Fiber-Reinforced Plastic Jackets for Ductility Enhancement of Reinforced Concrete Bridge Columns with Poor Lap-Splice Detailing

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Abstract: This paper presents an inclusive testing program conducted on scaled models of reinforced concrete (RC) bridge columns with insufficient lap-splice length. Thirteen half-scale circular and square column samples were tested in flexure under lateral cyclic loading. Three columns were tested in the as-built configuration whereas ten samples were tested after being retrofitted with different composite-jacket systems. A brittle failure was observed in the as-built samples due to bond deterioration of the lap-spliced longitudinal reinforcement. The jacketed circular columns demonstrated a significant improvement in their cyclic performance. Yet, tests conducted on square jacketed columns showed a limited improvement in clamping on the lap-splice region and for enhancing the ductility of the column.

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Introduction

Some existing bridge columns in California feature lap splices in the column reinforcement, which for ease of construction, are located at the column base to form the connection between the column and the footing. Starter bars for the column reinforcement are placed during the footing construction and lapped with the longitudinal column reinforcement with a typical lap length of 20 bar diameters. In addition, the transverse column reinforcement was typically Grade 40 ϕ13 mm bars spaced at 305 mm on centers, independent of column size, strength or deformation demands (Fig. 1). Where short lap splices are present and insufficient clamping action by transverse reinforcement is provided, lap-splice debonding occurs once vertical microcracks develop in the cover concrete and debonding gets progressively worse with increased vertical cracking and cover concrete spalling. As a consequence, the flexural strength of such columns degrades rapidly under lateral cyclic loading at low flexural ductilities. Fig. 2 shows damage to the base of a bridge column in the 1989 Loma Prieta earthquake, attributed to lap-splice bond failure.

In order to seismically upgrade bridge columns with insufficient lap-spliced reinforcement, various retrofitting measures have been developed by researchers and practicing engineers. At the University of California, San Diego, steel jacketing has been demonstrated to be an effective means to retrofit columns with insufficient lap-splice length (Chai et al. 1991). Even though steel jacketing has been widely used in practice in California and elsewhere, relatively higher costs are expected due to the complexity during installation. Moreover, the corrosion of the steel jacket will be a potential problem in the future. In addition, steel jackets increase the column stiffness by about 10–30%, which may alter the bridge dynamic characteristics.

Alternatively, advanced composite materials have been recently recognized and applied to seismic retrofit of bridge columns. The advantages of composite retrofit systems include: light weight, superior strength or stiffness-to-weight ratios, corrosion resistance, and in particular, the ease of installation. Accordingly, such materials are most suitable for retrofitting bridge columns. On the other hand, contrary to other retrofit techniques, composite-material jackets will not affect the lateral stiffness of the columns, and hence will not alter the bridge dynamic characteristics. The composite jacket retrofit technique is basically a passive system in which the jacket is not under any significant stress until an earthquake occurs (Priestley et al. 1996).

The behavior of circular composite-jacketed bridge columns with insufficient lap-splice length was investigated experimentally at the University of Southern California (Xiao and Ma 1997; Ma 1999). The retrofit system utilizes a series of prefabricated

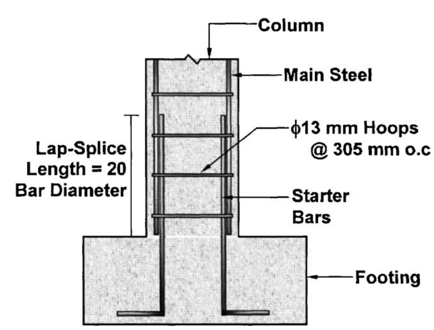

Fig. 1. Lap-splice details in older bridge columns

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Fig. 2. Brittle bond failure of lap splices at column base, 1989 Loma Prieta earthquake

E-glass fiber-reinforced composite cylindrical shells with slits. When a column is retrofitted, the shells are opened and clamped around the column in sequences and then glued together with urethane adhesive to form a continuous jacket. This system was used to retrofit circular half-scale bridge columns with insufficient lap-splice length at the base, and it proved to be very efficient in terms of clamping on the lap-splice region and enhancing the column ductility.

Most recently, the cyclic performance of composite-jacketed bridge columns with poor lap-splice details was studied through an experimental program conducted at the University of California, Irvine on both circular and square columns (Haroun and Feng 1997; Haroun et al. 1998; Haroun et al. 1999; Elsanadedy 2002). These columns were tested for flexural enhancement in a fixed-free condition.

Experimental Program

Thirteen half-scale bridge columns were constructed and tested in flexure; two circular as-built columns (CF-A1 and CF-A2), six circular columns retrofitted by six different composite jacket systems (CF-R1 to CF-R6), one square as-built column (RF-A1), and four square columns retrofitted by four different composite jacket systems (RF-R1 to RF-R4). It should be noted that in the designation of test samples, the letters "C" and "R" signify circular and square columns, respectively, the letter "F" denotes flexural testing, and the letters "A" and "R" stand for as-built and retrofitted columns, respectively. The height of all columns, measured from the top of the footing to the application point of the horizontal force was 3.66 m. Reinforcement details for lap-splice columnsare shown in Fig. 3 for circular and square samples. All columns were built with a 381-mm lap splice at

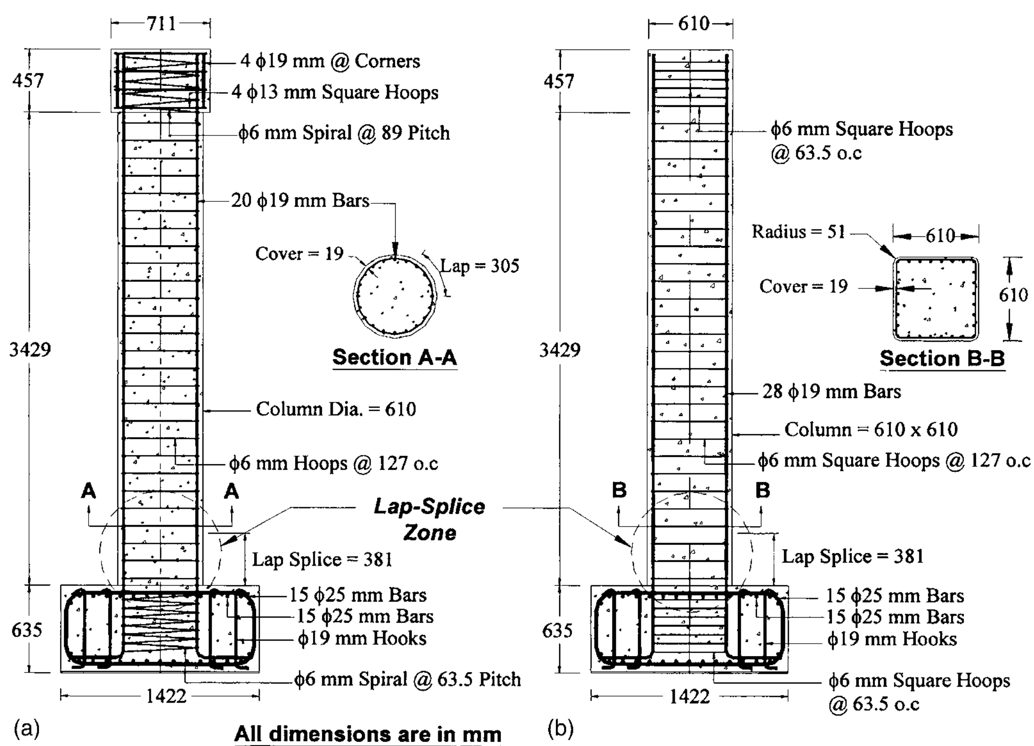

Fig. 3. Reinforcement details for lap-splice column samples: (a) circular columns and (b) square columns

Table 1. Properties of Lap-Splice Column Samples

Test sample	Concrete strength (MPa)	Yield stress of main steel (MPa)	Composite jacket properties: Type	Thickness within lap-splice zone (mm)	Tensile strength (MPa)	Tensile modulus (GPa)
CF-A1	35.7	299.1	As-built circular column			
CF-A2	38.7	299.1	As-built circular column			
CF-R1	36.0	299.1	Carbon/epoxy[a]	0.7	4,168	231.5
CF-R2	36.9	299.1	Carbon/epoxy[a]	0.7	4,430	230.1
CF-R3	32.8	299.1	E-glass/vinyl ester[b]	11.4	744	36.5
CF-R4	37.7	299.1	Carbon/epoxy[a]	1.7	4,382	226.0
CF-R5	39.7	299.1	E-glass/polyester[b]	12.7	641	36.4
CF-R6	33.1	299.1	Carbon/epoxy[c]	8.3	937	63.0
RF-A1	41.4	443.4	As-built square column			
RF-R1	35.4	443.4	Carbon/epoxy[a]	4.0	4,168	231.5
RF-R2	41.9	443.4	Carbon/epoxy[a]	4.0	4,430	230.1
RF-R3	42.2	443.4	Carbon/epoxy[a]	2.5	4,382	226.0
RF-R4	42.2	443.4	E-glass/vinyl ester[b]	22.9	744	36.5

[a]Properties are based on net-fiber area.

[b]Precured shells.

[c]Low-modulus carbon/epoxy composite system with properties based on net-fiber area.

the base. Circular columns had a diameter of 610 mm and were reinforced with 20 ϕ19 mm Grade 40 steel (nominal strength=276 MPa) to accurately reflect the field condition in most existing columns with lap splices. Circular columns were transversely reinforced by ϕ6 mm hoops spaced at 127 mm on centers. Square columns had a square cross section of 610 mm×610 mm and were reinforced by 28 ϕ19 mm as well as ϕ6 mm square hoops spaced at 127 mm on centers. Due to the difficulties in obtaining Grade 40 steel as specified in the circular columns, Grade 60 steel (nominal strength=414 MPa) was used in the square columns. For all columns, the longitudinal steel was uniformly distributed around the section with a concrete cover of 25.4 mm to the main steel. For all 13 samples, the same normal weight concrete with a target compressive strength of 34.5 MPa at 28 days was used. The concrete was designed to represent 67% overstrength above nominal design strengths of 20.7 MPa. The overstrength reflects both the typically conservative concrete mix designs and the strength gain expected in more than 20 years of natural aging. Material properties for all columns are presented in Table 1.

According to the guidelines of the California Department of Transportation (Caltrans) for composite column casings (Chapman et al. 1997), composite jackets for circular lap-splice columns should be designed for a hoop strain of 0.001 to give a minimum confinement pressure of 2.0 MPa within the lap-splice region. For square and rectangular columns, the required jacket thickness is increased by a factor of 1.5. According to Caltrans, the required composite jacket thickness is given by the following equations.

- For circular columns

$$t_j = \frac{1{,}000D}{E_j}(\text{mm}) \tag{1}$$

- For square columns

$$t_j = \frac{1{,}500d}{E_j}(\text{mm}) \tag{2}$$

where D=diameter of circular column (in mm); d=depth of square column section (in mm); and E_j=tensile modulus of FRP jacket (in MPa).

Caltrans limited the radial dilating strain to 0.001 to effectively clamp the lap splice in order to maintain fixity at the column base. Each composite jacket system in this study was individually designed by the manufacturer. It is imperative to mention that the composite system manufacturers did not follow exactly Caltrans guidelines when designing the FRP jackets for lap-splice clamping. FRP jackets for Columns CF-R1 and CF-R2 were designed for a jacket strain of 0.004 (instead of 0.001) to give a minimum confinement pressure of 2.0 MPa within the lap-splice zone. Composite jackets for Columns CF-R3 to CF-R6 were designed for a hoop strain of 0.001 to give a minimum confinement pressure of 1.0 MPa within the lap-splice zone. Square jackets for Columns RF-R1 and RF-R2 were designed for a jacket strain of 0.001 to provide a minimum confinement pressure of 2.0 MPa in the lap-splice region, and the required jacket thickness was increased by a factor of 1.5. For Sample RF-R3, premold mortar blocks were added at the bottom 50.8 cm of the column to provide a quasi-circular section with continuous confinement.

The new section had a curvature with a radius of about 72.5 cm as shown in Fig. 4. This column was retrofitted using 15 layers of carbon/epoxy composite jacket. The number of layers was designed for a jacket strain of 0.001 to give a minimum confinement pressure of 1.0 MPa with the increase of jacket thickness by a factor of 1.5. Jacket configuration for Sample RF-R3 is shown in Fig. 4. Lastly, Column RF-R4 was retrofitted using two layers of square E-glass/vinyl ester composite jacket, according to a jacket strain of 0.001 and a minimum confinement pressure of 1.0 MPa for the bottom 1.52 m of the column. Properties of composite jackets are listed in Table 1. It should be noted that a 25.4-mm

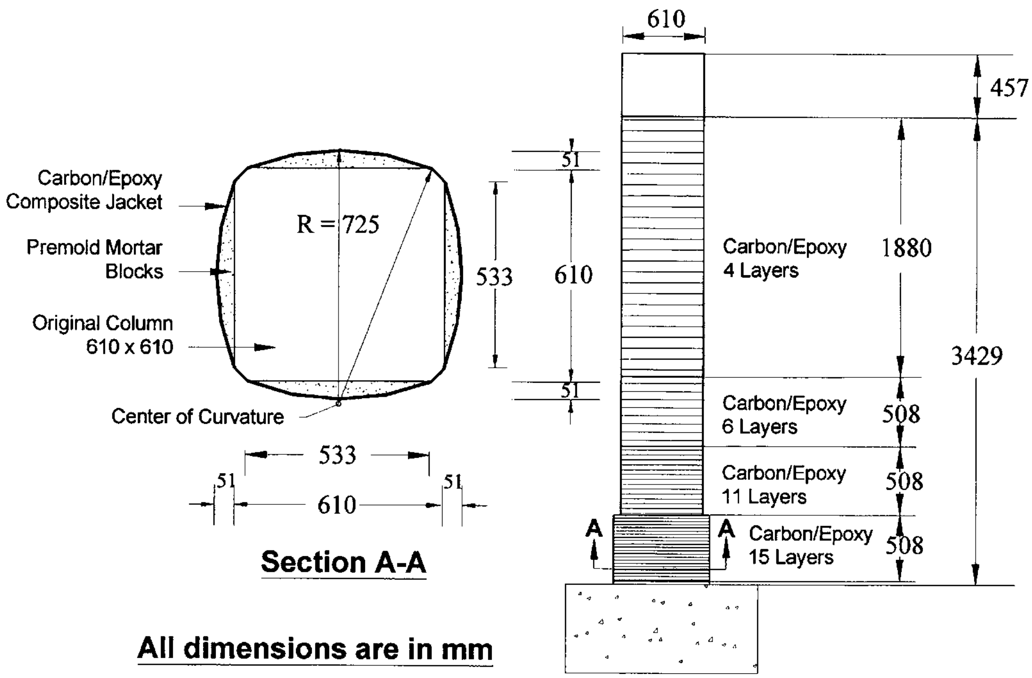

Fig. 4. Jacket configuration for Sample RF-R3

gap was provided between the bottom of the composite jacket and the footing in all retrofitted columns to avoid the possibility of the jacket acting as compression reinforcement by bearing against the footing at large displacements. This gap prevents the column from experiencing excessive flexural strength in the plastic hinge region, which could lead to increased actions in the footing.

Test Setup

The test setup was designed to subject the model columns to constant axial load and cyclic horizontal loads in a single curvature condition (Fig. 5). An axial load of 645 kN was applied to the circular samples, while the square columns were subjected to an axial load of 832 kN. The applied axial load satisfies the requirements of the California Department of Transportation (Caltrans 1993) for 10% of the column axial load capacity based on the original design strength of 22.4 MPa.

Instrumentation

Calibrated load cells were used to monitor and record applied lateral forces. Lateral displacements at different levels up the column were measured by 508-mm travel string potentiometers relative to a free-standing reference frame. Electric resistance

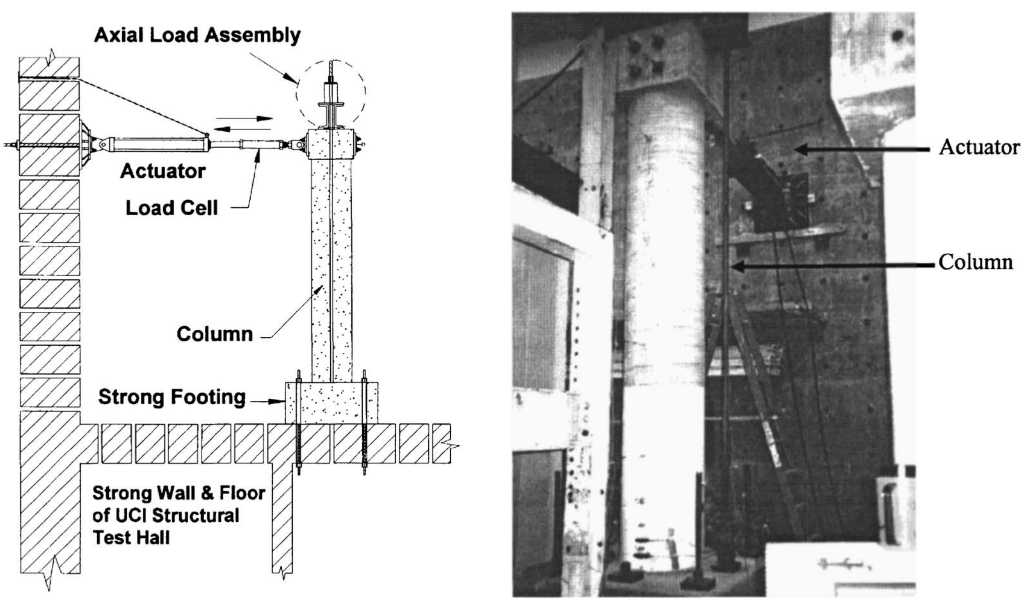

Fig. 5. Test setup for lap-splice column testing

Table 2. Test Results for Lap-Splice Column Samples

Test sample	V_y[a] (kN)	V_{if}[b] (kN)	Δ_1[c] (mm)	Δ_y[d] (mm)	K^e_{col}[e] (kN/mm)	$V_{u\text{-exp}}$[f] (kN)	$\Delta_{u\text{-exp}}$[g] (mm)	$\mu_{\Delta\upsilon\text{-exp}}$[h]	Drift ratio[i] (%)
(a) Circular columns									
CF-A1	114.5	147.1	22.4	29.0	5.12	158.2	57.7	2.0	1.58
CF-A2	114.1	148.4	20.8	27.2	5.48	162.0	67.3	2.5	1.84
CF-R1	111.8	149.7	26.9	36.1	4.15	158.5	218.7	6.1	5.98
CF-R2	111.7	150.1	22.9	30.7	4.89	177.6	204.0	6.7	5.58
CF-R3	110.3	149.1	20.6	27.7	5.36	187.9	193.5	7.0	5.29
CF-R4	110.6	151.4	18.8	25.9	5.88	188.0	201.7	7.8	5.51
CF-R5	111.0	153.1	22.1	30.5	5.02	186.1	201.7	6.6	5.51
CF-R6	109.8	150.0	24.9	34.0	4.41	187.4	241.3	7.1	6.60
(b) Square columns									
RF-A1	247.1	316.0	38.1	48.5	6.49	242.7	37.3	0.8	1.02
RF-R1	265.6	335.6	45.0	56.9	5.91	291.4	95.0	1.7	2.60
RF-R2	259.9	346.3	40.4	53.8	6.44	298.5	63.5	1.2	1.74
RF-R3	242.1	343.0	32.5	46.2	7.45	360.3	124.0	2.7	3.39
RF-R4	262.7	346.7	40.6	53.6	6.47	324.2	93.2	1.7	2.55

[a]Lateral load at first yield of longitudinal reinforcement.
[b]Lateral load at ideal flexural strength.
[c]Average measured displacement at first-yield state.
[d]Idealized yield displacement.
[e]Effective lateral stiffness.
[f]Average maximum measured lateral load.
[g]Ultimate average displacement at 80% of peak lateral load.
[h]Ultimate displacement ductility.
[i]Drift ratio at ultimate ductility (%).

strain gauges were mounted on the surfaces of main steel bars, transverse hoops, and composite jackets. Full details of strain gauge positions are given elsewhere (Haroun et al. 1999; Elsanadedy 2002).

Test Procedure

An axial load was applied to each column sample by posttensioning two steel rods with a hydraulic jack at the top of the column (Fig. 5). According to the guidelines of the California Department of Transportation (Caltrans 1993), peak forces controlled the initial loading cycles for each test until the column developed the lateral load corresponding to the first yield of longitudinal steel, V_y. Then, the test was stopped and the yield displacement was determined from

$$\Delta_y = \frac{V_{if}}{V_y}\Delta_1 \tag{3}$$

where Δ_1=average of the measured peak displacements corresponding to the first-yield lateral load, V_y, in the push and pull directions. The ideal flexural lateral load capacity, V_{if}, is computed based on the extreme concrete compressive strain of 0.004 (0.005 for the jacketed columns) and on measured material properties (Xiao and Ma 1997). After the column developed the first yield capacity, loading cycles were controlled by the peak displacement. For each load (or displacement level), three fully reversed cycles were completed. It is important to mention that the frequency of applied load (or induced displacement) is constant throughout the test program; it was picked up to be around one cycle per minute, which corresponds to a frequency of 0.0167 Hz. All cycles started with the push direction first then went into the pull direction.

Experimental Results

This paper only addresses representative samples from the test results. Detailed test results can be found elsewhere (Haroun et al. 1999; Elsanadedy 2002). A summary of the experimental results for all tested columns is presented in Table 2. In general, it is noted that the two circular as-built samples failed to satisfy the ductility requirements of current design guidelines [e.g., Caltrans Seismic Design Criteria (Caltrans 1999)]. From the table, it is illustrated that all circular fiber-reinforced plastic (FRP)-jacketed columns had approximately the same results, except for Samples CF-R1 and CF-R2, which were designed incorrectly by the manufacturer according to a jacket strain of 0.004 instead of 0.001 as mentioned earlier. Yet, all circular FRP-jacketed columns met their design needs considering the ductility demand. Even though square retrofitted Columns RF-R1 and RF-R2 had identical jacket design, Sample RF-R2 had bad results in terms of the ultimate displacement and ductility. It is also demonstrated that performance of Sample RF-R3 was better than all other square retrofitted columns. This is because Sample RF-R3 had a different jacket configuration as detailed previously. However, in view of ductility constraints, all four square jacketed columns (RF-R1 to RF-R4) failed to meet their design requirements. From the table, it is evident that composite-material jackets did not alter the

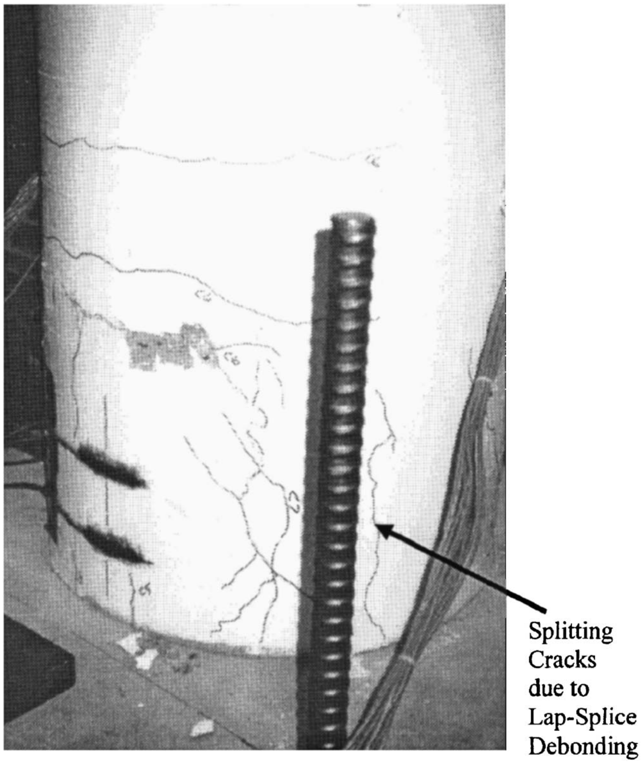

Fig. 6. Failure of circular as-built lap-splice column

effective lateral stiffness for both circular and square column samples, except for Sample RF-R3, which had about 15% stiffness increase over the as-built column. Representative samples of the experimental results are described in the following.

Circular As-built Columns

The as-built circular columns developed an unstable response due to bond deterioration of the lap-spliced longitudinal reinforcement. At low load levels, flexural cracks were observed on the column surface above the footing. As lateral load increased, flexural cracks were extended in the entire lap-splice region. At ductility 2, with a lateral load of about 160 kN, vertical splitting

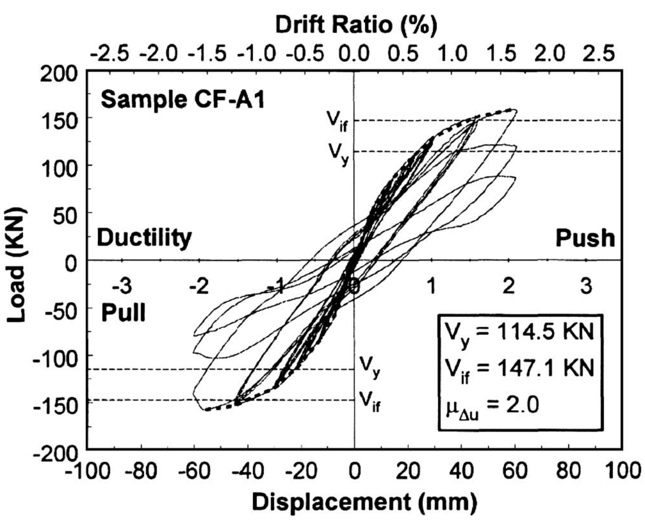

Fig. 7. Hysteresis loops for Sample CF-A1

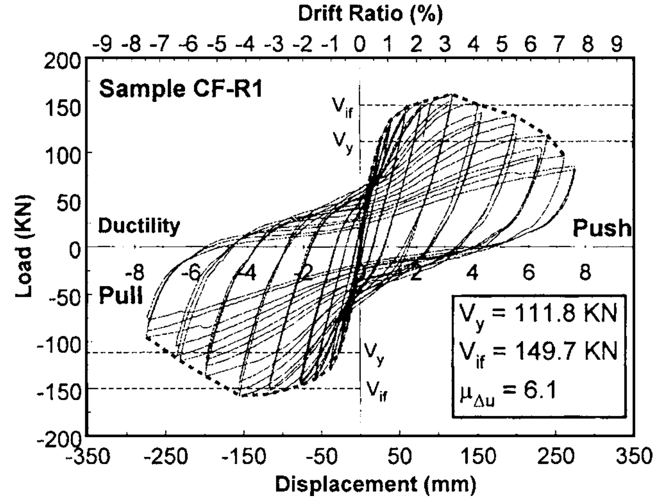

Fig. 8. Hysteresis loops for Sample CF-R1

cracks occurred in the lap-splice region. This is apparently due to lap-splice failure, causing the concrete cover to spall. This may be seen in Fig. 6 and the load-displacement plot shown in Fig. 7 for Sample CF-A1.

Circular Retrofitted Columns

In contrast to the as-built columns, the jacketed circular columns demonstrated a significant improvement in their cyclic performance by reaching ductility greater than 6. Yet, the retrofitted lap-splice enhancement circular columns did not behave similarly. The two Samples CF-R1 and CF-R2 performed differently than other tested columns as a result of jacket underdesign. At ductility 3, the columns reached their maximum lateral load of about 160 kN. At this point, partial slippage of the lap splice started to occur. The columns continued to carry 80% of their maximum lateral load until ductility 6 as shown in the hysteresis loops in Fig. 8 for Sample CF-R1.

The remainder of the columns behaved similarly to each other. At ductility 5, the columns reached their maximum lateral load of about 187 kN. At this point, the lap splice began to slip.

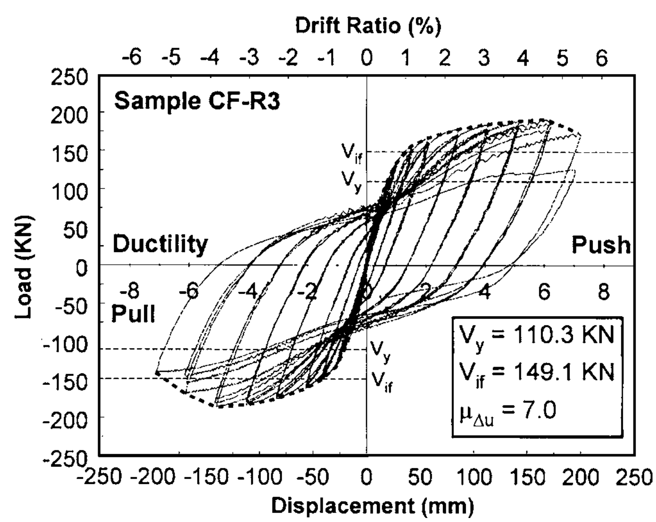

Fig. 9. Hysteresis loops for Sample CF-R3

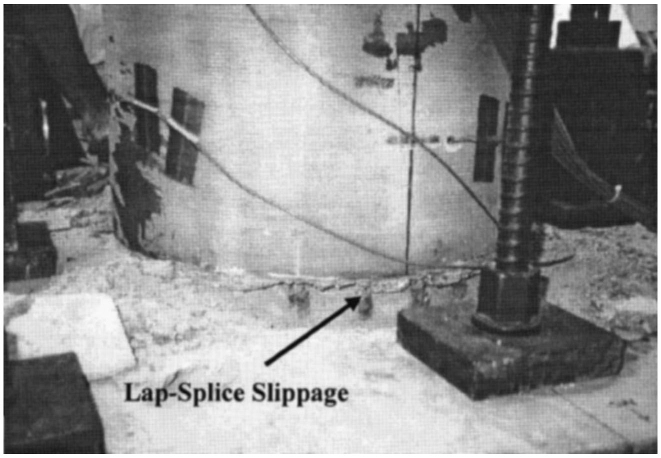

Fig. 10. Failure of circular retrofitted lap-splice column

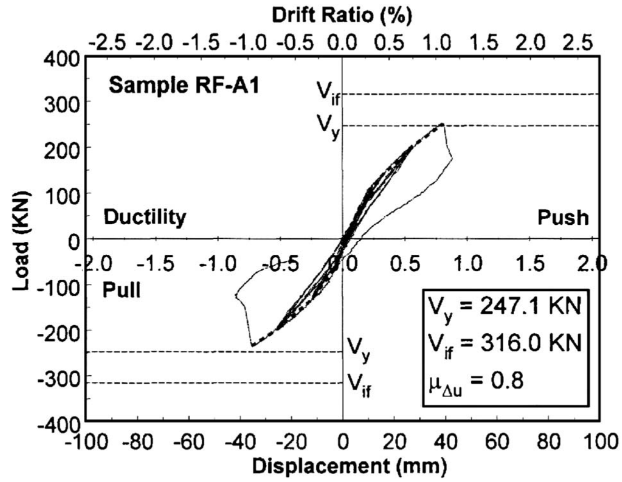

Fig. 12. Hysteresis loops for Sample RF-A1

The columns continued to carry 80% of their maximum lateral load until ductility 7. This may be seen in the load-displacement hysteresis loops in Fig. 9 for Sample CF-R3.

It is apparent that all of the jacketed columns failed due to lap-splice slippage at high ductilities, as the composite jackets showed no signs of tensile failure as a result of concrete confinement. Throughout the testing, no rupture in the longitudinal steel was observed. Failure of circular jacketed columns is illustrated in Fig. 10.

Comparison of Circular Lap-Splice Columns

A summary of load-displacement envelopes for all circular lap-splice columns is shown in Fig. 11.

Square As-Built Column

Sample RF-A1 could not reach its design strength or ductility, as it failed at the first-yield lateral load corresponding to a displacement ductility of 0.8 due to bond deterioration at the lap-splice zone as shown in the hysteresis loops in Fig. 12. Failure of Sample RF-A1 may be seen in Fig. 13.

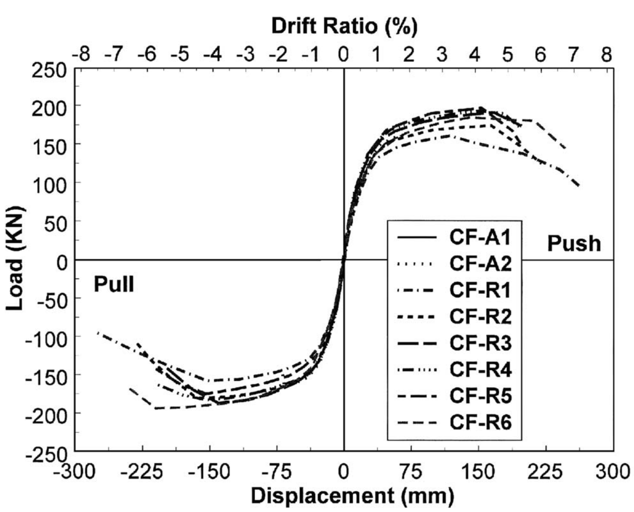

Fig. 11. Load-displacement envelopes for circular lap-splice columns

Square Retrofitted Columns

The square jacketed columns had a very limited improvement in clamping on the lap-splice region and for enhancing their ductility. Each of Columns RF-R1 and RF-R4 behaved similarly. At ductility 1, the column reached a lateral load capacity of about 311 kN, at which time, the lap splice failed. This may be seen in the hysteresis loops in Fig. 14 for Sample RF-R1.

For Column RF-R3, it was found that at ductility 1.7, it reached a lateral load capacity of 360 kN, at which time, bond deterioration of the lap splice occurred. This may be seen in the load-displacement plot in Fig. 15.

It is obvious that none of the square jacketed columns failed due to extreme concrete crushing within the plastic hinge zones, but rather due to lap-splice slippage at low ductilities, as the

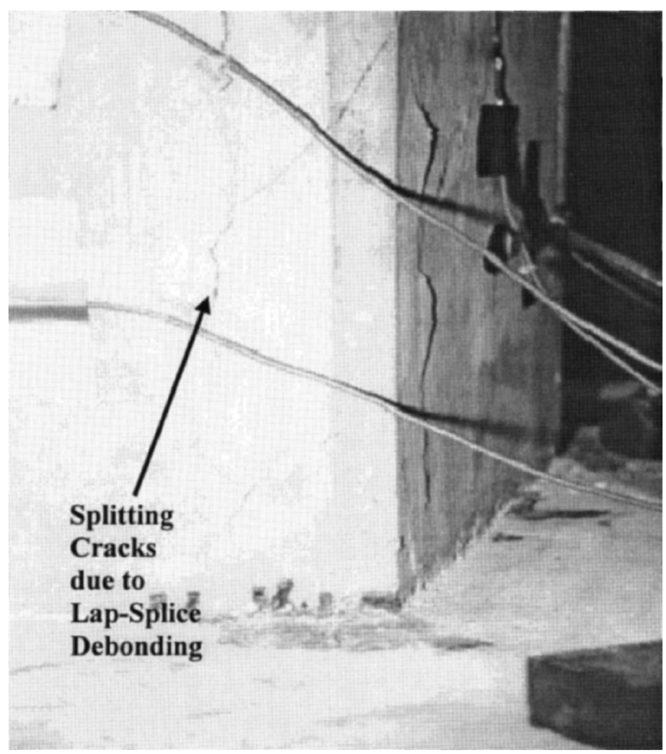

Fig. 13. Failure of square As-built lap-splice column

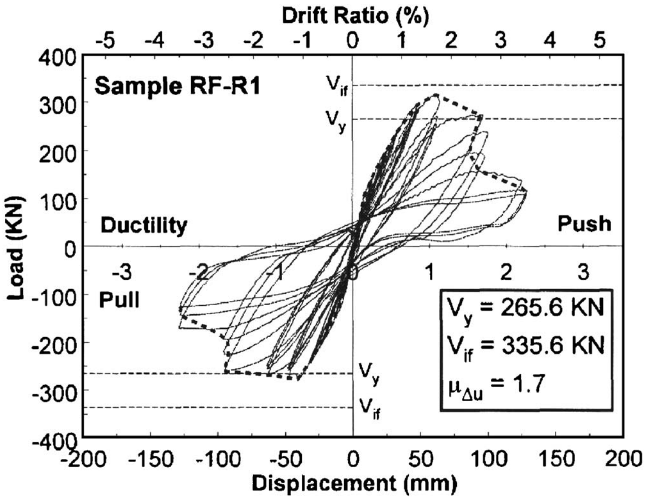

Fig. 14. Hysteresis loops for Sample RF-R1

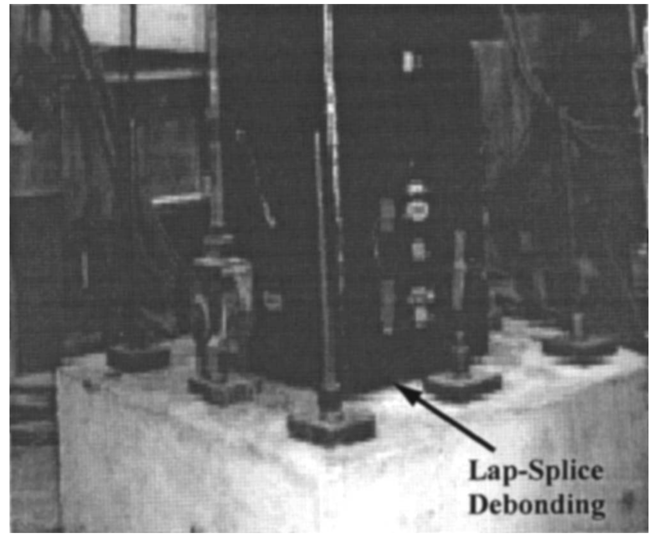

Fig. 16. Failure of square retrofitted lap-splice column

composite jackets showed no signs of tensile failure as a result of concrete confinement. This failure may be seen in Fig. 16. As for circular columns, no rupture in the longitudinal steel was noticed throughout the test.

Comparison of Square Lap-Splice Columns

Comparison between load-displacement envelopes for all square lap-splice columns is shown in Fig. 17.

Conclusions

The following conclusions are derived from the inclusive experimental program conducted on lap-splice columns.

1. Seismic assessment of as-built tall circular and square reinforced concrete bridge columns with insufficient lap-splice length was evaluated experimentally in this study. Due to the short lap-splice length (20 bar diameters) and the insufficient transverse reinforcement (usually Grade 40 ϕ13 mm hoops spaced at 305 mm on centers), the concrete cover may therefore start to spall prematurely and anchorage of the lapped bars may degrade rapidly due to the splitting action under fully reversed cyclic loads. In the experimental study, all as-built samples failed due to bond deterioration at the lap-splice zone at displacement ductility well below the ductility requirement of current design guidelines.
2. Seismic assessment of circular retrofitted columns showed the dramatic improvement of a column's seismic behavior. Circular jacketed columns tested in this study reached ductility greater than 6.0 and hence satisfied the ductility requirement of current design practice. Because of their shape, circular composite jackets are placed in hoop tension when the concrete expands due to vertical splitting cracks generated at the lap splices in the tension zone of the column section; therefore they are effective at clamping on the lap-splice region and then enhancing the ductility of the column. In addition to lap-splice clamping, FRP jackets are effective at increasing the lateral confinement of the as-built column (typically ϕ13 mm hoops at 305 mm on centers), allowing an increase in ductile behavior.

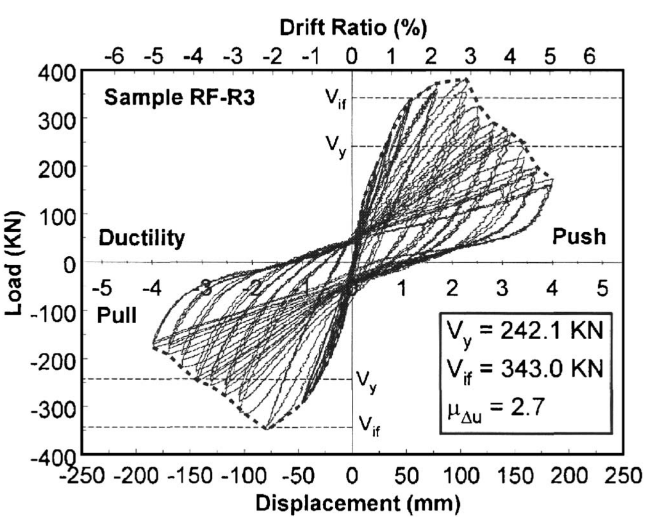

Fig. 15. Hysteresis loops for Sample RF-R3

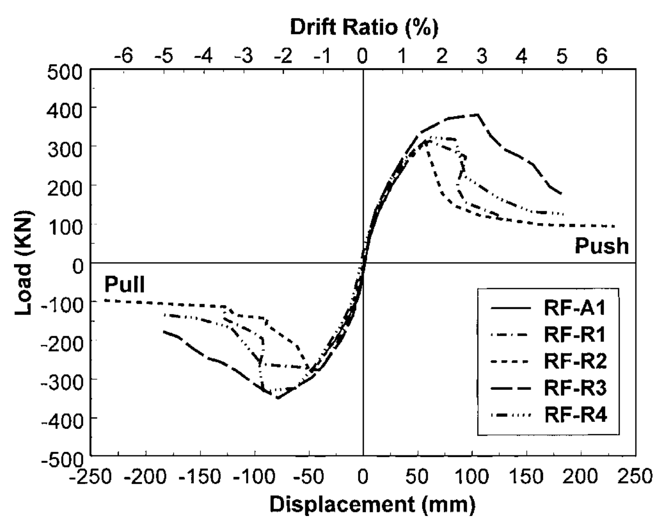

Fig. 17. Load-displacement envelopes for square lap-splice columns

3. Tests conducted on square jacketed columns showed very limited improvement in clamping on the lap-splice region and for enhancing the ductility of the column. Due to their shape, square or rectangular jackets can only induce confining reactions near the corners of the jacket, as the pressure of the concrete against the sides of the jacket tends to bend them outward. Accordingly, there should be adequate clamping action on the corner lap-spliced bars in square or rectangular jacketed columns, whereas bars at midsides of the column section should have insufficient lap-splice clamping. This was confirmed by strain gauge analysis as described previously. All square jacketed columns tested in this study experienced displacement ductility between 1.2 and 2.7. Therefore composite jackets cannot develop the strength necessary to inhibit lap-splice slippage in square or rectangular columns and will then fail to satisfy the ductility requirement of current design guidelines. In this case, circular or elliptical composite jackets may be more effective.
4. Composite jackets did not alter the effective lateral stiffness for both circular and square lap-splice samples and consequently the bridge dynamic characteristics will not be changed.
5. In addition to the comprehensive experimental program described herein, numerical models, based on moment-curvature analysis with the inclusion of a bond/slip mechanism, were developed in order to predict the seismic performance of column data. The models were calibrated using the experimental data in this study as well as data of columns tested elsewhere. Besides performance prediction, the developed models were used to propose generic retrofit design guidelines for bridge columns with insufficient lap-splice length.

Notation

The following symbols are used in this paper:

D = diameter of circular column;
d = depth of square column section;
E_j = tensile modulus of FRP jacket;
K^e_{col} = effective lateral stiffness;
V_{if} = lateral load at ideal flexural strength;
$V_{u\text{-exp}}$ = maximum experimental lateral load;
V_y = lateral load at first-yield state;
Δ_1 = displacement at first-yield state;
$\Delta_{u\text{-exp}}$ = ultimate experimental displacement;
Δ_y = idealized yield displacement; and
$\mu_{\Delta u\text{-exp}}$ = ultimate experimental displacement ductility.

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