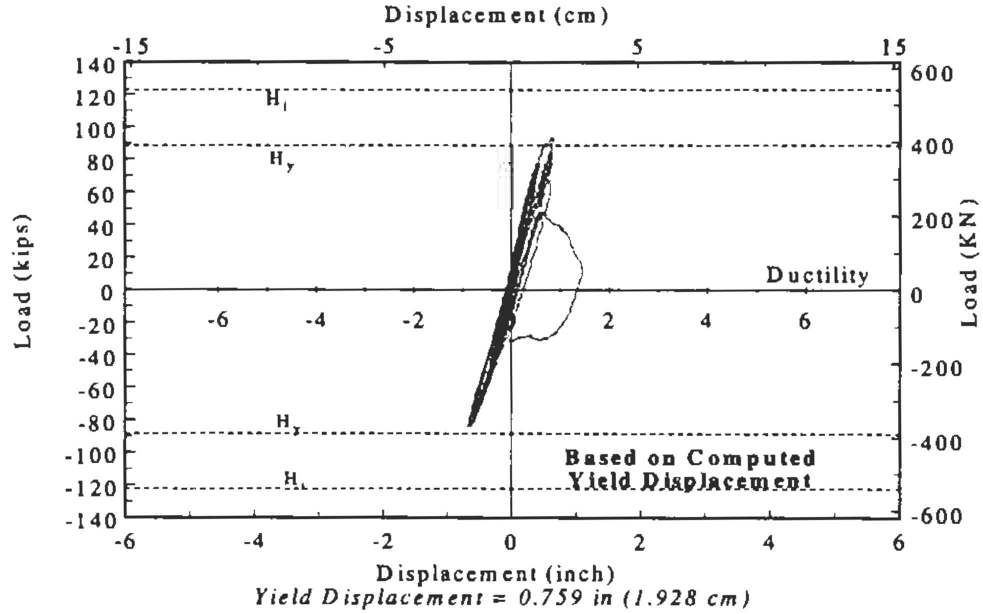

Figure G.4: Hysteresis for As-built Shear Enhancement Circular Column CS-4

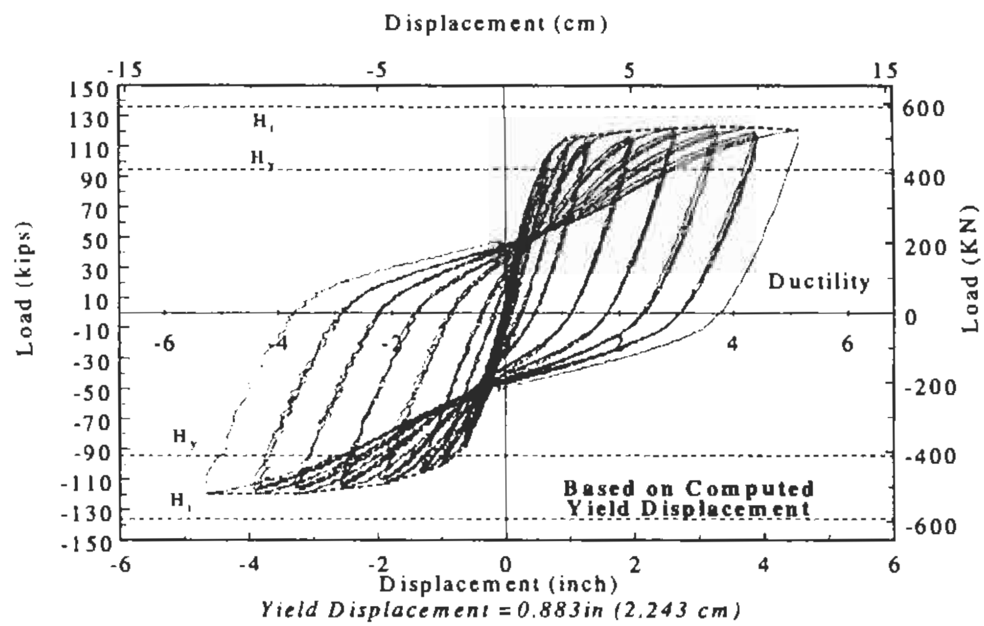

Figure G.5: Hysteresis for Shear Enhancement Circular Column CS-5

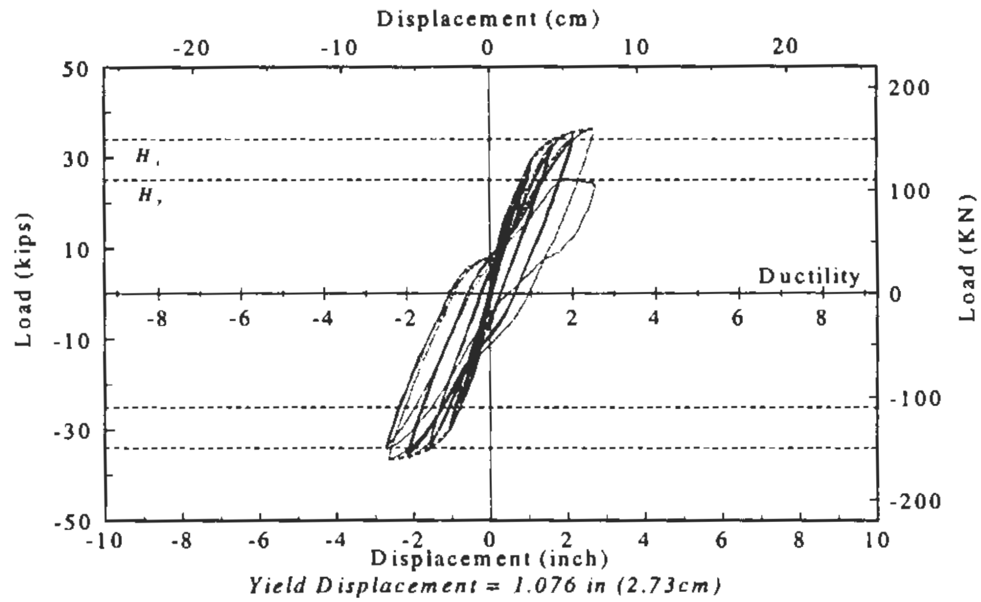

Figure G.6: Hysteresis for As-built Lap Splice Enhancement Circular Column CF-1

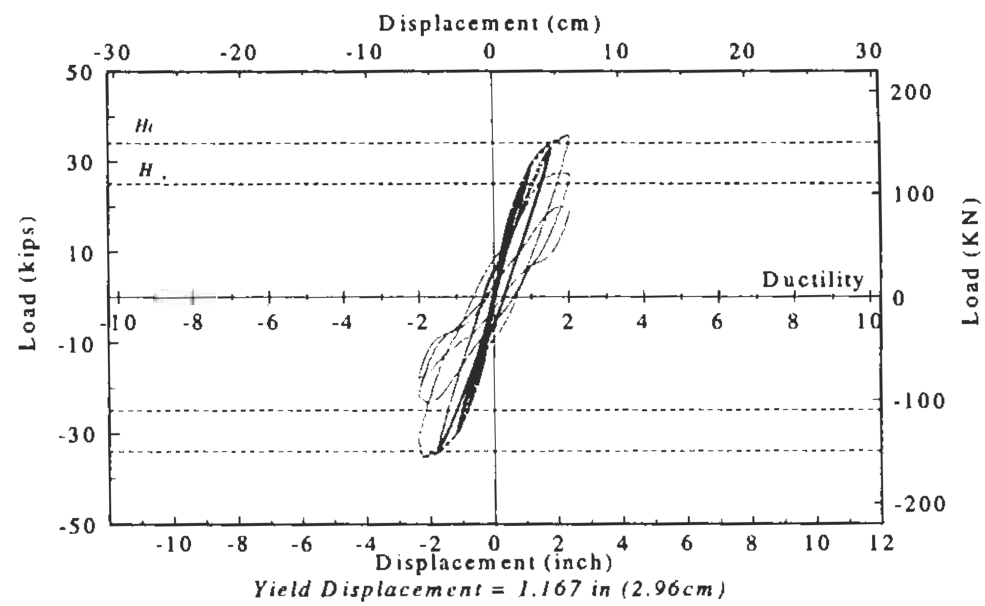

Figure G.7: Hysteresis for As-built Lap Splice Enhancement Circular Column CF-2

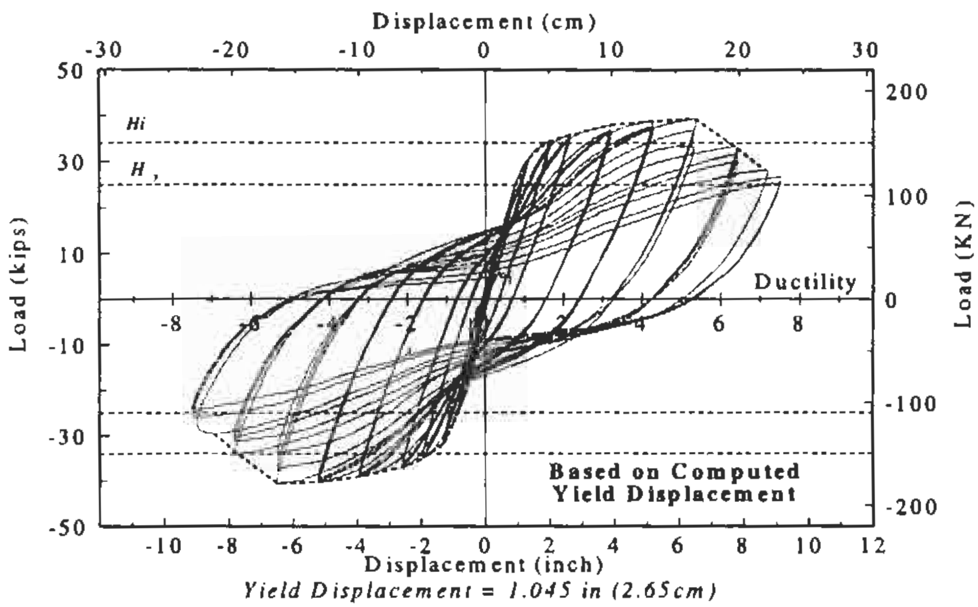

Figure G.8: Hysteresis for Lap Splice Enhancement Circular Column CF-3

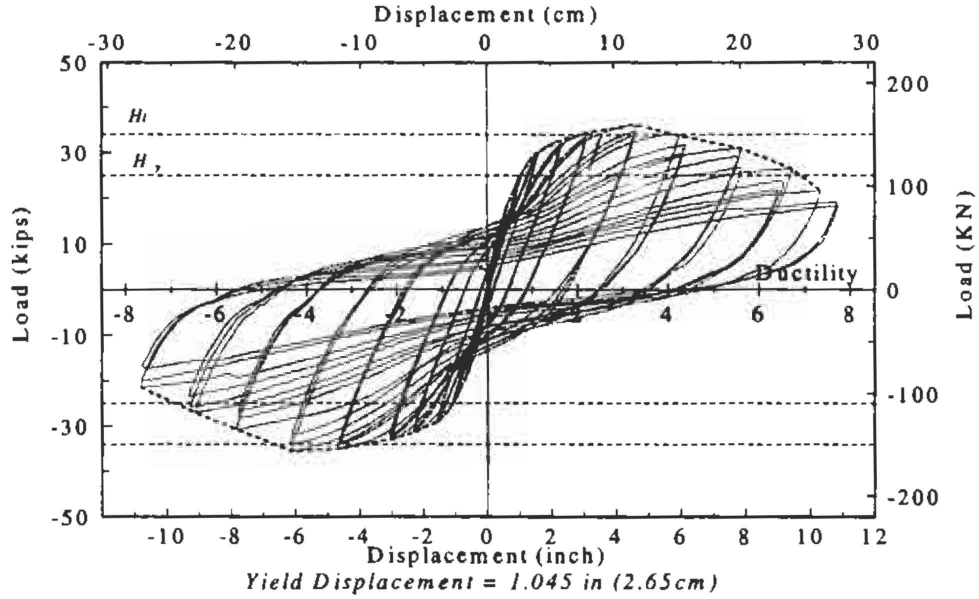

Figure G.9: Hysteresis for Lap Splice Enhancement Circular Column CF-4

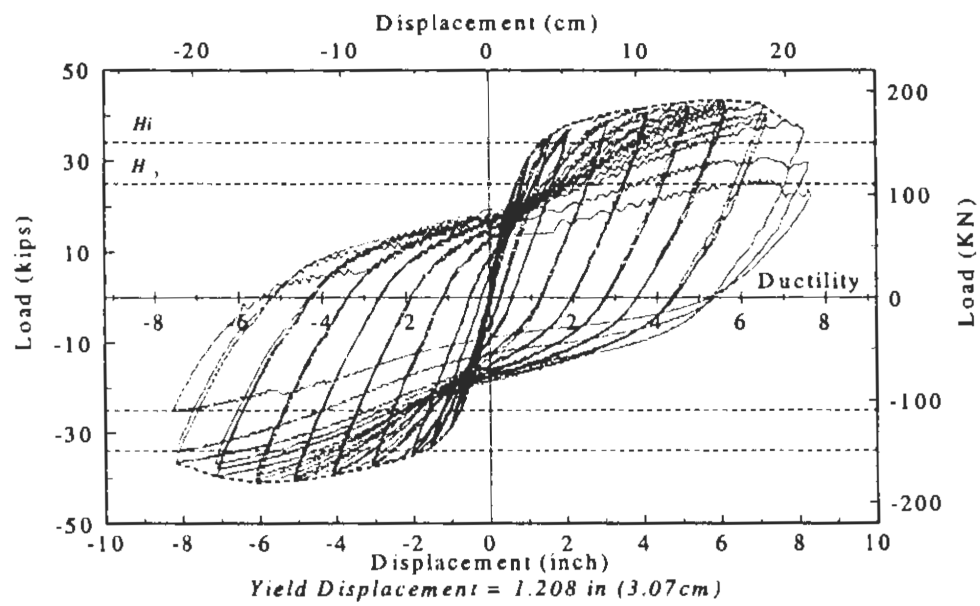

Figure G.10: Hysteresis for Lap Splice Enhancement Circular Column CF-5

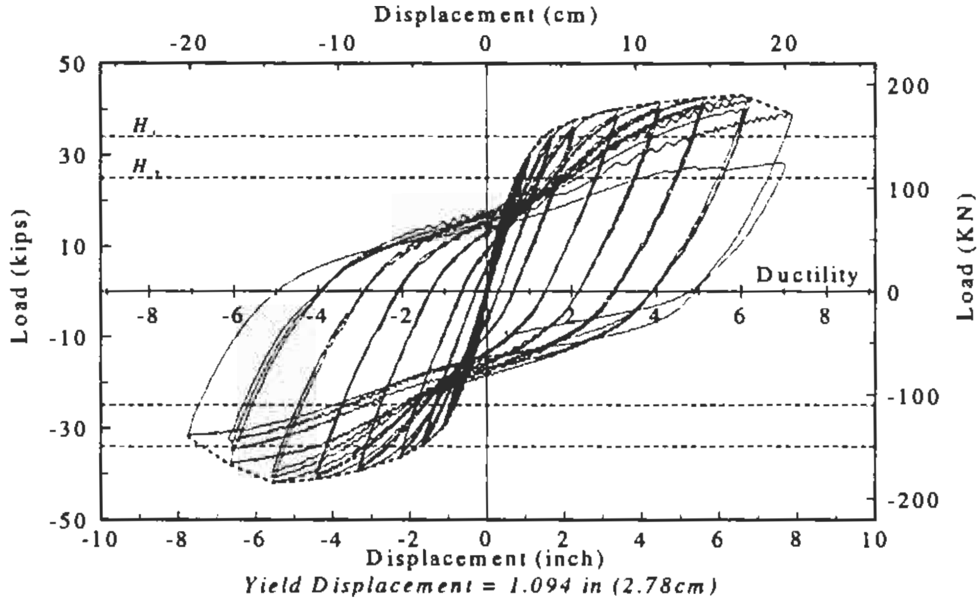

Figure G.11: Hysteresis for Lap Splice Enhancement Circular Column CF-6

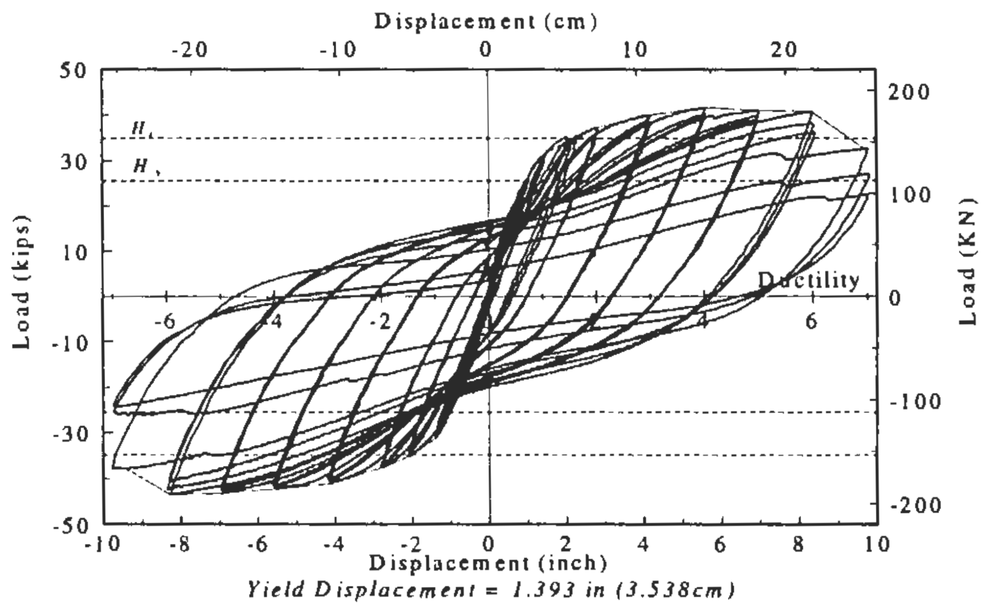

Figure G.12: Hysteresis for Lap Splice Enhancement Circular Column CF-7

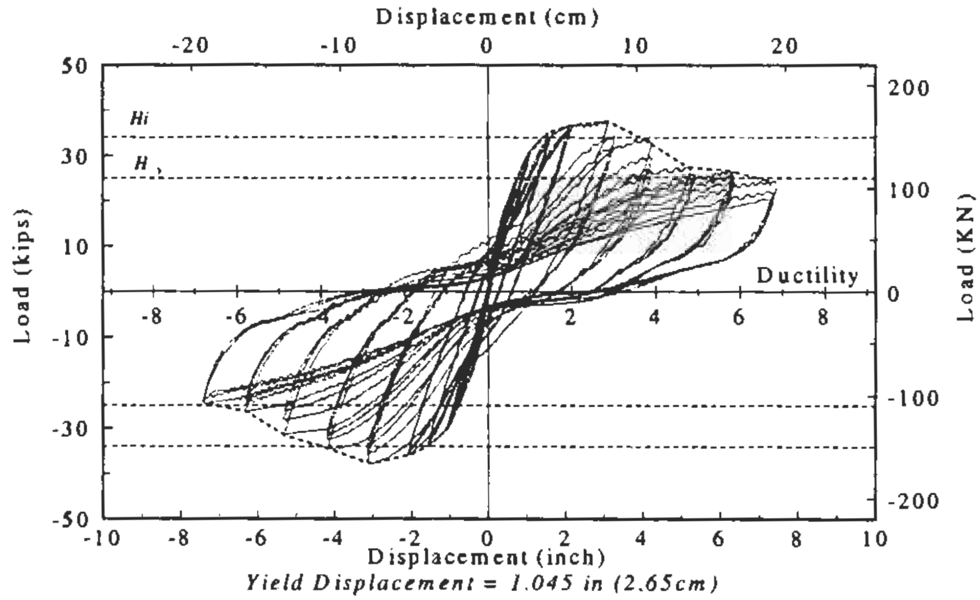

Figure G.13: Hysteresis for Lap Splice Enhancement Circular Column CF-8

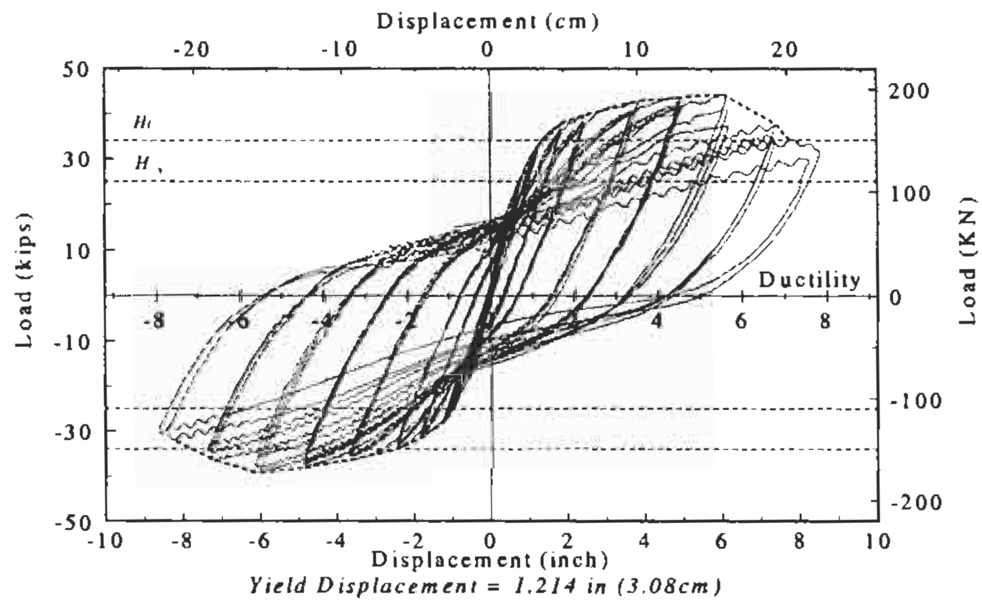

Figure G.14: Hysteresis for Lap Splice Enhancement Circular Column CF-9

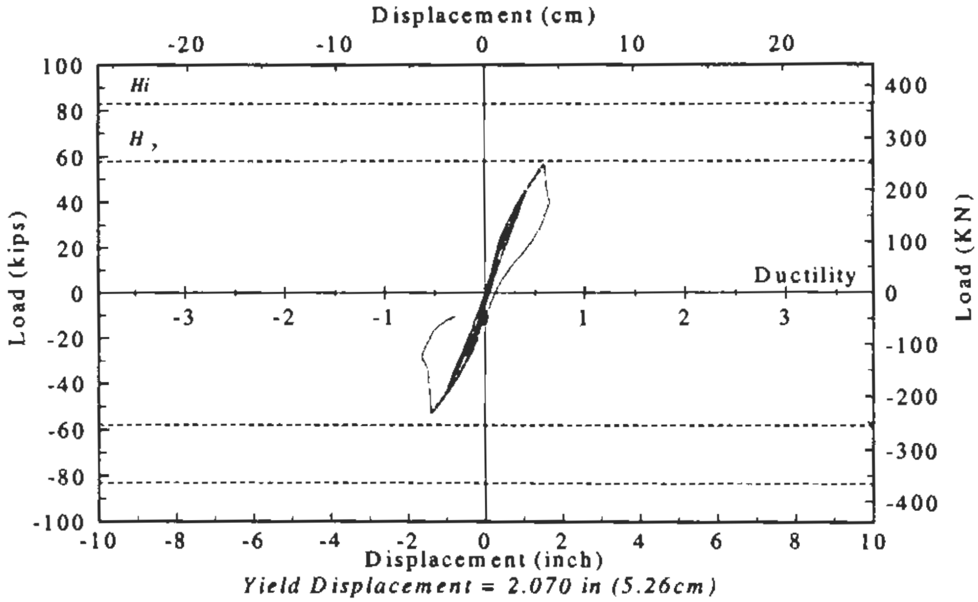

Figure G.15: Hysteresis for As-built Lap Splice Enhancement Rectangular Column RF-1

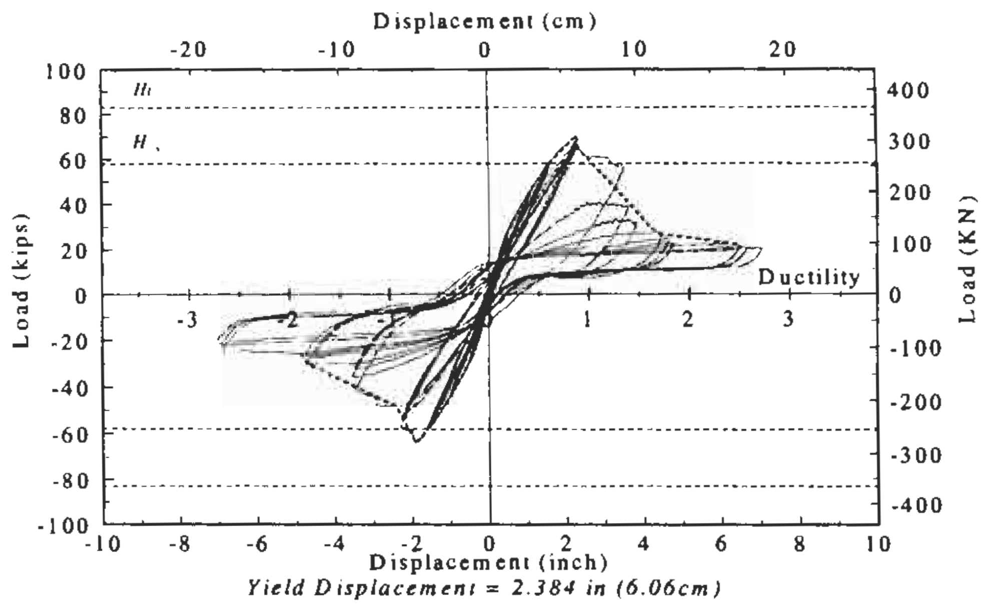

Figure G.16: Hysteresis for Lap Splice Enhancement Rectangular Column RF-2

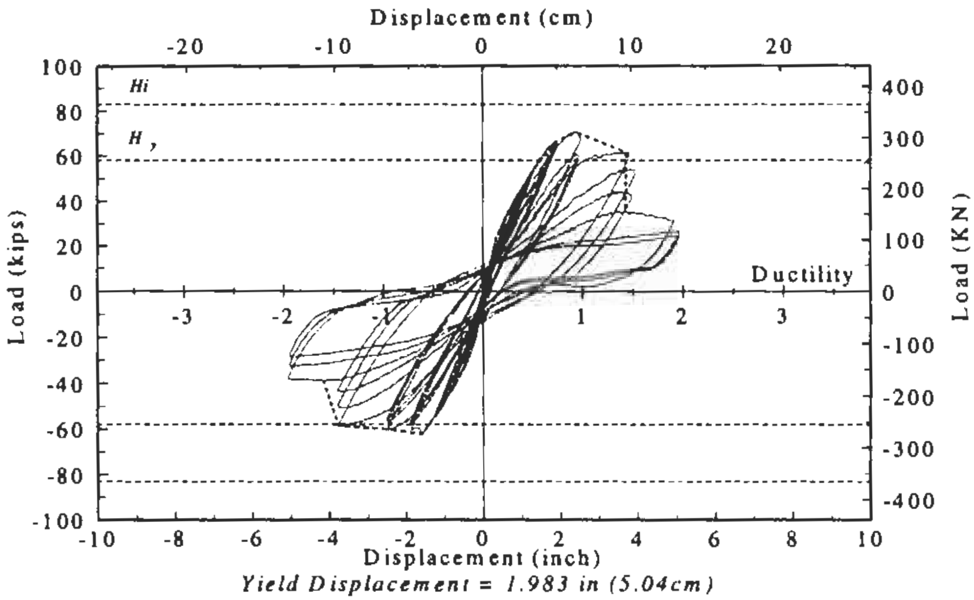

Figure G.17: Hysteresis for Lap Splice Enhancement Rectangular Column RF-3

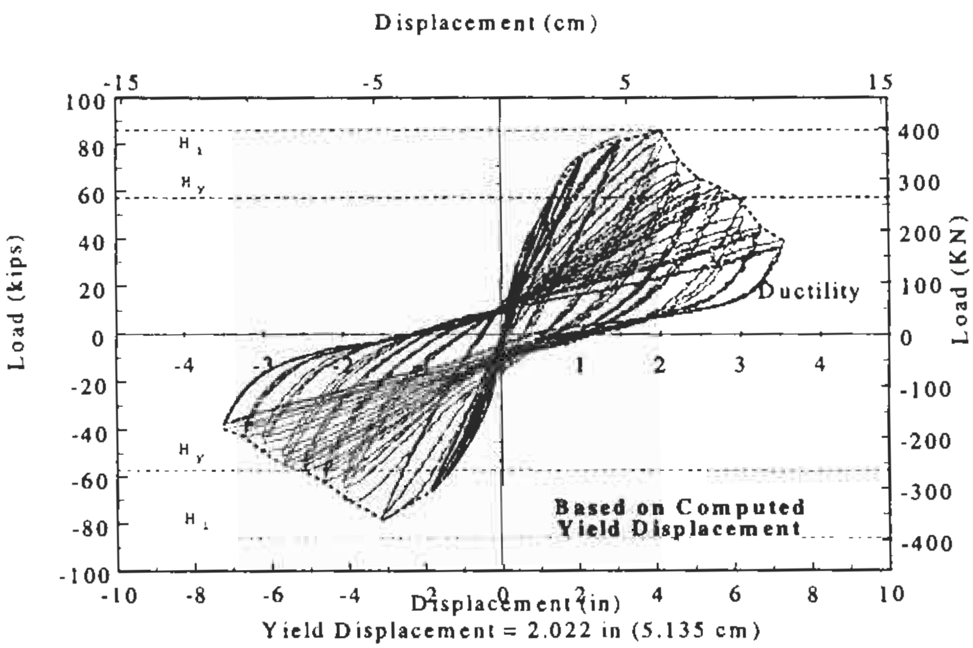

Figure G.18: Hysteresis for Lap Splice Enhancement Rectangular Column RF-5

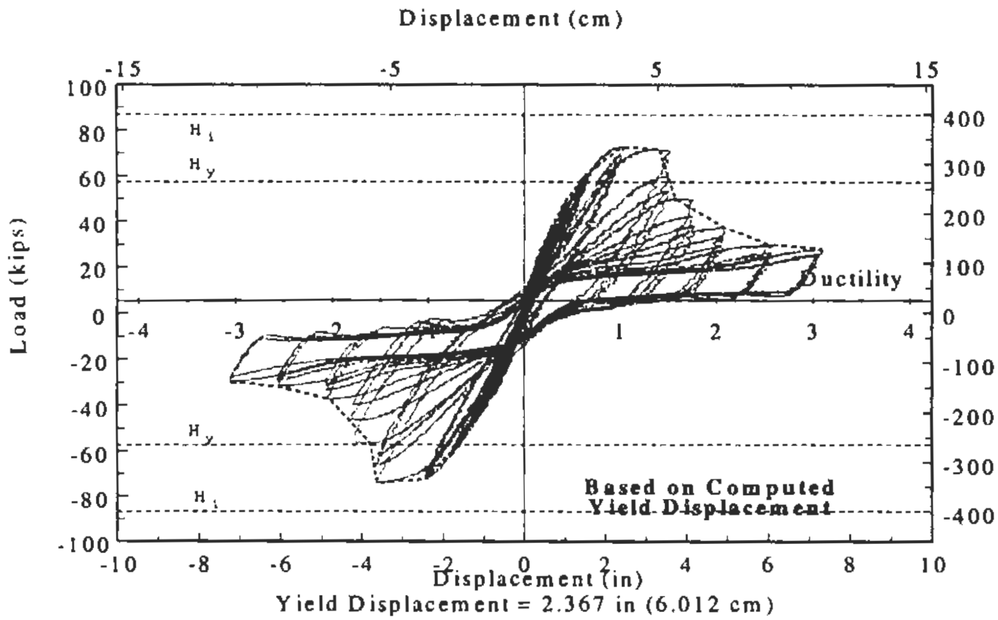

Figure G.19: Hysteresis for Lap Splice Enhancement Rectangular Column RF-6

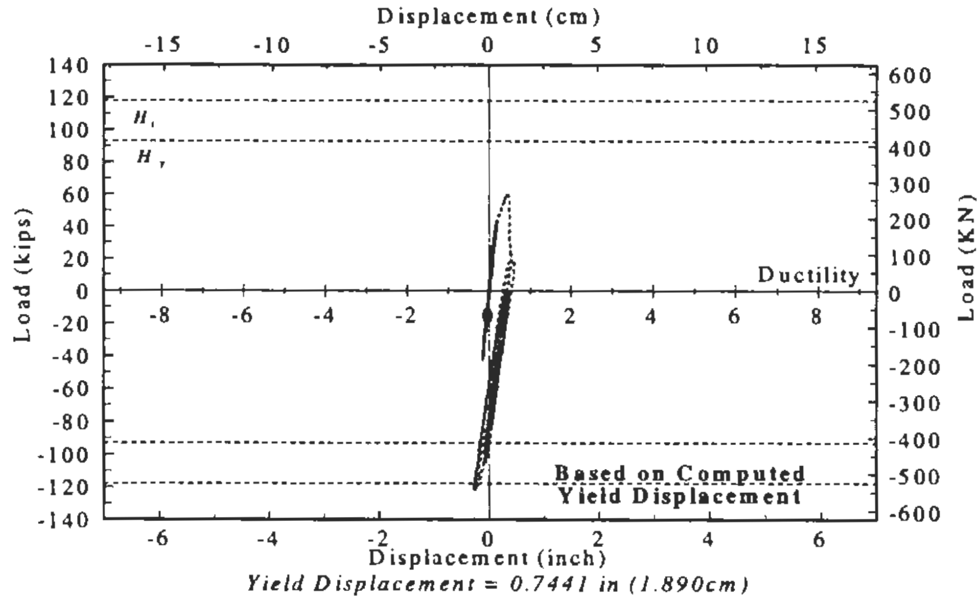

Figure G.20: Hysteresis for As-built Shear Enhancement Rectangular Column RS-1

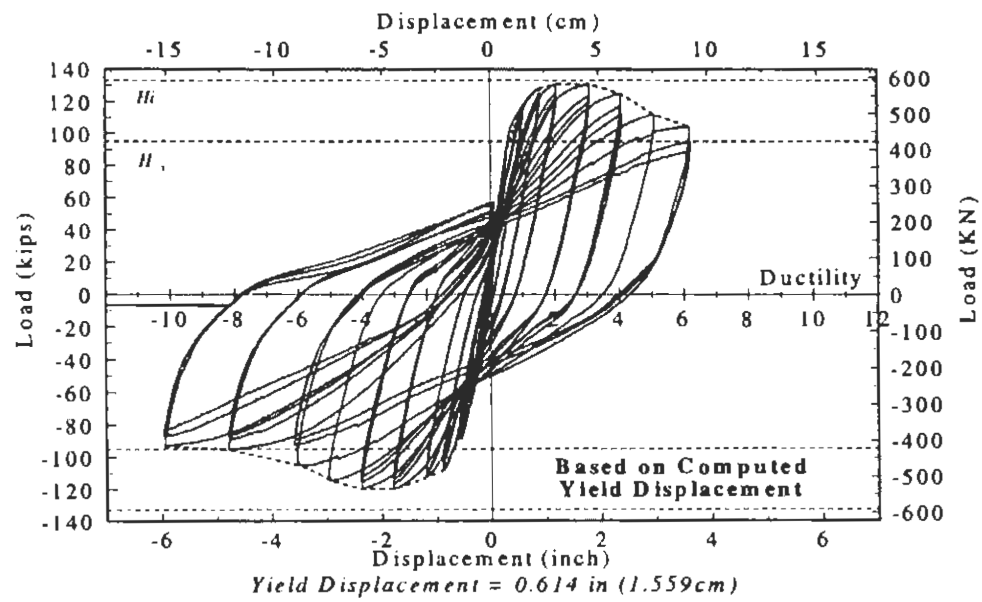

Figure G.21: Hysteresis for Shear Enhancement Rectangular Column RS-2

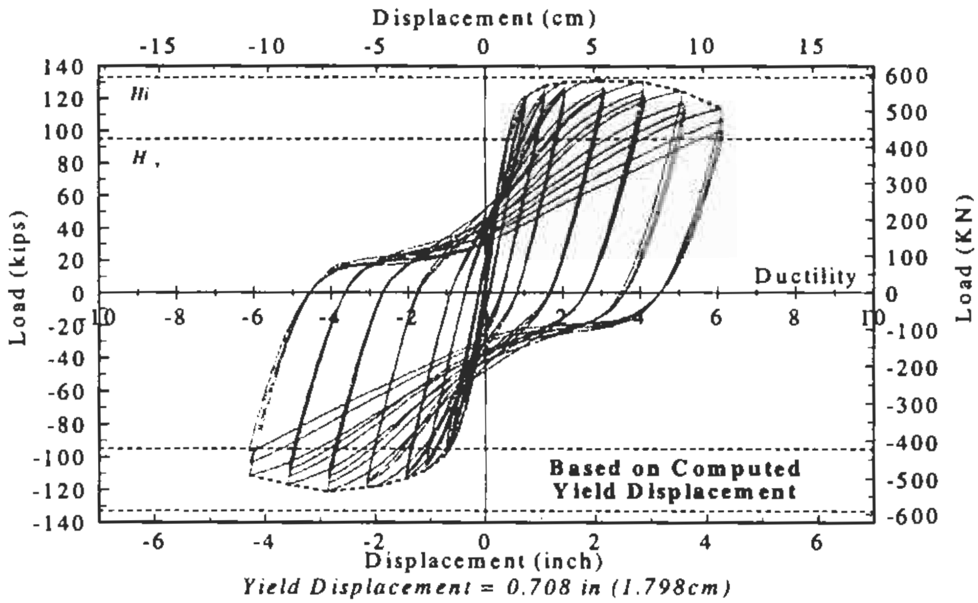

Figure G.22: Hysteresis for Shear Enhancement Rectangular Column RS-3

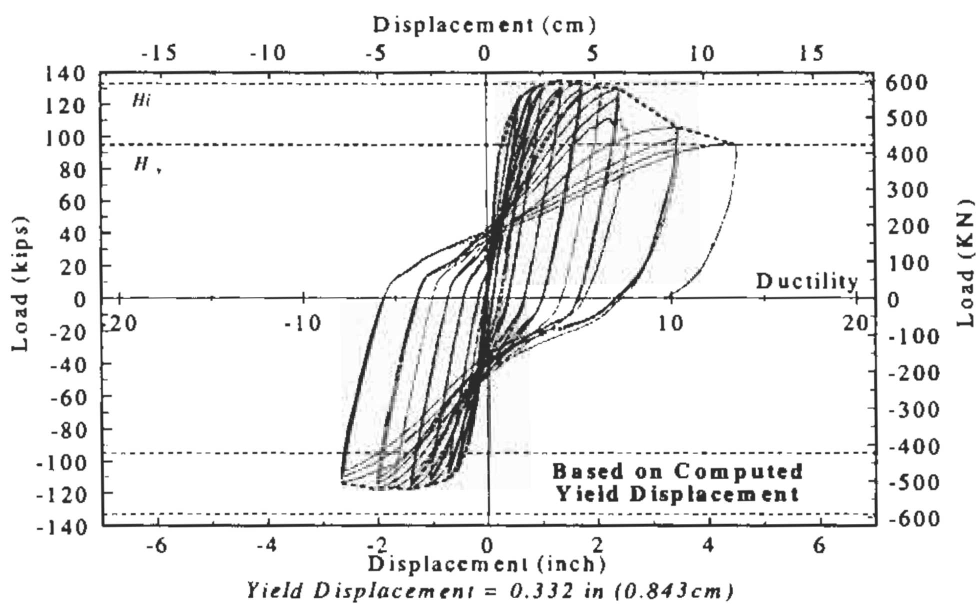

Figure G.23: Hysteresis for Shear Enhancement Rectangular Column RS-4

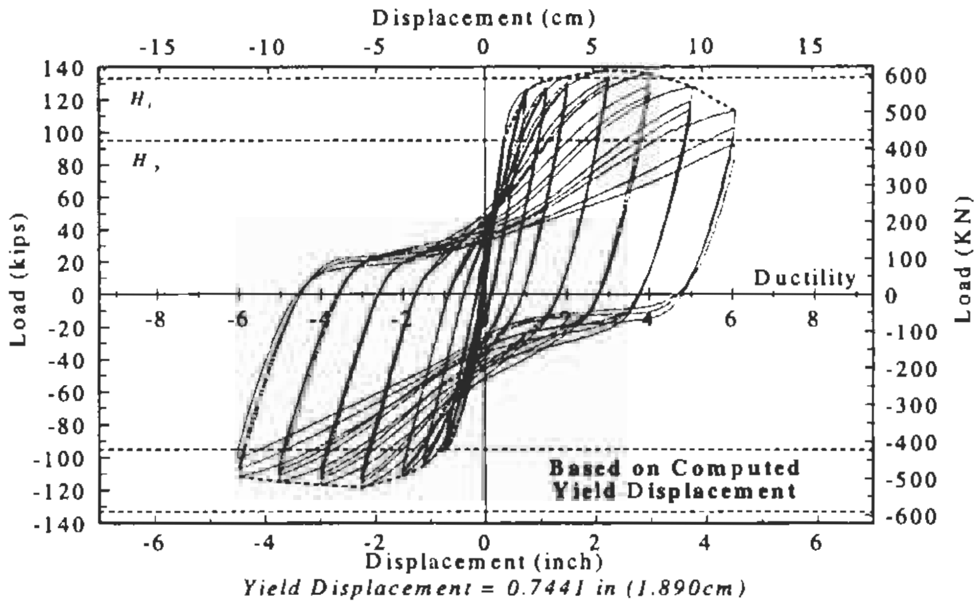

Figure G.24: Hysteresis for Shear Enhancement Rectangular Column RS-5

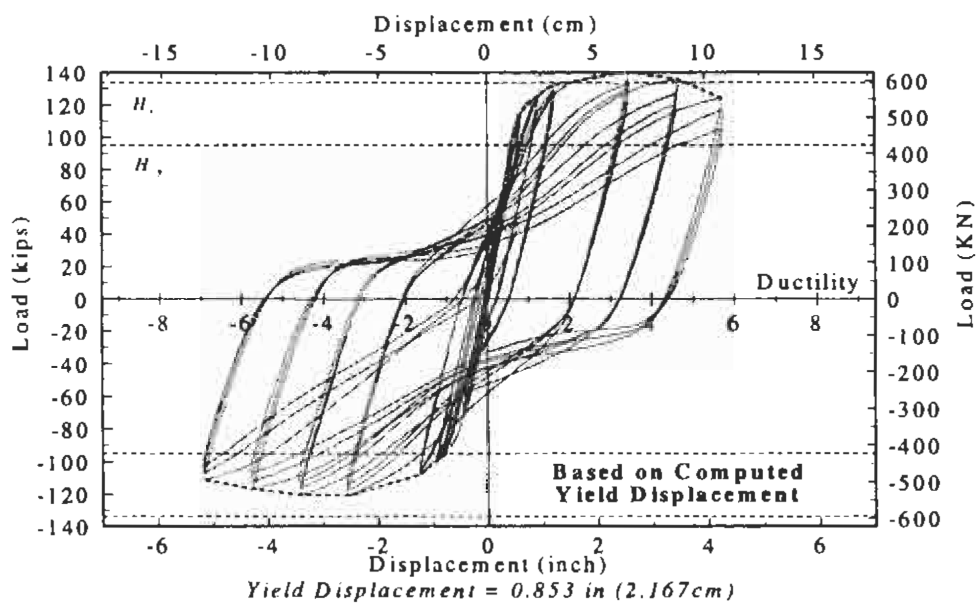

Figure G.25: Hysteresis for Shear Enhancement Rectangular Column RS-6

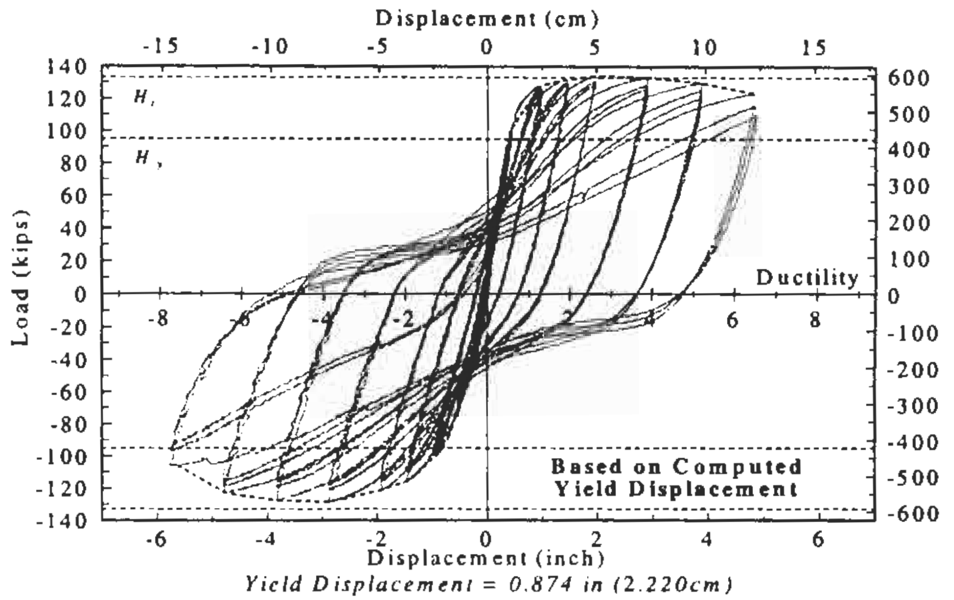

Figure G.26: Hysteresis for Shear Enhancement Rectangular Column RS-7