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SEISMIC PERFORMANCE OF HIGH-STRENGTH CONCRETE COLUMNS CAST IN STAY-IN-PLACE FRP FORMWORK

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SUMMARY

The use of high-strength concrete (HSC) in seismically actively regions poses a major concern because of the brittle nature of material. The confinement requirements for HSC columns may be prohibitively stringent since they require proportionately higher confinement than columns of normal-strength concrete. An alternative to conventional confinement reinforcement is the use of fiber reinforced polymer (FRP) casings, in the form of a stay-in-place formwork, which can fulfill multiple functions of; i) formwork, ii) confinement reinforcement, and iii) protective shell against corrosion, weathering and chemical attacks. This paper investigates the use of stay-in-place FRP formwork as concrete confinement reinforcement for HSC columns with square and circular cross-sections. Large-scale specimens with 270 mm cross-sectional dimension and 90 MPa strength concrete, were tested under constant axial compression and incrementally increasing lateral deformation reversals. FRP casings were manufactured from carbon fiber sheets and epoxy resin. One of the square columns was equipped with internal FRP crossties, a new technique introduced by the authors, to provide well-distributed lateral restraints along the column face, thereby improving the mechanism of confinement. The results indicate that the deformation capacity of HSC columns can be improved significantly by using FRP casings. The results further indicate that the confinement effectiveness of FRP-confined square sections can be substantially increased with the use of FRP crossties.

INTRODUCTION

The use of high-strength concrete (HSC) in building and bridge construction has increased over the last two decades. HSC offers advantages over normal-strength concrete in terms of increased strength and improved performance. The gain in strength, however, is achieved at the expense of deformability. Indeed, HSC structural elements exhibit brittle behavior at failure, jeopardizing its use in seismically active regions where significant inelastic deformability and energy dissipation are required to resist seismic induced inertia forces. Inelastic deformability of concrete can be improved through confinement. Concrete confined by properly designed transverse reinforcement can develop adequate ductility to allow structures develop sufficient lateral drift without significant strength degradation. However, the confinement

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requirements become prohibitively stringent for HSC elements when conventional steel ties, hoops, overlapping hoops and spirals are used. The excessive amount of conventional confinement reinforcement required for HSC columns leads to the congestion of column cage and resulting concrete placement problems. On the other hand, fiber reinforced polymer (FRP) materials offer an attractive alternative to confine concrete. FRP pre-formed shapes, in the form of stay-in-place formwork with circular and square cross-sections offer multiple advantages of; i) light and effective formwork with superior handling characteristics, ii) efficient and durable transverse confinement reinforcement with ability to generate high lateral confinement pressures, and iii) protective shell against corrosion, weathering and chemical attacks. The objective of this investigation is to determine the effectiveness of pre-shaped FRP formwork as concrete reinforcement for HSC columns having circular and square cross-sections, subjected to simulated seismic loading.

It has been established that circular spirals are more effective in confining concrete than rectilinear ties. Similarly, it has been reported that the effectiveness of FRP jackets was higher in circular columns than square columns [1, 2, 3]. This may be explained by hoop tension generated in circular columns, resulting in uniform passive confinement pressure. Square jackets, on the other hand, develop high confining pressures at the corners, which diminish quickly between the edges. The confining pressure in square sections depends on the restraining forces that develop against lateral expansion. The pressure is generated by the membrane action that develops along the sides, whereas it depends on the flexural rigidity of FRP jacket between the side walls. Therefore, both corner radius (R) and the column depth (D) affect the effectiveness of confinement. These two parameters can be expressed in the form of R/D ratio. Similar phenomenon was observed in sections with conventional rectilinear steel reinforcement [4]. However, FRP casings offer an advantage over conventional reinforcement, in that they allow increased corner radius, thereby increasing the effectiveness of confinement.

A relatively high diameter-to-depth ratio (R/D) of 1/6 was employed in the current study to prevent early rupturing of fibers at column corners. Furthermore, one of the square columns was equipped with internal FRP crossties to provide improved distribution of lateral restraints along the column face, generating near-uniform confinement pressure.

RESEARCH SIGNIFICANCE

External FRP systems have become increasingly popular in field applications despite limited experimental data available on their seismic performance. Most of the existing research focuses on repair, rehabilitation and retrofit of existing normal-strength concrete columns, overlooking potentials for application to new construction, especially to new HSC columns. On the other hand, multiple functions and effectiveness of FRP stay-in-place formwork offer advantages for use as confinement reinforcement, especially for a brittle material like HSC. Despite its potential, no earlier research was conducted on the topic. The current investigation provides pertinent seismic performance data on such columns for potential use in practice. Furthermore, it reports on a new technique investigated for square formwork which consists of the use of internal FRP crossties in FRP casings, emulating conventional crossties used in conventional column construction.

EXPERIMENTAL PROGRAM

Test specimens

Circular and square columns were tested under simulated seismic loading. Each specimen consisted of a 270 mm cross-section and 1,720 mm cantilever height. The shear span for each column was 2,000 mm since the point of application of lateral force was located on a steel loading beam that was 280 mm above the column. The specimens represented the lower half of a first-storey building column with an interstorey height of 4.00 m between fully fixed ends. One of the square columns was equipped with internal FRP crossties, spaced at 68 mm, corresponding to 1/4th of the column dimension for improved confinement. This column had 12 longitudinal bars. Other two FRP casings were in the form of hollow tubes having either square or circular geometry. The corner radius for square columns was 45 mm. Figs. 1 and 2 illustrate the geometry and reinforcement arrangements. Table 1 provides a summary of geometric and material properties.

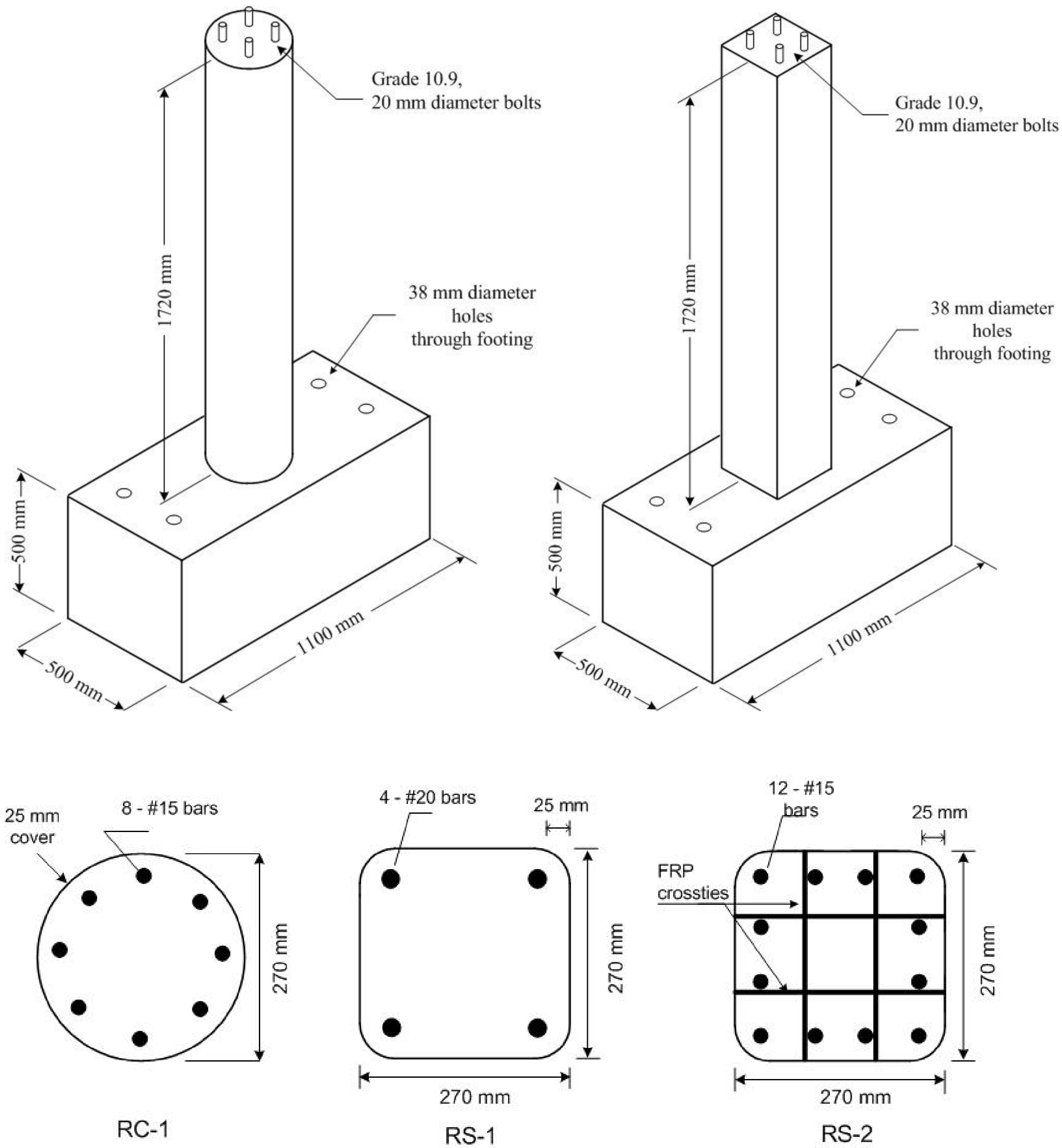

Figure 1 Geometry and reinforcement arrangements used in column tests

(a) Column RC-1 **(b) Column RS - 1** **(c) Column RS - 2**

Figure 2 Column cross-sectional arrangements

Table 1 Properties of test specimens

Specimen	Cross-Section	f'_c, MPa	Layers of FRP	Longitudinal steel			Axial load
				Reinforcement Arrangement	f_y, MPa	ρ_l, %	P/P_o
RS-1	Square	90	5	4-no.20	475	1.68	0.32
RS-2	Square	90	5	12-no.15	500	3.36	0.32
RC-1	Circular	90	4	8-no.15	500	2.79	0.32

Material properties

FRP Material

A carbon fiber composite system was used to manufacture the stay-in-place formwork for all columns. The same FRP composite material was used for all casings with fibers in the circumferential/transverse direction. The thickness of carbon fiber sheets was 0.165 mm/ply, which increased to 0.8 mm/ply when impregnated with epoxy resin. The stress-strain relationship of the composite material was established by coupon tests and showed linear-elastic behavior up to rupture. Table 2 provides the properties of carbon fibers as provided by the manufacturer. These properties were verified against coupon tests of the FRP composite conducted in the laboratory, with due consideration given to the thickness of the composite casing.

Table 2 Proprieties* of carbon fibers used in manufacturing FRP casings

Fibers	Nominal Thickness, (mm/ply)	Ultimate Tensile Strength, MPa	Elastic modulus, GPa	Ultimate Rupture Strain, (%)	Areal Weight, (g/m^2)
Carbon	0.165	3800	227	1.67	300

*Reported by the manufacturer.

The manufacturing process involved wrapping FRP composites around templates. The templates consisted of plywood and sona tubes for square and circular columns, respectively, as illustrated in Fig.3. PVC pipes, split into four quarters, were used to obtain the desired corner radius for square sections. FRP sheets were then wrapped around the templates one layer at a time, without any overlap along the longitudinal direction. A 100 mm overlap was provided along the circumferential/transverse direction to ensure proper bond. FRP crossties were prepared by wrapping FRP sheets around phenolic bars, which had very low tensile strengths and essentially used as templates. This is depicted in Fig. 4. The circular and square casings had four and five plies of FRP material, respectively. The number of FRP plies was established based on the results of recent research [5, 6] on stress-strain behavior of FRP sheets while also using widely accepted confinement models for conventional steel reinforcement [4, 7]. Two important parameters were considered in estimating the required plies of FRP sheets. These were; i) the limiting strain of FRP material and ii) the effect of corner radius for square columns.

(a) Sona tube template **(b) Plywood template**

Figure 3 Templates used to manufacture FRP casings

(a) Fiber strips prior to wrapping **(b) FRP crossties after wrapping**

Figure 4 Manufacturing of FRP crossties

The square column with 12-bar reinforcement arrangement had four FRP crossties at each level, two in each of the two orthogonal cross-sectional directions. After the installation of the first three plies of impregnated FRP sheets, 8 mm diameter small holes were drilled to insert the FRP crossties. The final two plies of the composite material were applied after the insertion of FRP crossties. This is illustrated in Fig. 5. Once the FRP casings were ready, they were placed on footings, while accommodating longitudinal bars, where they would function as stay-in-place formwork during casting.

(a) Crossties inserted **(b) End fibers glued on** **(c) Final layer of FRP sheet**

Figure 5 Placement of crossties in square columns

Concrete
All the columns were cast together, using the same batch of concrete. The concrete mix was designed and ordered from a ready-mixed company. The mix consisted of 10SF cement (8% Silica fume blended Normal Portland cement), crushed limestone with 10 mm maximum size and a water cement ratio of 0.22. The target strength of concrete was 90 MPa at the time of testing. The strength and workability were the main criteria in mix design, which were achieved by selecting a low water-cement ratio and high cement content. It was necessary to use superplasticizers and retarders to achieve and maintain the desired level of workability. An initial concrete slump of 200 mm was achieved and maintained during casting. The specimens were cast vertically and vibrated thoroughly. Cylinder tests were conducted periodically and the columns were tested when the average concrete strength reached 90 MPa.

Steel Reinforcement
Canadian Standard No. 15 and No. 20 deformed steel bars were used as longitudinal reinforcement with a nominal diameter of 16 mm and 19.5 mm with yield strengths of 475 MPa and 500 MPa, respectively. The stress-strain relationships were established by performing at least three coupon tests for each type of reinforcement. Table 3 gives average properties for the two sizes of reinforcement used. None of the columns had any transverse steel reinforcement, except within the footing and at the very top, where the longitudinal bars were positioned and tied with three hoops and one hoop, respectively, to keep the bars in place.

Instrumentation, test setup, and loading program
The columns were instrumented with Linear Variable Displacement Transducers (LVDT) and strain gages to measure horizontal displacements, rotations of the plastic hinge region, anchorage slip, and horizontal

and circumferential/transverse strains. All instrumentation was connected to a data acquisition system and a microcomputer for data recording. The acquisition of strain data on FRP casings was particularly of interest to develop a better understanding of the strain profile on the casings. Therefore, a large number of strain gages (26 to 29), were placed on the surface of FRP casings oriented in the direction of carbon fibers.

Table 3 Properties of reinforcing steel

Bar size	Stress-strain relationships						
	f_y, MPa	ε_y	E_s, MPa	ε_{sh}	f_u, MPa	ε_u	ε_r
No. 15	500	0.0024	208,750	0.0062	620	0.0120	0.0135
No. 20	475	0.0026	182,690	0.0070	570	0.0125	0.0144

Each column was tested under constant axial compression and incrementally increasing lateral deformation reversals, simulating seismic loading. Three 1000 kN capacity servo-computer-controlled MTS hydraulic actuators were used to apply the loads. Two of the actuators were positioned vertically, one on each side of the column, to apply constant axial compression throughout the test. The third actuator was placed horizontally for the application of lateral deformation reversals. Figure 6 illustrates the test setup.

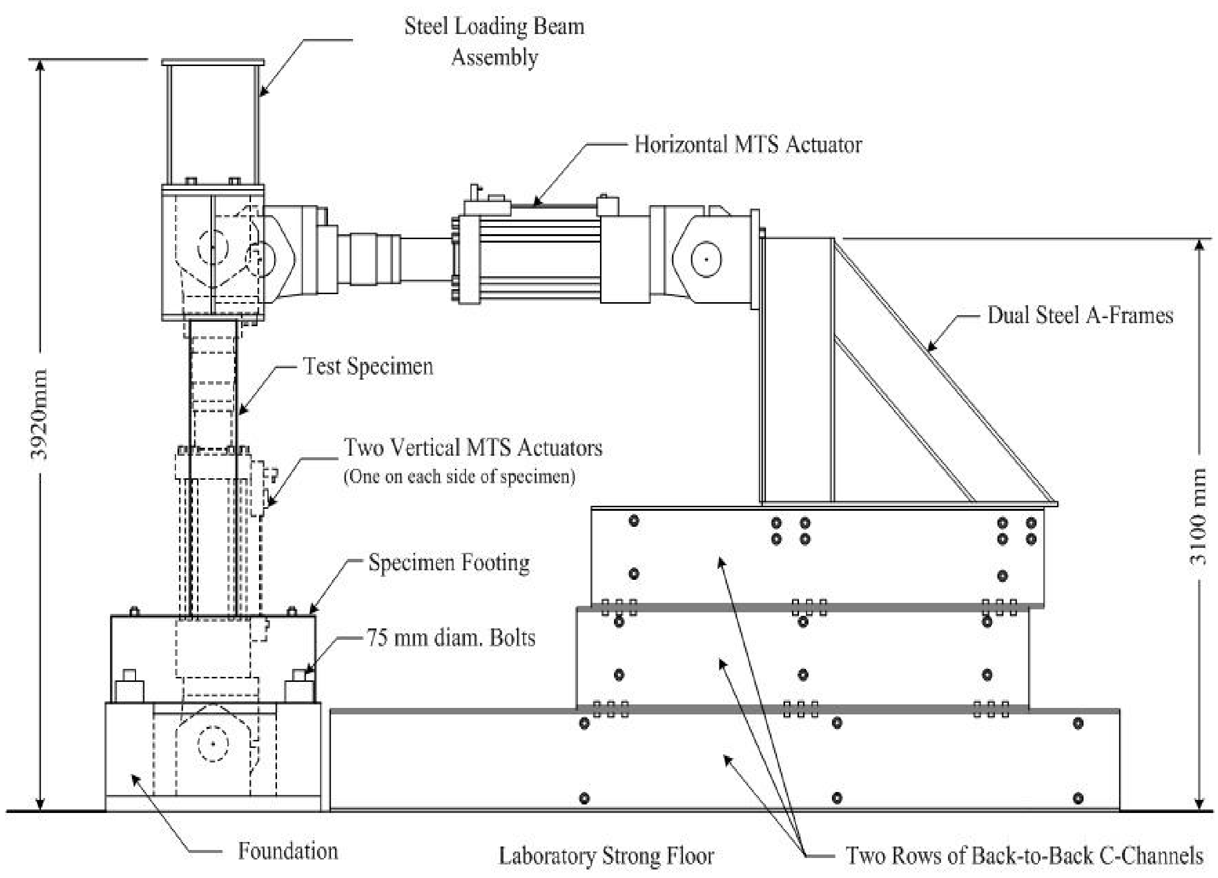

Figure 6 Tests setup

All columns were tested under 32 % of their concentric capacity, P_o, computed as indicated below:

$$P_o = 0.85f_c' (A_g - A_s) + A_sf_y \tag{1}$$

The computed value of P_o was 1,880 kN for columns RS-1 and RS-2, and 1,580 kN for column RC-1. The specimens were subjected to lateral displacement excursions, consisting of incrementally increasing deformation reversals. Three full cycles of deformation were applied at each deformation level, starting with 0.5% drift ratio and increasing to 1%, 2%, 3% etc., in deformation control mode of the horizontal actuator. Lateral loading continued until the specimen was unable to maintain a significant fraction of its maximum lateral load resistance. The rate of lateral loading was low and the total duration of a typical test was about four to five hours, depending on the deformability of column.

TEST RESULTS

Observed behavior

All columns initially behaved in a similar manner up to 2 % lateral drift ratio. There were no visual signs of damage in any column until the end of 2% lateral drift cycles. At 3% drift, localized changes in FRP color was observed within the plastic hinge region of column RS-1, indicating the separation of FRP material from concrete as the concrete began crushing. A similar discoloration was observed at 4% drift ratio in Columns RS-2 and RC-1. As the applied displacement increased, the regions of discoloration extended up to about twice the theoretical plastic hinge length (540 mm). These visual observations were also supported by the strain data recorded on FRP casings. After 4% drift ratio, any increase in applied displacement substantially increased fiber dilatation within the plastic hinge region. When the testing of the circular column was halted at 12% drift, there were signs of delamination up to approximately 800 mm from the column-footing interface, showing the magnitude of the propagation of plastic hinge region.
Rupturing of fibers was observed in square columns, initiating at or near one of the column corners. This occurred during the third cycle at 8% drift in Column RS-1, and the first cycle of 12% drift in Column RS-2. Maximum moment resistance for the square column without FRP crossties (RS-1) was attained at 2.8 % drift, while it was attained at 4% lateral drift for the companion square column with FRP crossties (RS-2). The maximum moment resistance was recorded at 11% lateral drift ratio for the circular column (RC-1).

The most extensive damage occurred at 100 to 150 mm from the column-footing interface, which generally coincided with the location of first fiber rupture in all columns. This was attributed to the confining effect of the footing, which resulted in the shifting of the critical section from the interface. Similar observations were previously reported by other researches [8]. Figure 7 illustrates the behaviour of the hinging region in Columns RS-1 and RS-2. Fiber rupture was the failure mode for square columns RS-1 and RS-2. A snapping noise accompanied by the release of previously built-up pressure in FRP casings resulted in the failure of columns. Table 4 summarizes the strength values and locations of most damaged sections for all columns.

Hysteretic Behaviour

It is generally believed that some strength decay in column resistance can be tolerated in multistory buildings before the column is considered to have failed. A 20% decay in moment resistance is used in this research study as the limiting strength decay beyond which the column is considered to have reached its useful limit [9, 10]. Figure 8 illustrates experimentally recorded moment-drift hysteretic relationships. No significant strength degradation was observed in Columns RS-2 and RC-1 until the end of the test program. On the other hand, the moment resistance of RS-1 started to decay gradually after 3% lateral drift. The 20% limit for strength decay was reached at about 8% drift cycles, just before the failure of column by fiber rupturing. The moment-drift hysteretic relationships indicate that, Columns RS-2 and RC-

1 exhibited very similar behavior and their strength never dropped to 80% of their moment capacities until the end of testing. Column RS-2 failed at 12% lateral drift ratio, following the rupture of fibers it the critical section. Testing of Columns RC-1 was stopped at 12% lateral drift ratio when the stroke capacity of the horizontal actuator was reached. The strain data collected during the last loading cycle suggested that the failure of the specimen was imminent.

(a) Column RS–1 **(b) Close-up view of RS–1** **(c) Close-up view of RS-2**

Figure 7 Failure of column critical region within plastic hinge region

Table 4 Summary of experimental values

Column	Column Moment Resistance				Damage zone , mm
	M_{max} , kNm	Drift at 80% M_{max} , (%)	Drift at 90% M_{max} , (%)	Drift at M_{max} , (%)	
RS-1	220	8	4	2.8	140
RS-2	258	12	8	4	110
RC-1	174	12+	12+	11	100-150

M_{max} represents average of maximum moments recorded in each direction of loading.

Variation of transverse FRP strains with lateral drift

Strain gages were placed on the loading side of each FRP casing, at eight different levels along the height. Of these strain gages, those located at 135 mm and 203 mm above the column-footing interface consistently gave the highest strain readings for square and circular columns, respectively. The variations of transverse strains with lateral drift ratio are shown in Fig. 9 for all columns. The maximum transverse strain recorded on casings of all columns was in excess of 1%, which was significantly higher than those recommended for design in some of the current design guidelines [11, 12]. It should be noted that the rounding of the corners of square sections reduced the stress concentration and probably allowed the FRP material to develop higher strains along the entire column face before it ruptured. Even though all the columns reached approximately the same maximum transverse strain, the corresponding maximum lateral drift was different in each column. Figure 9 clearly demonstrates that the strains on Column RS-1 were higher than those on Columns RS-2 and RC-1 at the same level of lateral drift. This is attributed to the superior confinement of the latter two columns. The casing of Column RS-2 with internal crossties was more effective than that of Column RS-1 without the crossties. Furthermore, Column RC-1 with circular geometry developed hoop tension and attained the highest confinement effectiveness. This observation indicates that the effectiveness of confinement can be improved significantly when crossties are provided, with behavior approaching to that of circular columns.

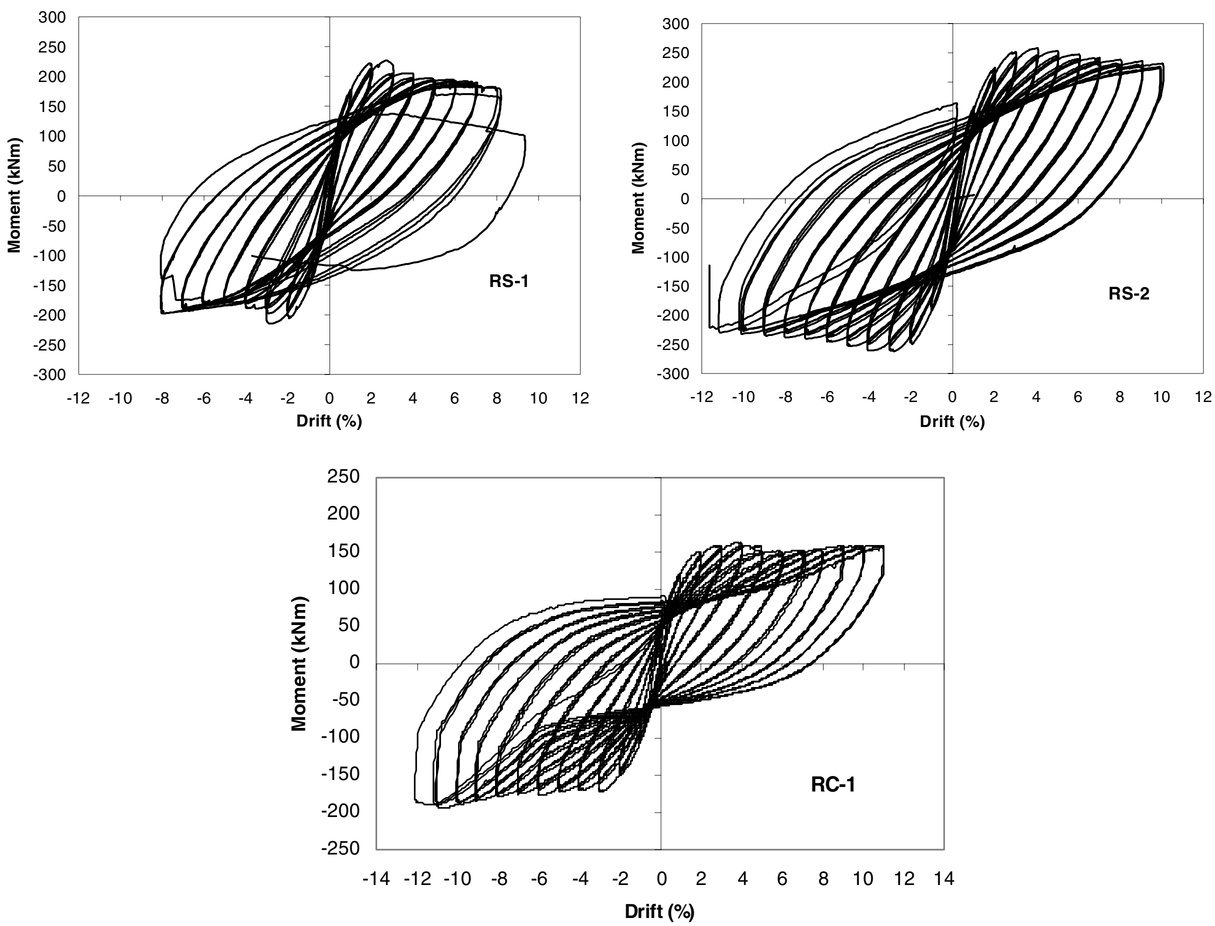

Figure 8 Experimentally recorded hysteretic moment-lateral drift relationships

Variation of transverse FRP strains along column height

Plots of transverse strains along column height are shown in Figure 10 for all three columns. The strains plotted correspond to the last cycle at 4% and 7% lateral drift ratios. The Figure represents the maximum transverse strains on compression side of columns during loading. Figure 10 also demonstrates the confining effect of the column footing. Accordingly, the strains recorded are consistently higher at 135 mm from the column-footing interface when compared with those at 68 mm. The figure also demonstrates the propagation of plastic hinge region under increasing lateral deformations.

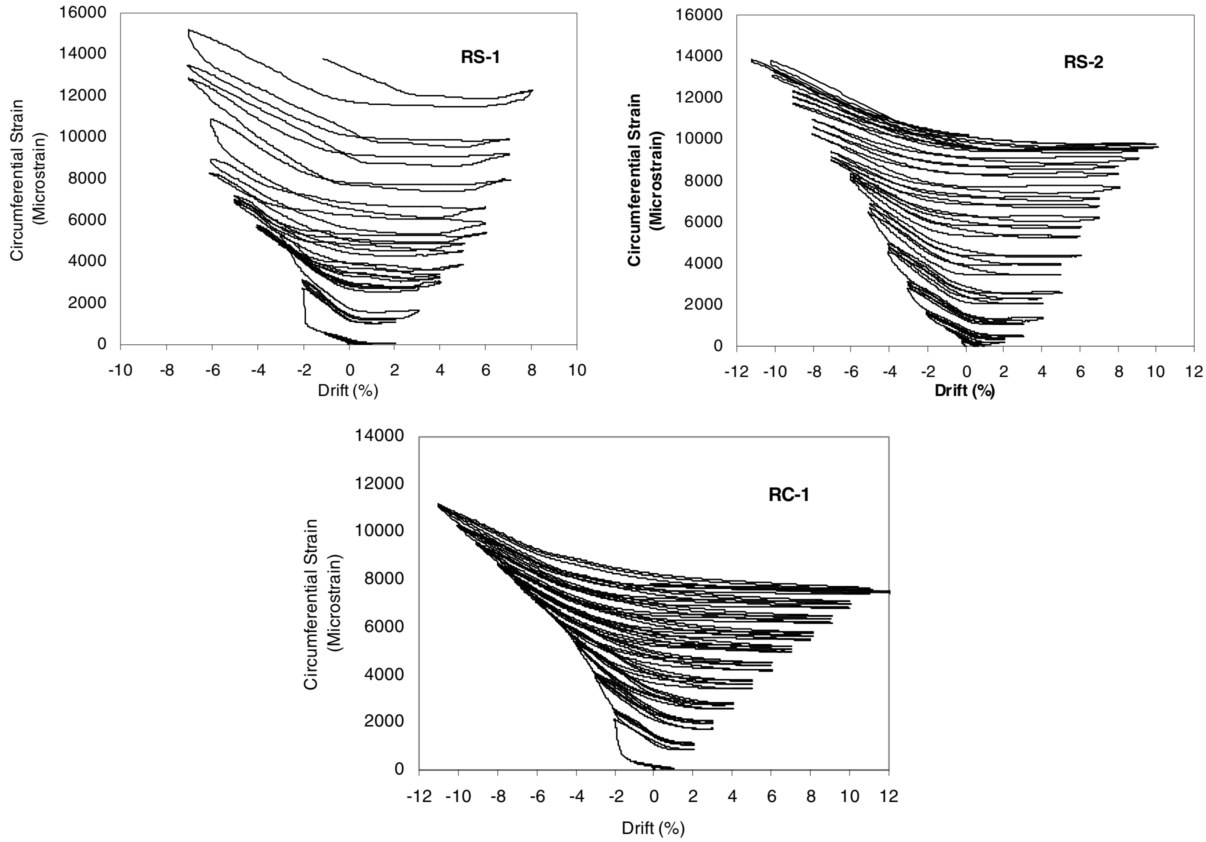

Figure 9 Transverse strains recorded on FRP casings at locations of highest strain (135 mm and 203 mm above the footing for square and circular columns, respectively)

Effects of Test Parameters

The examination of strain values recorded and plotted in Figures 8 to 10 reveals that circular casing (RC-1) was superior to square casing (RS-1) even with one less ply of FRP. This observation is in line with those reported by previous researchers who conducted similar tests with either conventional steel reinforcement or FRP wraps [1, 2, 3]. On the other hand, the effectiveness of square FRP casing can be improved very significantly by providing internal crossties. The hysteretic moment-drift relationships of these columns indicate that, RS-1 without the crossties showed a strength decay starting at approximately 3% lateral drift ratio. In contrast, RS-2 with internal crossties placed at 68 mm of spacing resulted in virtually no strength degradation up to about 12 % lateral drift. Furthermore the strain data from both columns indicate that, even though the ultimate transverse strain was approximately the same for both columns, column RS-1 reached that level of strain at a much lower drift level than RS-2.

CONCLUSIONS

The following conclusions can be drawn from the experimental study reported in this paper:

1. High-strength concrete columns confined with carbon FRP stay-in-place formwork can develop extremely ductile behavior under simulated seismic loading. The use of FRP formwork as confinement reinforcement substantially increases deformability of both square and circular columns. Column tests reported in this paper indicate that inelastic deformability of 90 MPa concrete columns can be increased up to 12% lateral drift ratio with FRP stay-in-place formwork.

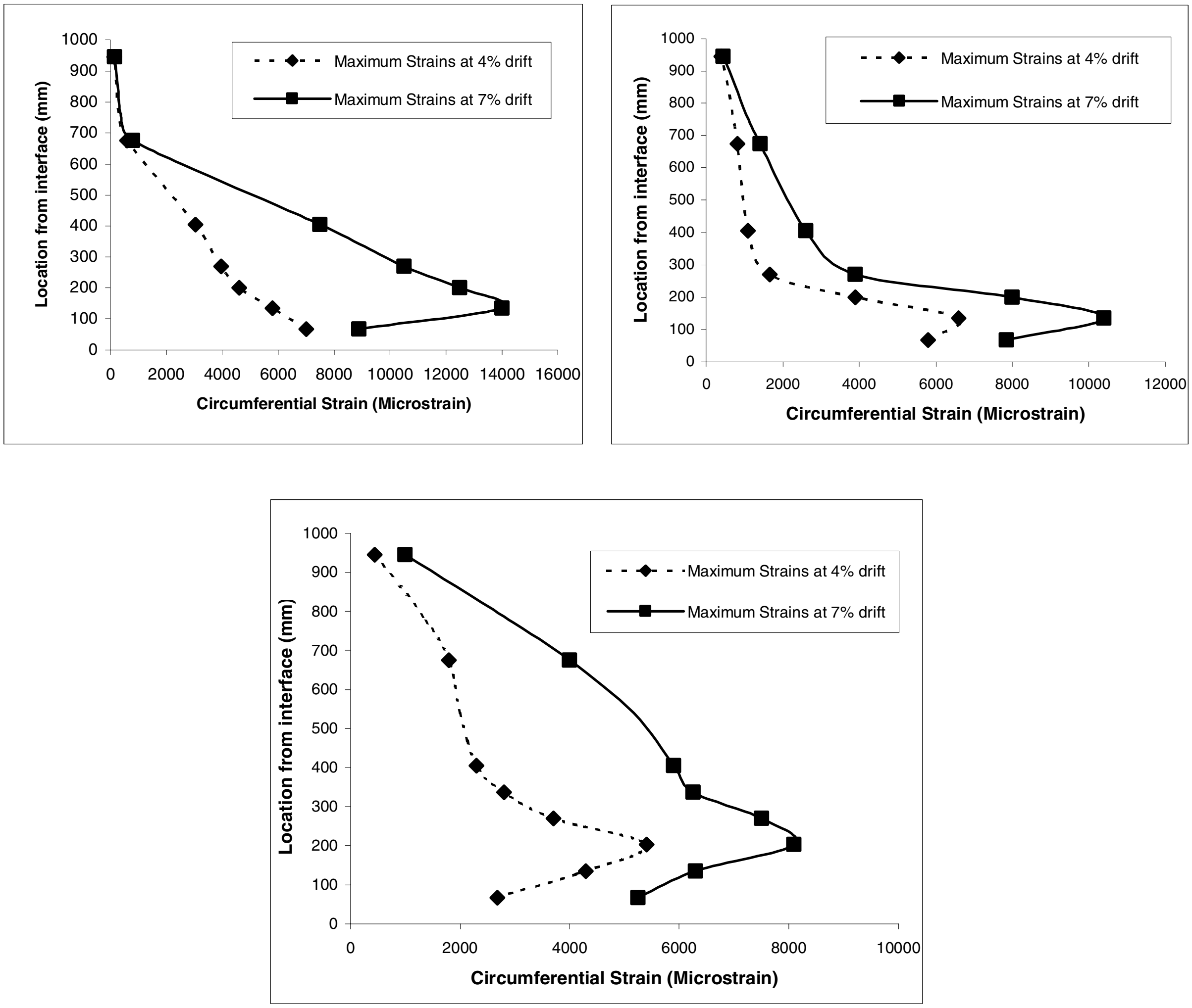

Figure 10 Variation of transverse strains on FRP casings along column height

2. The increased confinement requirements for HSC columns can be met by using FRP stay-in-place formwork. Unlike the conventional steel reinforcement that only confines the core concrete, FRP stay-in-place formwork effectively confines the entire column section. Furthermore, unlike the discrete nature of conventional steel reinforcement, placed at certain spacing, FRP formwork provides continuous confinement, covering the entire column face.
3. Rounding column corners reduces stress concentrations in FRP formwork, allowing the development of higher strains along its perimeter prior to fiber rupturing. This aspect requires further investigation.
4. The effect of transverse steel arrangement on ductility of rectilinear concrete columns reinforced with conventional steel ties is well established. It was reported by a number of researches that the existence of transverse restraints, in the form of overlapping hoops or crossties, improved confinement effectiveness of transverse reinforcement. Similarly, confinement effectiveness of FRP confined rectilinear columns can be increased substantially with the use of FRP crossties, a new construction technique introduced by the authors.

5. The strain data recorded during column tests reported in this paper illustrates that the design transverse strain of 0.4% recommended by current FRP design guidelines is conservative for the columns tested. Transverse strains of 1% and above were recorded in FRP formwork, when subjected to simulated seismic loading.
6. Additional confinement provided by a footing appears to strengthen the column critical section at column-footing interface, which consequently shifts the failure away from the interface. This shift was observed to be approximately equal to half the column cross-sectional dimension in the columns tested and the axial load applied.

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