Ninth Canadian Conference on
Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

BEHAVIOR OF REINFORCED CONCRETE COLUMNS UNDER REVERSED CYCLIC TORSION

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ABSTRACT

This paper experimentally investigates the cyclic behavior of circular reinforced concrete columns confined using a new confinement technique consisting of two opposing spirals (cross spirals). This new technique enhances a column's strength and ductility or increases the spiral spacing in order to facilitate the flow of concrete during construction. Eighteen approximately one-sixth scale bridge columns confined with several spiral spacings and effective lengths varying from 1000 mm to 400 mm were tested. The columns were subjected to reversed cyclic torsional deformation to study the influence of the new confinement technique on the torsional strength and ductility of circular columns as compared to columns confined with a conventional single spiral.

Introduction

In an effort to equalize the seismic design factors of safety across all seismic regions, recent building code changes have increased the design seismic loading in traditionally low seismic regions. Seismic design of concrete structures requires a great amount of ductility, which can be provided through the use of lateral reinforcement. One commonly used method for confining circular members is the spiral confinement technique where a single spiral is wrapped around longitudinal bars to provide lateral reinforcement. This method places the confined core of concrete into a triaxial state of stress. ACI 318-05 imposes limits on the vertical spacing of spirals to provide minimum levels of ductility but also ensure constructability (ACI 2005). As building codes increase seismic design requirements, the ability to achieve greater ductility in concrete structures will become increasingly important in all regions of the country.

ACI 318-05 limits spiral spacing to a minimum of 25 mm to guarantee the passage of aggregate between spirals. In structures being designed for ductility, this limitation on minimum spiral spacing can limit ductility. The inability to adequately confine concrete in order to fully develop ductility has affected the acceptance of high-strength concrete. High-strength concrete is potentially a very useful building material but has a tendency to fail in a brittle manner unless well confined, which requires larger amounts of steel. Providing adequate amounts of confining steel has proven difficult to achieve because of the minimum spacing allowed by current codes and confinement techniques. It is clear that a new confinement technique is needed to provide increased confinement and fully utilize the benefits of high strength concrete.

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The 75 mm maximum spiral spacing allowed by ACI 318-05 also causes problems in certain applications. In the case of large diameter columns with maximum reinforcement, such as bridge columns, maintaining equal spacing around the entire circumference of the column can prove difficult, requiring more labor and therefore more cost. Drilled piles, on the other hand, would benefit from an increase in maximum spiral spacing which would allow more spiral movement as the reinforcement is lowered into the hole. In the case of heavily reinforced beam – column connections the ability to increase the spiral spacing of the column without compromising strength would allow for less congestion and easier constructability in the connection region.

A column reinforced with a conventional single spiral has a torsional rotation-direction bias. Torsional capacity is significantly reduced when the torsional loading is applied such that it is attempting to “unwind” the spiral. Due to this phenomenon a single spiral reinforcement scheme will produce a column with unsymmetrical torsional strength. Ideally, care should be taken to ensure that the spiral is wound in the direction that will see the higher torsional loading. However, the required direction of the spiral is typically not specified or monitored. Additionally, in the case of equal torsional loading in both directions there is no logical choice for the direction of the spiral. A confinement technique that provides equal torsional strength in both directions eliminates the possibility of columns being loaded in their torsionally weaker direction.

Torsional loads can be substantial in unsymmetrical structures, especially when wind, seismic, and other lateral loads must be considered. Torsion is a very critical issue in the seismic design of bridge columns especially when single column bents are used or geometric irregularity exist (outrigger bents).

Hindi (2005) proposed that by using two cross spirals instead of a single spiral the strength and ductility characteristics of a column can be improved or the spiral spacing can be increased to aid in constructability and concrete flow. When maximum ductility is needed, or high strength concrete is being used, cross spirals can be used with each spiral at a spacing of S, which will effectively double the volume of confining reinforcement without affecting the clearance for aggregate. In circumstances where constructability is of primary concern a spacing of 2S can be used for each cross spiral. The result would be a column with the standard amount of confining reinforcement, and therefore the same load carrying characteristics, but twice the standard clearance and more likelihood that the reinforcement can be constructed within given tolerances. The cross spiral will also provide torsional strength that is equal in both directions. This will provide a more symmetrical response to torsional load and eliminate any rotation-direction bias, as well as the possibility of a column being loaded in its torsionally weaker direction.

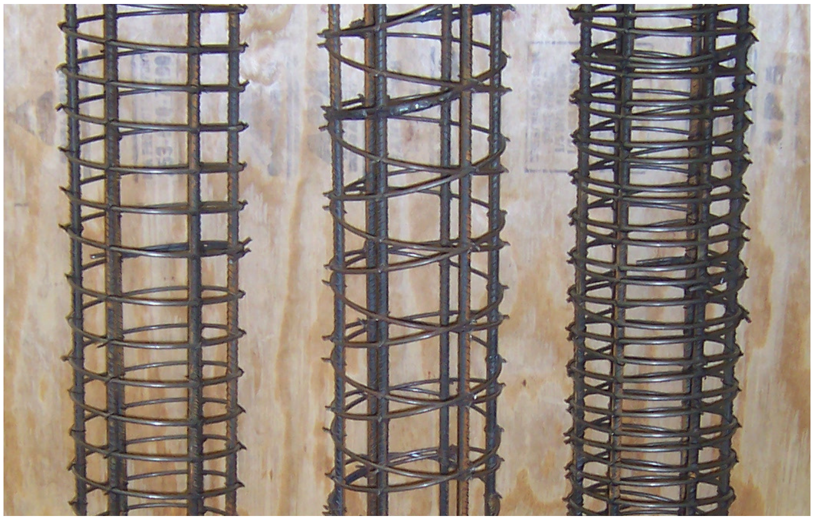

Figure 1. Single and cross spiral reinforcement.

Several experimental research projects have been completed to investigate the new confinement technique under various types of loading. Columns confined with cross spirals were first experimentally studied under monotonic axial load (Hindi and Al-Qattawi 2005). Another set of testing subjected columns reinforced with cross spirals to a constant axial load and cyclic lateral displacements to study the moment carrying capacity of the new cross spiral reinforcement technique (Turechek 2006). The results gathered from those tests showed that when compared by volumetric ratios of lateral reinforcement, the regular and the cross spiral confinement method showed comparable results in strength and ductility; however, the cross spirals showed more symmetric behavior. It was concluded that the new confinement technique could be used to improve the strength and ductility or to facilitate the construction of reinforced concrete columns and piles. The proposed confinement technique may be used to increase the spacing of the confining spiral without jeopardizing the strength and ductility of the column. It may also be used to improve the ductility and strength without reducing the spiral spacing and hindering the flow of concrete during construction.

The objective of this research is to experimentally investigate the cyclic behavior of reinforced concrete bridge columns confined using the new cross spiral confinement technique. This will be compared to columns confined with single conventional spiral. It is believed that the cross spirals will provide symmetry due to torsional loading due to the symmetrical geometry they provide

Experimental research on spirally reinforced circular concrete members subjected to cyclic torsion is extremely limited. In fact, after an extensive review of existing documents, no previous publications with this focus were found. Experimental tests applying torsional loading have been conducted on rectangular sections (i.e. Pandit 1973), rectangular high-strength concrete sections (i.e. Ashour 1999), and rectangular sections under cyclic loading (i.e. Venkappa 1987). However, any research on torsionally loaded members with circular cross sections was not found.

Experimental Program

The eighteen reinforced concrete columns considered in this research were based on typical bridge columns that satisfy all requirements of ACI 318-05 specifications. The physical dimensions and reinforcing steel were built to approximately a 1:6 scale. Four different lengths ranging from 1000 mm to 400 mm and various spiral spacings were experimentally investigated under a reversed cyclic torsional loading pattern. These experimental specimens were constructed at Bradley University in Peoria, IL and tested at the Milwaukee School of Engineering in Milwaukee, WI. The columns are compared based on their damage progression through the length of the test, failure mode, load at intermediate and ultimate rotational displacements, and reinforcement strain levels. The 18 columns were divided into six direct comparison groups of three each. Within each group is a control specimen reinforced by the conventional single spiral pattern and two experimental specimens reinforced by the experimental cross spiral pattern. The control specimen has a spiral spacing of S and the two experimental specimens have cross spiral spacings of S and 2S. Typical details of the reinforcement schemes are shown in figure 2.

Columns with lengths of 1000 mm, 800 mm, 600 mm, and 400 mm were built and tested. Three additional comparison groups with four columns in each group will also be formed from 12 of the 18 columns. Columns with the same confinement pattern and spacing will be compared from each length to investigate any possible correlation between torsional capacity and the length to diameter ratio of a column.

The experimental specimens were cast using a mix design specified for a compressive strength of 40 MPa. The experimental specimens needed to be cast in two groups of nine due to space limitations in the lab where they were being constructed. Six test cylinders were cast with each batch of experimental specimens. From each batch three cylinders were tested after 28 days and the other three cylinders were tested with the experimental specimens to obtain an accurate record of the actual concrete strength. The batch was ordered from a local ready mix concrete plant. The concrete aggregate was pea gravel with a diameter no larger than 9.5 mm to ensure passage between the various spiral spacings used to reinforce the columns. Although the concrete had a specified design compressive strength of 40 MPa, the average 28 day compressive strengths of batch 1 and batch 2, respectively, were 46 MPa and 46.9

MPa. The ultimate compressive strengths of batch 1 and batch 2 at the time of testing were, respectively, 52 MPa and 52.5 MPa.

The deformed reinforcing bars used for the longitudinal reinforcement and the smooth steel wire used for the spiral reinforcement were both tested (Hindi and Al-Qattawi 2005) in accordance with ASTM A-370 to obtain stress-strain relationships. The deformed bars were standard Grade 60 (414 MPa yield strength) reinforcing bars, although their actual tested yield strength was 467 MPa. The spiral wire yield strength was 680 MPa.

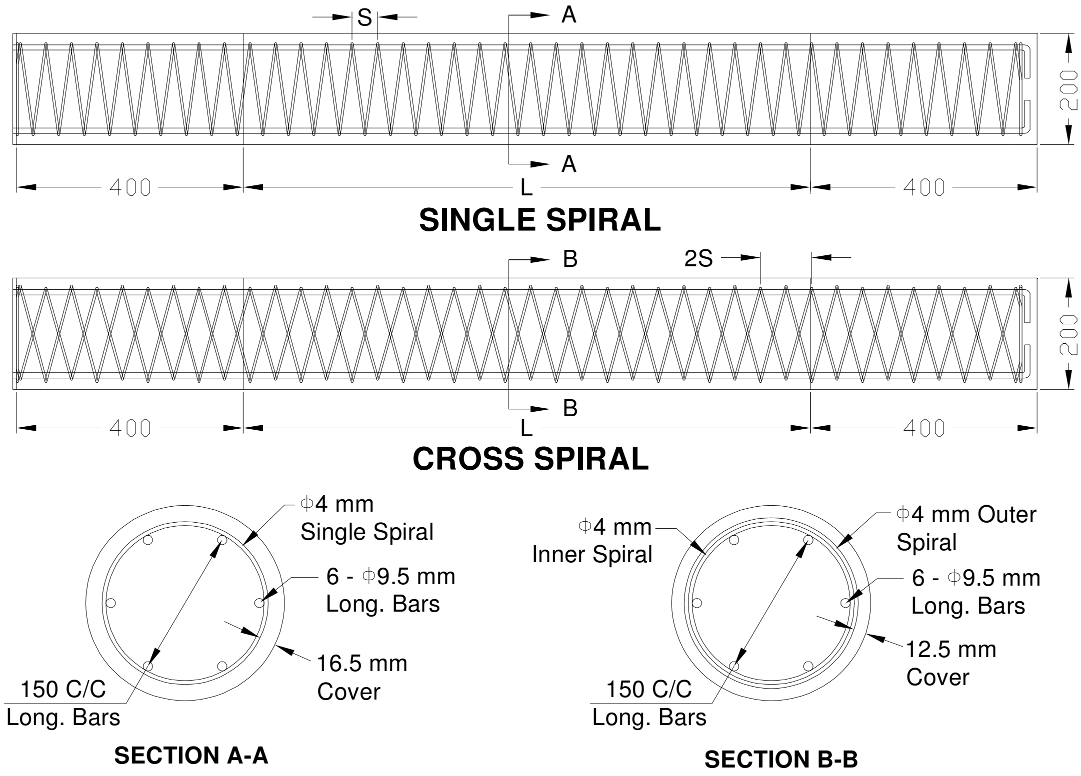

Figure 2. Specimen elevations and cross-section details.

Specimen Details

The 18 experimental specimens were built in six basic comparison groups of three specimens in each group. Three of the groups had an effective length of 1000 mm. The three remaining groups had effective lengths of 800 mm, 600 mm, and 400 mm. The experimental specimens were 200 mm in diameter and all had 200 mm square bases 400 mm long at both ends to allow the specimens to be securely fixed to the testing frame to prevent rotation.

One column in each comparison group was a control specimen confined using the conventional single spiral technique. This column's single spiral had a spiral spacing of S. The other two specimens in the comparison group were confined using the experimental cross spiral technique. One of these specimens had cross spirals with each spiral at a spacing of S and the other specimens had cross spirals with each spiral at a spacing of 2S.

The longitudinal reinforcement of all eighteen columns consisted of six typical 9.5 mm diameter (#3) deformed steel bars. The longitudinal reinforcement ratio, ρ_l, based on the gross section area was 0.013 for all columns. The spiral reinforcement was made from 4 mm diameter smooth wire. The transverse (confinement) reinforcement ratio, ρ_s, for each column is shown in Table 1. This ratio was calculated based on the column's concrete core area determined from the centerline of the spiral(s). In the cross spiral columns the average of the two spirals, or the outside of the inner spiral, was used to determine the area of the concrete core.

Each column was outfitted with six 350.0±0.3% Ω CEA Series precision strain gauges located 100 mm from the fixed base. Two gauges were placed on longitudinal bars that were oriented roughly 90 degrees from each other with respect to the center of the cross section. The remaining four gauges were placed on spirals equally spaced at the four quadrants of the circular cross section of the column. In the single spiral columns all four gauges were placed on that spiral. In the cross spiral columns two gauges were fixed to the inner spiral and two gauges were fixed to the outer spiral.

Table 1. Specimen Details.

Specimen	**Spiral Type**	**Spiral Spacing** (mm)	**Effective Length** (mm)	$\frac{L}{D}$	ρ_L	ρ_S	**f'c 28 Day** (MPa)	**f'c at Test** (MPa)
25S-10	Regular	25	1000	5	0.013	0.012	46	52
25X-10	Cross	25	1000	5	0.013	0.024	46	52
50X-10	Cross	50	1000	5	0.013	0.012	46	52
35S-10	Regular	35	1000	5	0.013	0.009	46	52
35X-10	Cross	35	1000	5	0.013	0.017	46	52
70X-10	Cross	70	1000	5	0.013	0.009	46	52
45S-10	Regular	45	1000	5	0.013	0.007	46	52
45X-10	Cross	45	1000	5	0.013	0.013	46	52
90X-10	Cross	90	1000	5	0.013	0.007	46	52
35S-8	Regular	35	800	4	0.013	0.009	46.9	52.5
35X-8	Cross	35	800	4	0.013	0.017	46.9	52.5
70X-8	Cross	70	800	4	0.013	0.009	46.9	52.5
35S-6	Regular	35	600	3	0.013	0.009	46.9	52.5
35X-6	Cross	35	600	3	0.013	0.017	46.9	52.5
70X-6	Cross	70	600	3	0.013	0.009	46.9	52.5
35S-4	Regular	35	400	2	0.013	0.009	46.9	52.5
35X-4	Cross	35	400	2	0.013	0.017	46.9	52.5
70X-4	Cross	70	400	2	0.013	0.009	46.9	52.5

Test Setup and Loading

The columns were tested at the Milwaukee School of Engineering Construction Science and Engineering Center in Milwaukee, Wisconsin. The idealized testing frame setup is shown in Figure 3 and an example of the actual test setup is shown in Figure 4. The square base at one end of the column was securely clamped to the rigid end of the testing frame to prevent rotation. The other square base was clamped to a W8x31 spandrel beam.

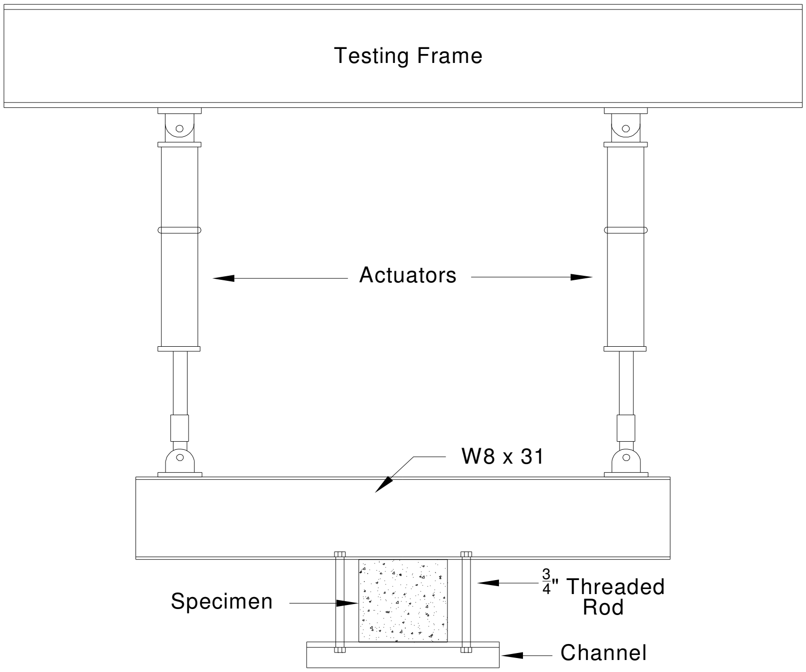

Figure 3. End view elevation.

Actuators were attached to each end of the spandrel beam. These two actuators worked in tandem to produce the torsional deformations. As can be seen in Figure 3, the ends of the actuators did not attach on a line that passed through the center of the column. Due to this, the loading program was carefully developed to ensure that rotation occurred about the center of the column only and no shear was applied to the column. Applying a particular rotation to the column required a different displacement from each actuator. Two LVDT's were located at the actuated end of the column. One LVDT was mounted to monitor the vertical position of the column end to ensure that no shear was applied from vertical displacement. The other LVDT was positioned to monitor the axial deformation of the column. In addition to the LVDT there were also vertical brackets to keep the column free of shear and in the center of the testing frame. These brackets removed any shear caused by the deformation and ensured that the effective length of the column was experiencing pure torsion. The loading was paused at various cycles during the test to mark, measure, label, and photograph cracks in addition to generally documenting the behavior and damage progression of the specimens.

The loading history used in these tests was determined from the theoretically predicted monotonic torsional capacity of the concrete. The cracking twist of the cover concrete was estimated to be 0.00221 radians per meter of column length. The loading history was developed as a function of the length of the column being tested. Expressing the twist as a rate of radians per meter of length allowed all of the columns, regardless of their length, to be compared directly. The maximum rotations in the loading history corresponded to the maximum travel limitations of the actuators used in the testing. The maximum rotations in the last cycle of the loading history coincided well with the actual ultimate capacities of the columns and therefore did not affect the test.

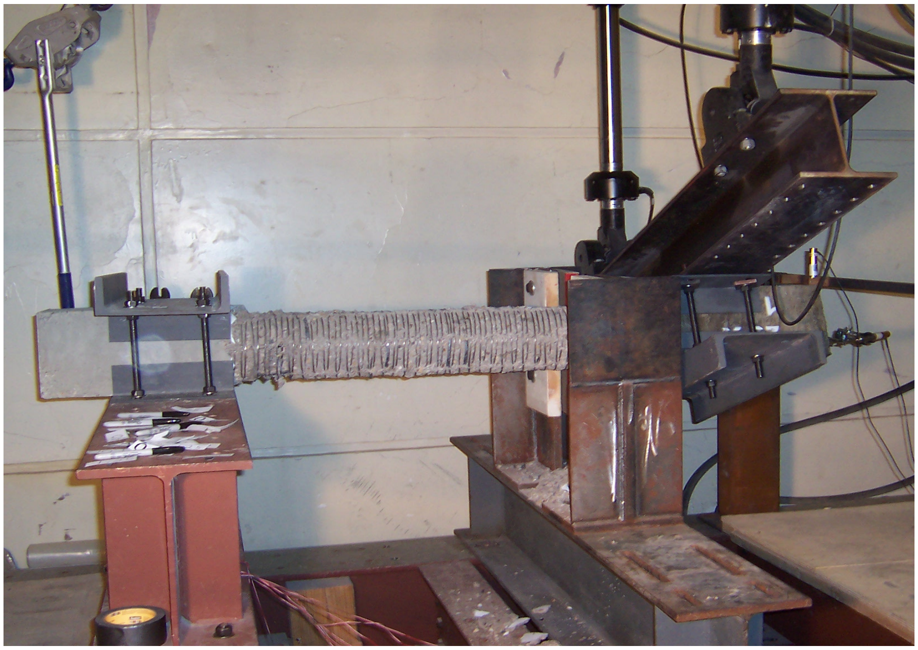

Figure 4. Actual test setup.

Results and Comparisons

The displacement (either positive or negative from the origin) of each actuator, the force in each actuator, the LVDT readings, and the six strain gauge readings were all recorded at one second intervals throughout the duration of the test. The positions of the actuators were used to determine the twist rate of the column. Each column's torsional capacity in KiloNewton-Meters was plotted against the twist rate in radians per meter. Since all of the columns were being placed in a state of pure torsion they were all expected to experience the same failure mode: yielding and eventually rupturing of the spiral in tension. The pure torsional forces caused cracks to form at nearly a perfect 45° angle to the column, which can be seen in Figure 5.

Figure 5. Typical 45° concrete crack angle.

Damage Progression

Significant events in the course of the tests happened at very similar times in the test between all specimens. Since the loading history was adjusted based on the length of the column being tested, even columns of different lengths experienced many of the significant events in the same cycles. Descriptions of the damage progression for the 1000 mm length columns 35-S, 35-X, and 70-X are provided in this paper to offer some insight into the process of failure for the torsionally loaded circular columns. Details on other specimens can be found in Browning (2007).

Specimen 35-S developed cracks in the cover concrete with widths up to 0.5 mm in Cycle 4 (0.02 rad/m). Cycle 5 (0.03 rad/m) caused 0.75 mm wide cracks. The cracks grew to as much as 1.0 mm in width by cycle 7 (0.06 rad/m). Cycle 8 (0.08 rad/m) caused significant spalling of the cover concrete. Cycle 9 (0.1 rad/m) caused the remaining cover concrete to spall off. Column failure occurred by means of the fracture of the single spiral in cycle 11 (0.2 rad/m). The fracture occurred 500 mm from the fixed end. Note that 500 mm is exactly halfway down the effective length of the column.

Cycle 3 (0.0 rad/m) caused the first cracks to form in the cover concrete of specimen 35-X. Cycle 4 (0.02 rad/m) caused the cracks to widen to as large as 0.5 mm. The cracks were widened to as much as 0.75 mm in cycle 6 (0.04 rad/m). Minor spalling along the wider cracks occurred in cycle 8 (0.08 rad/m). Cycle 9 (0.1 rad/m) caused complete spalling of the cover concrete. Column failure occurred in the form of an inner spiral fracture 100 mm from the fixed end in cycle 13 (0.4 rad/m) and is shown in Figure 6 below. The test continued to observe the behavior of the outer spiral but the core concrete crumbled, which is shown in Figure 7, due to cycling at excessive deformations.

Figure 6. Spiral rupture (35-X).

Figure 7. Core damage.

The damage progression of specimen 70-X began with cracking of the cover concrete in cycle 4 (0.02 rad/m). Cracks reached widths of up to 0.4 mm in cycle 4 and 0.5 mm in cycle 5 (0.03 rad/m). Crack widths enlarged to as much as 0.75 mm in cycle 6 (0.04 rad/m). Cycle 7 (0.06 rad/m) caused cracks to widen to 1.0 mm. Crack widths of up to 3.0 mm were present in cycle 8 (0.08 rad/m). Extreme cover spalling occurred in cycle 9 (0.1 rad/m). An inner spiral fracture caused column failure in cycle 13 (0.4 rad/m). The specimen was cycled several more times since the outer spiral had not yet ruptured. The core concrete crumbed, however, before the outer spiral failed. The inner spiral ruptured 570 mm from the fixed end.

Comparisons

Various comparisons between the columns are presented in Table 2. The twist which caused yielding in each column is compared as well as the torque resisted by the column at yielding. Also compared in the table is the torque at cycle 11 and cycle 12. These cycles induced rotations of 0.2 and 0.3 radians per meter, respectively. The final comparison is the ultimate torque capacity of the columns. The positive and negative values for each column are presented, which correspond to the values attained in the first half of a cycle and the second half of a cycle, respectively.

Table 2: Specimen results comparison.

Specimen	Yield Twist (rad/m)		Torque at Yield Twist (kN*m)		Cycle 11 Torque (0.2 rad/m)		Cycle 12 Torque (0.3 rad/m)		Ultimate Torque (kN*m)	
	+	-	+	-	+	-	+	-	+	-
25S-1000	0.014	-0.017	7.0	-5.2	11.6	-10.3	12.7	-9.0	12.7	-10.3
25X-1000	0.013	-0.011	5.8	-4.3	14.6	-13.2	16.3	-14.4	17.1	-14.7
50X-1000	0.019	-0.010	6.6	-5.6	8.5	-7.7	*	*	8.7	-8.0
35S-1000	0.013	-0.010	6.7	-5.6	9.5	-4.3	3.3	-2.5	9.7	-7.7
35X-1000	0.012	-0.009	6.0	-6.0	13.0	-11.8	14.5	-12.4	14.5	-12.4
70X-1000	0.010	-0.012	6.6	-7.0	11.5	-10.0	10.7	-10.4	11.5	-10.4
45S-1000	0.010	-0.009	6.8	-6.4	8.4	-6.4	6.3	-4.1	8.4	-7.0
45X-1000	0.012	-0.013	7.1	-5.3	11.3	-10.8	12.5	-10.7	12.5	-10.8
90X-1000	0.011	-0.013	6.4	-4.4	4.9	-3.3	2.0	-1.8	8.1	-6.8
35S-800	0.015	-0.012	7.3	-5.3	10.0	-8.0	8.4	-4.3	10.0	-8.0
35X-800	0.019	-0.020	6.9	-5.8	11.7	-11.3	12.9	-11.8	13.1	-11.8
70X-800	0.018	-0.013	7.4	-5.9	8.9	-7.7	7.9	-4.3	9.4	-8.4
35S-600	0.020	-0.025	6.3	-6.1	8.9	-5.6	6.1	-4.3	8.9	-7.1
35X-600	0.019	-0.020	7.0	-6.5	11.6	-11.5	12.5	-11.8	12.5	-11.8
70X-600	0.020	-0.026	6.5	-5.7	8.3	-8.1	8.5	-6.4	8.5	-8.1
35S-400	0.030	-0.029	6.4	-6.5	9.4	-8.0	9.7	-7.7	9.7	-8.0
35X-400	0.030	-0.027	6.8	-6.8	11.4	-11.5	12.6	-12.0	12.6	-12.0
70X-400	0.040	-0.031	6.8	-6.8	8.4	-8.1	8.0	-6.8	8.6	-8.2

* Data lost during testing due to equipment malfunction.

The similarity in the progression of events through the test was amazingly similar and predictable. Specific values of rotation and capacities varied between columns but overall the predictability of the columns' responses was reassuring. The columns typically began showing hairline cracks in cycle 4 (0.02 rad/m) and by cycle 9 (0.1 rad/m) the cover concrete had completely spalled off. Most of the variations in column performance occurred in the testing beyond cycle 9 (0.1 rad/m).

Torque vs. twist

Although many events occurred during the same cycles the forces associated with certain twists varied significantly between specimens. The torque (in kilonewton - meters) versus twist (in radians per meter) was plotted for various groups of columns to make certain comparisons. Figure 8 shows the comparison between the 1000 mm length columns 35S, 35X, and 70X. Column 35S (the experimental control) had the smallest capacity and least ductility of the three columns in this comparison. Column 70X with the same amount of steel as 35S but twice the spacing had greater capacity and greater ductility, making it to cycle 13 before failure as opposed to cycle 11 for 35S. Column 35X had the greatest capacity and ductility, as would be expected, since it contained twice the amount of reinforcing steel at the same spacing as 35S. It is important to note that not only did the 70X and 35X columns have greater strength and ductility, they also had much improved symmetry as opposed to column 35S. Once column 35S experienced failure in the first half of cycle 11 the column had very little strength in the second half of the cycle. Additional results can be found in Browning (2007).

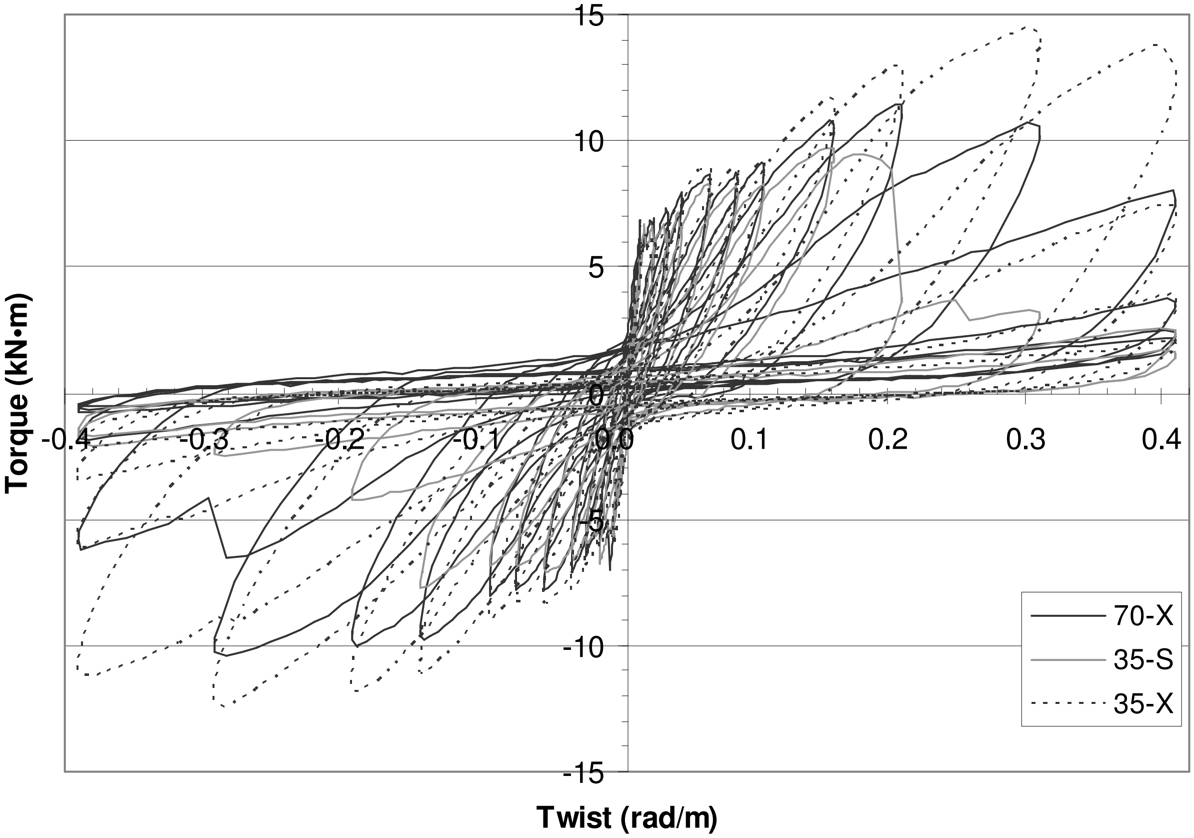

Figure 8. Torque vs. twist behavior.

Conclusions

The eighteen circular reinforced concrete columns considered in this experimental research provide two important functions. This testing provided an important fundamental base for understanding the behavior of single spiral reinforced circular concrete columns under reversed cyclic torsion. Additionally, analysis of the testing data yielded positive results regarding the benefits of the new cross spiral reinforcement pattern. The following major conclusions may be drawn from this testing:

1. Rupturing of the confining spiral was the predominant mode of failure from the pure torsional loads, as would be expected.
2. Single spiral columns are inherently stronger in one direction of rotation than the other. In this experimental research the cyclic loading patterns revealed the problematic unsymmetrical strength of the conventionally reinforced single spiral columns. The single spiral columns, on average, had 23% greater ultimate strength in their torsionally stronger direction of rotation. In contrast, the cross spiral columns had an 11% difference in ultimate strength between the two directions.
3. During testing, the single spiral columns had effectively no torsional capacity after the single spiral ruptured. The columns confined using the new technique of cross spirals have the advantage of

rupturing the two spirals at different times. The second spiral allowed the column to retain some capacity even after the first spiral had ruptured.

4. The cross spiral columns were more ductile, especially when twice the amount of lateral reinforcement was provided. Strength deterioration was greatly reduced by cross spiral confinement. The large deformation cycles typically caused the single spiral columns to reach their maximum capacities and then abruptly lose capacity. The cross spirals tended to reach maximum capacity and continue to maintain a higher level of capacity through several large deformation cycles.

Acknowledgements

The National Science Foundation and Bradley University supported this research. This support is greatly appreciated. Kyle Harris and Lonnie Marvel were instrumental in the construction and casting of the columns. Special thanks also go to Dr. Doug Stahl of MSOE for his preparation and operation of the testing equipment at MSOE and to Mr. Dave Miller, shop supervisor at Bradley University, for his assistance in constructing the specimens.

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