Axial load behavior of reinforced concrete columns with high-strength steel coiled strips as confinement

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- This paper experimentally investigates the axial load behavior of square reinforced concrete columns confined using dual-phase high-strength steel coiled strips.
- Two phases of testing were conducted on reduced-scale specimens using varied parameters, including confinement type, confinement reinforcement ratio, confinement layout, and strip anchorage.
- The results of this study show that steel strip confinement reinforcement is a potentially disruptive technology that can have a major impact on the concrete industry.

This paper experimentally investigates the novel use of ductile high-strength (Grade 100 [690 MPa]) coiled steel strips (**Fig. 1**) as embedded transverse reinforcement in reinforced concrete columns under concentric axial compression loads. In current practice, transverse reinforcement typically consists of deformed reinforcing steel bar hoops and crossties in rectangular sections (Fig. 1), and circular reinforcing bar or wire hoops or spirals in circular sections. Compared with conventional reinforcing-bar hoop reinforcement, coiled steel-strip reinforcement (Fig. 1) can provide the following advantages:

- greater volume of effectively confined concrete from the wider and thinner strip
- greater effective depth of the extreme longitudinal reinforcing bar (for flexure) from the thinner tie, hoop, or spiral
- improved lateral support against longitudinal reinforcing bar buckling after spalling of the cover concrete from the greater width of the strips

Coiled strips can also accelerate fabrication of precast concrete components because strips can be rapidly uncoiled, bent, wrapped, and tied to longitudinal reinforcing bar with no need for splices; and strips with smaller bend radii reduce congestion, thereby easing placement of longitudinal reinforcing bar and concrete.

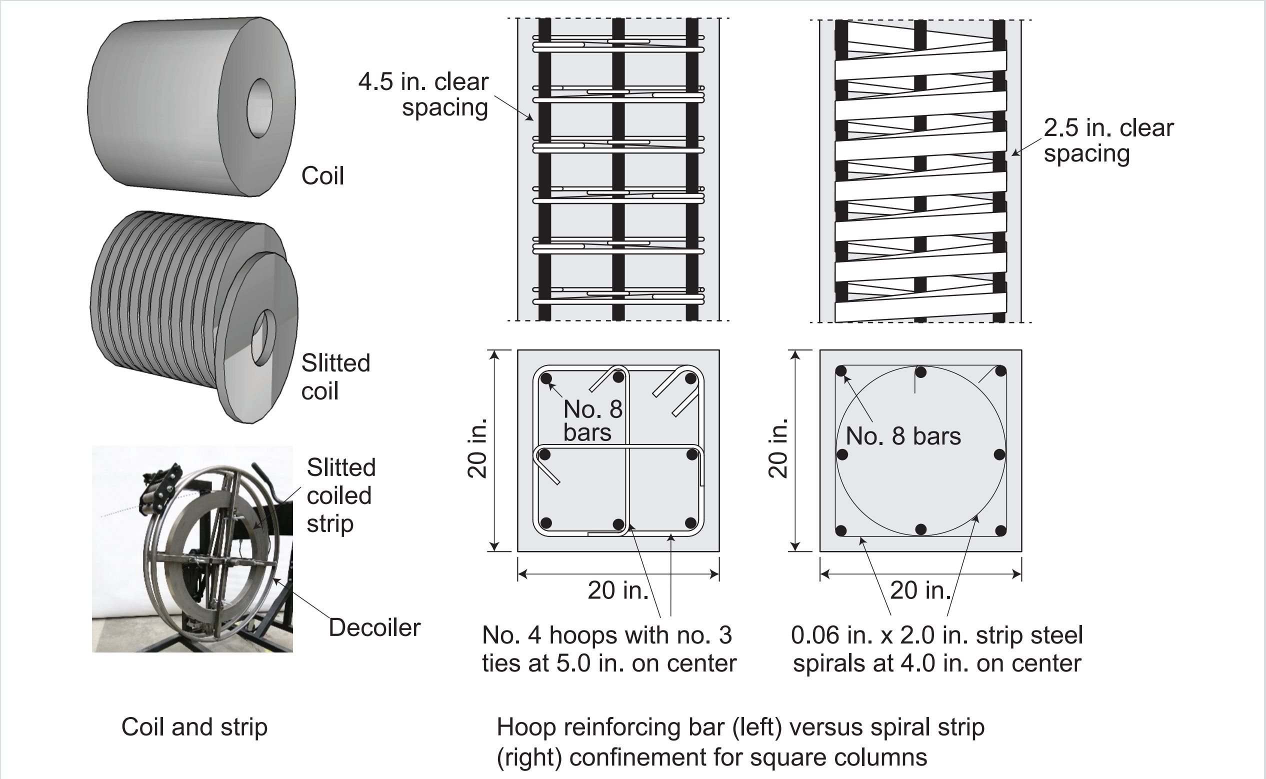

Figure 1. High-strength steel strip reinforcement. Note: no. 3 = 10M; no. 4 = 13M; no. 8 = 25M; 1 in. = 25.4 mm.

As an example, Fig. 1 shows a column cross section confined by conventional Grade 100 (690 MPa) reinforcing bar hoops compared with Grade 100 spiral coiled steel-strip confinement. Both configurations satisfy the transverse reinforcement requirements for columns of special moment frames in the American Concrete Institute's (ACI's) *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19).*[1]

Existing ductile high-strength coil products in the United States (particularly for the automotive industry) were used and slit to the necessary strip widths by the manufacturer (Fig. 1). **Figure 2** shows the stress-strain behavior of dual-phase (DP) 980/700 coil steel[2] compared with state-of-practice Grades 60 and 100 (414 and 690 MPa) deformed reinforcing bar.[3,4] The tensile strength of DP 980/700 steel is significantly greater than that of Grade 60 reinforcing bar while also being significantly more ductile than Grade 100 reinforcing bar. As such, a reduced lateral tie volume of DP 980/700 steel-strip confinement compared with Grade 60 reinforcement may be needed to achieve similar confinement. The higher ductility of the DP 980/700 steel compared with Grade 100 reinforcing bar indicates that the strip confinement has the potential to provide increased ductility in reinforced concrete columns under seismic loading while achieving similar capacities.

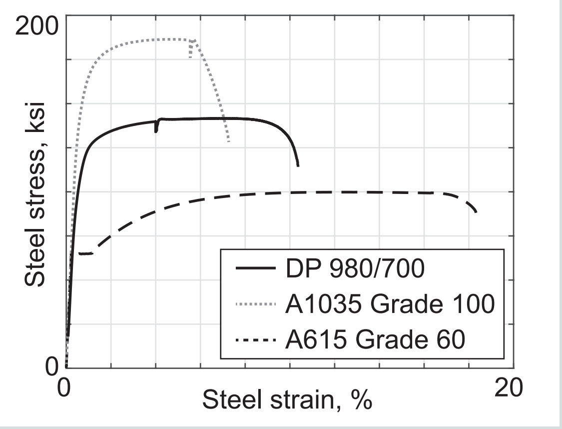

Figure 2. Comparison of stress-strain behavior for DP 980/700 steel and reinforcing bar. Note: Grade 60 = 414 MPa; Grade 100 = 690 MPa; 1 ksi = 6.895 MPa.

To experimentally evaluate the performance of steel coiled strips as transverse reinforcement, this paper reports on the measured axial compression behaviors of reduced-scale square columns with varying confinement configurations under concentric axial loading. The primary objectives of the research are to conduct experimental testing of strip-confined precast concrete columns under concentric axial loading and use the measured results to evaluate the applicability of current confinement design methods for strip-confined columns.

Although the experimental testing is specifically on confined concrete columns, the results may also be relevant to the boundary regions and plastic-hinge zones of beams, walls, and piers. This is a pilot study focused on evaluating the viability of strip-confined reinforcement under axial compression tests. Further testing to investigate behavior under combined axial and reversed-cyclic lateral (flexural) loads is necessary to fully evaluate coiled steel strips as a confinement strategy.

Background

The current requirements for the design of confinement reinforcement in the plastic hinge zones of special moment frames and boundary regions of special structural walls are specified in chapter 18 of ACI 318-19.[1] ACI 318-19 permits the use of deformed bars and deformed wire[5] with steel yield strengths up to 100 ksi (690 MPa) for concrete confinement in special seismic building structural systems and for spirals. Previous research on conventionally confined concrete columns with deformed reinforcing bar and wire is extensive[6–17] and led to the current ACI 318-19 requirements for the design of confinement reinforcement. This includes a significant number of laboratory tests on columns under both concentric axial loading and combined axial and flexural loading. Recently, researchers have also investigated reinforcing bar bent into rectangular or square spirals for continuous confinement or shear reinforcement in reinforced concrete members.[18–22] Headed reinforcing bar[9,23] and welded wire reinforcement[24–29] have also been investigated as methods for concrete confinement.

No previous experimental work exists on the use of steel strips as embedded transverse reinforcement for reinforced concrete structures in the United States; however, strip hoop reinforcement was used in the United States by Robert Cummings as early as 1911.[30] Outside of the United States, Shafqat and Ali[31] investigated the use of steel strips in a hoop layout by experimentally evaluating three reinforced concrete columns (two with steel strip hoops and one control with conventional reinforcing bar) in axial compression. They found that one of the strip-confined specimens, which had equivalent confinement steel area and spacing to the reinforcing-bar-confined specimen, had higher strength and ductility than the reinforcing-bar-confined specimen. Ilyas et al.[32] experimentally investigated the use of steel strips as confinement reinforcement for masonry columns.

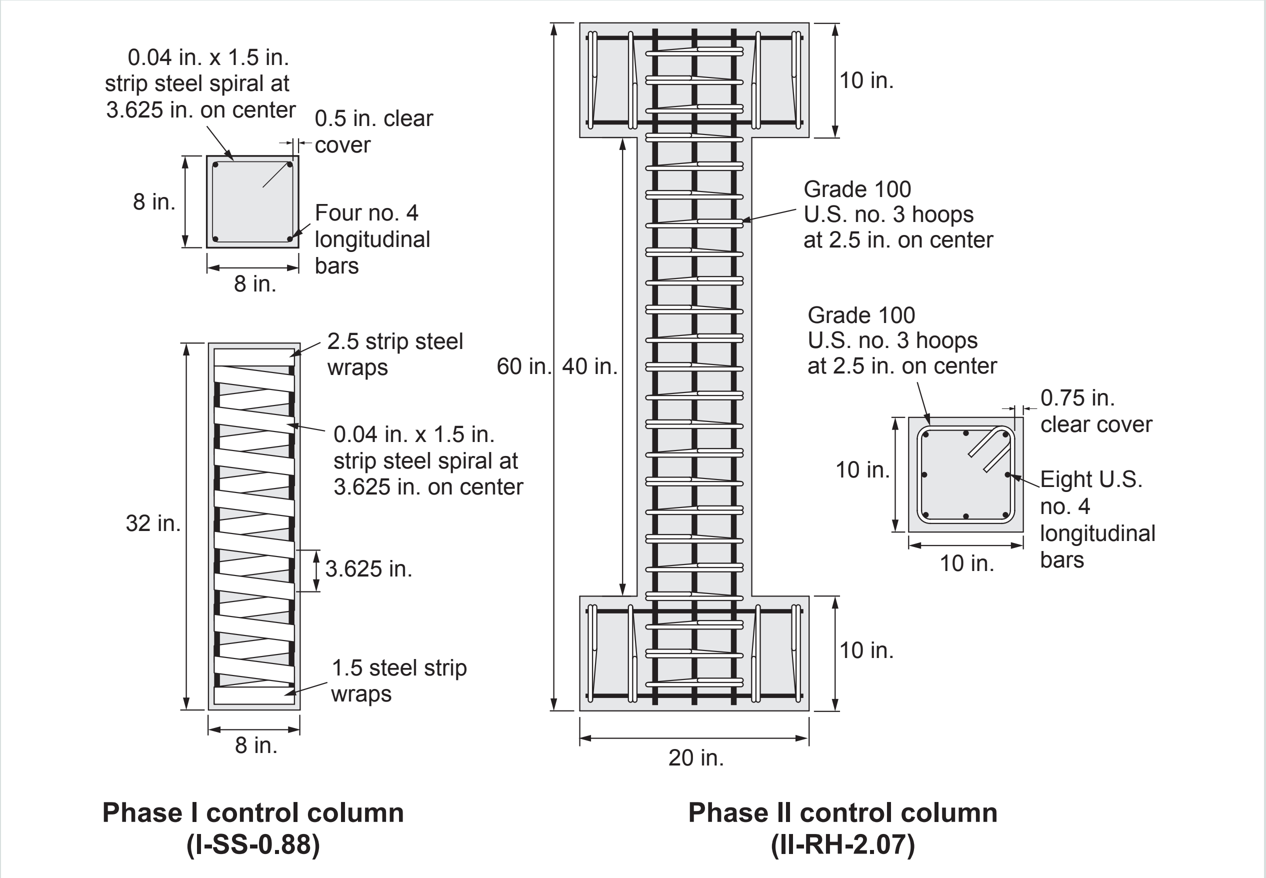

Figure 3. Phase I and II control columns (I-SS-0.88 and II-RH-2.07). Note: For specimen labels, the first term denotes test phase (I or II), the second term denotes confinement reinforcement type and layout (RH = reinforcing bar hoops, SS = strip spiral, SH = strip hoops, 2SS = two strip spirals, and UNC = unconfined), and the third term denotes confinement volumetric ratio as a percentage. Grade 100 = 690 MPa; no. 3 = 10M; and no. 4 = 13M; 1 in. = 25.4 mm.

Experimental program

A total of 15 square reinforced concrete column specimens were cast horizontally, rotated vertically 90 degrees, and evaluated under monotonic concentric axial load. The testing was conducted in two phases with different column geometries (**Fig. 3**) and loading setups. In phase I, prismatic column specimens were evaluated with cross-section widths b_c and depths d_c of 8.00 in. (203 mm) and column heights h_{ct} of 32.0 in. (813 mm), resulting in a height-to-depth aspect ratios h_{ct}/d_c of 4.00. The phase II columns were evaluated at a larger scale (b_c and d_c equal to 10.0 in. [254 mm]) to allow for more direct comparisons to the typical sizes and layouts of reinforcing bar in full-scale precast concrete columns. This increase in size enabled the use of strip reinforcement with a cross-sectional area equivalent to a no. 3 (10M) reinforcing bar without violating the minimum clear spacing requirements in ACI 318-19 for confinement, thus providing an opportunity for direct comparison with conventional reinforcing bar. Further, an eight-bar longitudinal layout is possible, which is more representative of typical column layouts. While it would have been ideal to test a full-scale column with larger longitudinal bars, the experimen-

Table 1. Test specimen details

Column specimen†	f'_c, ksi	E_c, ksi	No. 4 longitudinal reinforcement			Confinement reinforcement						
			n_b	f_{yl}, ksi	ρ_{sl}, %	Type	w_s, in.	t_s, in.	d_b, in.	s_t, in.	f_{yt}, ksi	ρ_{st}, %
Phase I (8 × 8 in.)												
I-SS-0.88‡										3.63	93.3	0.88
I-SS-0.75										4.25	93.3	0.75
I-SS-0.69						Strip spiral	1.50	0.04	n/a	4.88	93.3	0.69
I-SS-0.55	7.87	5860	4	65.9	1.25					5.88	93.3	0.55
I-SS-0.44										7.25	93.3	0.44
I-SS-0.88*										3.63	n/a	0.88
I-UNC						Unconfined						
Phase II (10 × 10 in.)												
II-RH-2.07‡	3.86	5450				Reinforcing bar hoops	n/a	n/a	0.38	2.50	150	2.07
II-RH-3.11	3.77	4770				Reinforcing bar hoops and ties	n/a	n/a	0.38	2.50	150	3.11
II-SH-2.07	5.37	5210				Strip hoops	2.00	0.06	n/a	2.50	108	2.07
II-SS-2.07	5.31	5740	8	64.5	1.60					2.50	108	2.07
II-SS-1.38	5.60	6100				Strip spiral	2.00	0.06	n/a	3.75	108	1.38
II-SS-1.04	5.73	5950								5.00	108	1.04
II-2SS-1.64	5.52	5350				Two strip spirals	1.50	0.04	n/a	2.50	93.3	1.64
II-2SS-1.35	5.70	5200								2.5/5.0§	93.3	1.35

Note: n/a = not applicable; d_b = reinforcing bar diameter; E_c = concrete elastic modulus (3 × 6 in. cylinders) on column test day; f'_c = measured concrete compressive strength (3 × 6 in. cylinders) on column test day (28-day strengths given in Table 3); f_{yl} = measured longitudinal steel yield strength; f_{yt} = measured confinement steel yield strength; n_b = number of longitudinal bars; n/a = not applicable; s_t = confinement steel center-to-center spacing (pitch); t_s = steel strip thickness; w_s = steel strip width; ρ_{sl} = longitudinal steel reinforcement ratio; ρ_{st} = volumetric reinforcement ratio of confinement steel. No. 4 = 13M. 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

* Alternative anchorage.

† The first term denotes the test phase (I or II), the second term denotes confinement reinforcement type and layout (RH = reinforcing bar hoops, SS = strip spiral, SH = strip hoops, 2SS = two strip spirals, and UNC = unconfined), and the third term denotes confinement volumetric ratio as a percentage. Figure 4 lists corresponding column cross-section layouts.

‡ Control column.

§ Center-to-center spacing (pitch) of outside and inside steel strip spirals, respectively.

tal program was limited by the capacity of the testing equipment. The specimen height h_{ct} of 40.0 in. (1020 mm) maintained the height-to-depth aspect ratio of 4.00 over the column test height. An enlarged end-cap region beyond the test height at each column end was also detailed for the phase II specimens to improve the boundary conditions and force the failure away from the top and bottom load application points (Fig. 3). The overall height of the phase II columns including the end-cap regions was 60.0 in. (1520 mm).

Column design overview

Table 1 summarizes the important column specimen details, including the following:

- confinement reinforcement type and layout
- test-day concrete compressive strength f'_c and concrete elastic modulus E_c
- longitudinal reinforcement details (number of bars n_b, bar size, measured yield strength f_{yl}, and reinforcement ratio ρ_{sl})
- confinement reinforcement details (strip width w_s, strip thickness t_s, reinforcing bar diameter d_b, spacing s_t, measured yield strength f_{yt}, and volumetric reinforcement ratio ρ_{st})

Figure 4 illustrates the six different confinement layouts used for the specimens between the two phases of testing (one layout for phase I and five for phase II). Specimens are labeled with a first term that denotes test phase (I or II), a second term that denotes confinement reinforcement type and layout (RH = reinforcing bar hoops, SS = strip spiral, SH = strip hoops, 2SS = two strip spirals, and UNC = unconfined), and a third term that denotes the confinement volumetric ratio as a percentage. All columns featured U.S. no. 4, Grade 60 (no. 13, Grade M420) ASTM A615 bars for the longitudinal reinforcement and either high-strength ASTM A1035 bars or DP 980/700 coiled strip steel with specified yield strength greater than 100 ksi (690 MPa) for the confinement reinforcement. The target design unconfined compressive strengths for the concrete f'_{dc} in phases I and II were 6.00 and 5.00 ksi (41.4 and 34.5 MPa), respectively. The target concrete compressive strength for the phase II columns was less than phase I to limit the increase in the column axial strength due to the larger cross-sectional area and maximum capacity of the test setup.

The code requirements for the design of confinement regions in reinforced concrete columns of special moment frames are

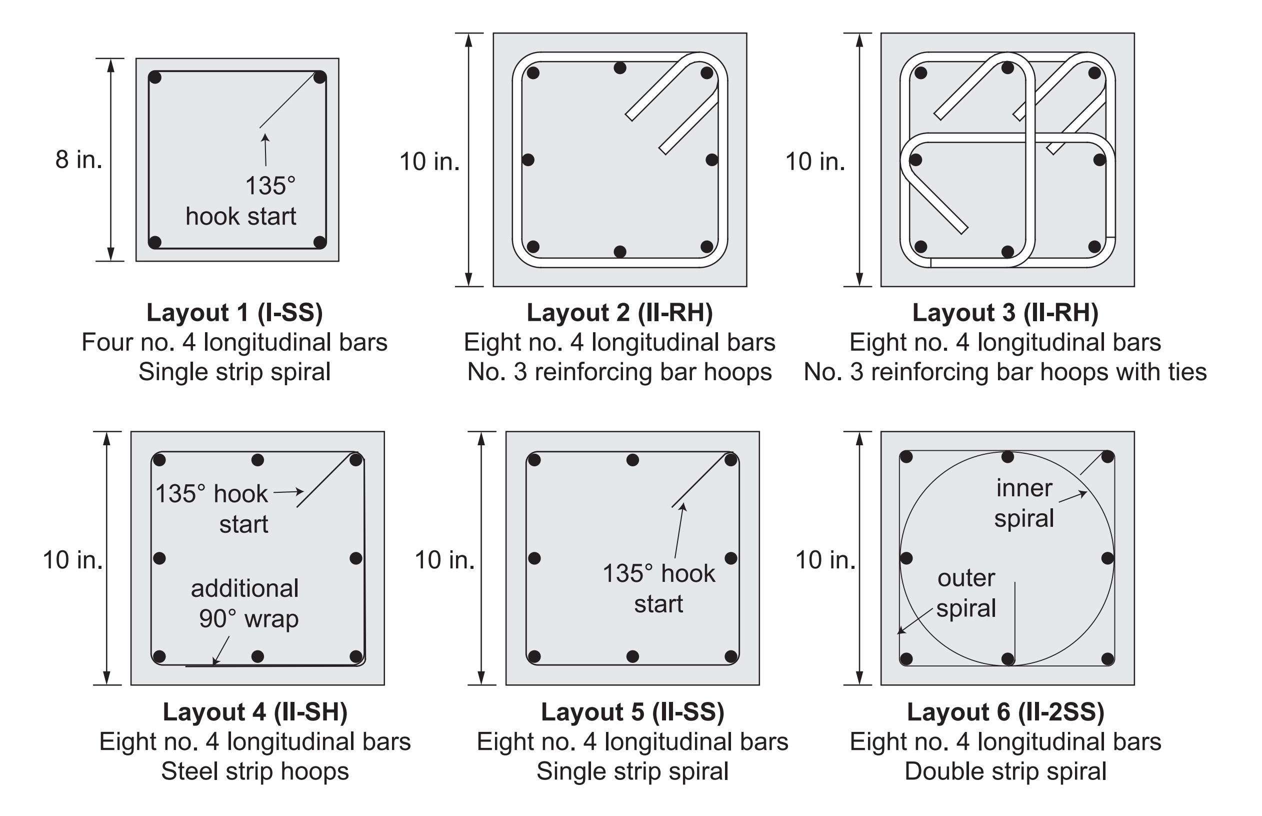

Figure 4. Column confinement layouts. Note: For specimen labels, the first term denotes test phase (I or II), and the second term denotes confinement reinforcement type and layout (RH = reinforcing bar hoops, SS = strip spiral, SH = strip hoops, 2SS = two strip spirals, and UNC = unconfined). No. 3 = 10M; no. 4 = 13M; 1 in. = 25.4 mm.

outlined in section 18.7.5 of ACI 318-19.[1] Table 18.7.5.4 in ACI 318-19 provides the applicable equations for determining the minimum volumetric confinement ratios for rectilinear hoops $\rho_{st,min1}$ (Eq. [1]) and circular spirals and hoops $\rho_{st,min2}$ (Eq. [2]).

$$\rho_{st,min1} = 0.60\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f'_{dc}}{f_{syt}} \tag{1}$$

where

A_g = gross area of column cross section

A_{ch} = cross-sectional area of concrete core measured to the outside edges of the confinement reinforcement

f'_{dc} = design concrete compressive strength

f_{syt} = specified yield strength of confinement reinforcement

$$\rho_{st,min2} = 0.45\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f'_{dc}}{f_{syt}} \tag{2}$$

Equation (1) was adjusted from the original equation in ACI 318-19 for area-based reinforcement ratio to determine the volumetric (volume-based) reinforcement ratio for rectilinear hoops in a symmetrically reinforced square column. Because rectilinear spiral reinforcement does not fall under either the category of rectilinear hoops (Eq. [1]) or circular or spiral hoops (Eq. [2]), both equations are used as a point of comparison. Equation (1) for rectilinear hoops can be considered the most applicable (and conservative) equation for the spiral strip because the spiral strip does not strictly meet the definition of a spiral per section 2.3 of ACI 318-19, which defines spiral reinforcement as "continuously wound reinforcement in the form of a cylindrical helix." Equation (2) for circular or spiral hoops is still used as a point of comparison. **Table 2** compares the selected confinement reinforcement parameters for the column specimens in this study with the corresponding ACI 318-19 requirements for the following:

- maximum center-to-center confinement spacing $s_{t,max}$ (section 18.7.5.3 of ACI 318-19)
- maximum clear spacing $s_{tc,max}$ (section 25.7.2.1[a] of ACI 318-19)
- minimum clear spacing $s_{tc,min}$ (section 25.7.3.1[b] of ACI 318-19)
- minimum volumetric confinement ratios using Eq. (1) and (2)

Phase I test program

Summary of phase I columns All six columns with confinement reinforcement in phase I had reinforcement details in Fig. 4 layout 1 and featured continuous strip spirals with a strip thickness t_s of 0.040 in. (1.0 mm) and width w_s of 1.50 in. (38.1 mm). Because of the smaller cross-sectional area of the phase I columns, the number of longitudinal bars n_b was 4 (with one bar at each corner) and a small concrete clear cover of 0.500 in. (12.7 mm) was detailed. No. 4 (13M), Grade 60 (414 MPa) ASTM A615 bars were selected for this reinforcement, resulting in a longitudinal steel ratio ρ_{sl} of 1.24%. This percentage is within the allowable range specified in section 18.7.4.1 of ACI 318-19. Anchorage of the control steel strip spiral in phase I started with a 135-degree hook around a corner bar at the bottom of the column cage and then 1.5 horizontal wraps around the perimeter of all four longitudinal bars of the column specimen. The pitch was then increased to the specified confinement spacing s_t and spiraled over the column test height before being terminated in another 2.5 horizontal wraps at the top of the column (Fig. 3 for the phase I control column with s_t of 3.63 in. [92.2 mm]).

The parameters that varied in phase I were confinement reinforcement ratio through varied strip pitch and spacing (columns I-SS-0.88 through I-SS-0.44) and steel strip anchorage (columns I-SS-0.88 and I-SS-0.88*).

A baseline column (column I-UNC) with four longitudinal bars and no confinement reinforcement was evaluated for comparison purposes. To evaluate the effectiveness of anchoring the steel strip, the strip spiral in one column specimen (I-SS-0.88*) was terminated at the top by wrapping around the column longitudinal bars 1.5 times (rather than 2.5 times at the top in the other specimens). For columns I-SS-0.88 through I-SS-0.44, the confinement steel center-to-center spacing (pitch) s_t was increased from 3.63 to 7.25 in. (92.2 to 184 mm), with the corresponding volumetric steel ratios ρ_{st} decreasing from 0.88% to 0.44%. The confinement ratios for all phase I specimens did not meet the minimum volumetric confinement ratios for rectilinear hoops $\rho_{st,min1}$ of 1.10% specified by Eq. (1) (Table 2); however, the volumetric steel ratio for the control column (I-SS-0.88) did meet the minimum required for circular spirals or hoops ($\rho_{st,min2}$ is 0.830% from Eq. [2]). The phase I columns exceeded the maximum center-to-center confinement spacing requirement $s_{t,max}$ from section 18.7.5.3 of ACI 318-19, and three of the six specimens with confinement exceeded the maximum clear spacing requirement $s_{tc,max}$ (Table 2).

Phase I test setup and instrumentation The small-scale phase I columns were evaluated in a 600 kip (2670 kN) universal testing machine (**Fig. 5**). A 10.0 in. (254 mm) square and 1.50 in. thick (38.1 mm) bearing plate was placed at the top and bottom ends of each column to evenly distribute the compression load. A swivel-head attachment above the top bearing plate allowed for small rotations due to any asymmetries in the column specimen. Before testing, an initial load equal to 10% of the predicted column axial strength (about 50 kip [220 kN]) was applied (at a load rate of 320 lb/sec [1420 N/sec]) to seat the specimen in the testing machine and check that the instrumentation was functioning properly. This initial load was then removed and the test to failure was conducted in two stages. In the first stage, the testing machine was operated in load control at a rate of 320 lb/sec until a greater than 50% load drop from the peak axial strength. One column (I-SS-0.88*) was evalu-

Table 2. ACI 318-19 confinement requirements

Column specimen[†]	ACI 318-19 requirement					Specimen confinement reinforcement		
	$s_{t,max}$,[‡] in.	$s_{tc,min}$,[§] in.	$s_{tc,max}$,[‖] in.	$\rho_{st,min1}$,[#] %	$\rho_{st,min2}$,[**] %	s_t, in.	s_{tc}, in.	ρ_{st}, %
I-SS-0.88						3.63[††]	2.13	0.88[††]
I-SS-0.75						4.25[††]	2.75	0.75[††]
I-SS-0.69	2.00	0.50	3.00	1.10	0.83	4.88[††]	3.38[††]	0.69[††]
I-SS-0.55						5.88[††]	4.38[††]	0.55[††]
I-SS-0.44						7.25[††]	5.75[††]	0.44[††]
I-SS-0.88[*]						3.63[††]	2.13	0.88[††]
II-RH-2.07						2.50	2.13	2.07
II-RH-3.11			n/a			2.50	2.13	3.11
II-SH-2.07						2.50	0.50	2.07
II-SS-2.07	2.50	0.50		1.15	0.86	2.50	0.50	2.07
II-SS-1.38						3.75[††]	1.75	1.38
II-SS-1.04			3.00			5.00[††]	3.00	1.04[††]
II-2SS-1.64						2.50	1.00	1.64
II-2SS-1.35						2.5/5.0[††‡‡]	1.0/3.5[††‡‡]	1.35

Note: s_t = center-to-center spacing of confinement steel; $s_{t,max}$ = maximum center-to-center confinement spacing; s_{tc} = clear spacing of confinement steel; $s_{tc,max}$ = maximum clear spacing of confinement steel; $s_{tc,min}$ = minimum clear spacing of confinement steel; ρ_{st} = volumetric reinforcement ratio of confinement steel. 1 in. = 25.4 mm.

* Alternative anchorage.

† The first term denotes test phase (I or II); second term denotes confinement reinforcement type and layout (RH = reinforcing bar hoops, SS = strip spiral, SH = strip hoops, 2SS = two strip spirals, and UNC = unconfined), and the third term denotes confinement volumetric ratio as a percentage. Figure 4 lists corresponding column cross-section layouts.

‡ From section 18.7.5.3 of ACI 318-19.

§ From section 25.7.2.1(a) of ACI 318-19 with nominal coarse aggregate size equal to ⅜ in.

‖ From section 25.7.3.1(b) of ACI 318-19 for spirals.

\# Adapted from expression (a) in Table 18.7.5.4 of ACI 318-19 for rectilinear hoops.

** From expression (d) in Table 18.7.5.4 of ACI 318-19 for spirals and circular hoops.

†† Specimen parameters that did not meet one or more ACI 318-19 requirements. For minimum reinforcement ratios, $\rho_{st,min1}$ governs for spiral strips as opposed to $\rho_{st,min2}$ because the spiral strips do not meet the strict definition of spirals in ACI 318-19.

‡‡ Center-to-center or clear spacing (pitch) of outside and inside strip spirals.

ated under load control (at a load rate of 320 lb/sec) until an initial load of 250 kip (1110 kN), and then testing continued in displacement control at a rate of 0.005 in./sec (0.13 mm/sec) through failure. The test was ended when there was a greater than 50% load drop from the peak axial strength. This loading protocol was used to determine differences in behavior due to the loading method.

The test-day measured concrete compressive strengths f'_c provided in Table 1 for phase I correspond to the first day of evaluating each virgin column. The second stage of testing was conducted later, when each column was reset in the testing machine and loaded again under displacement control (a rate of 0.005 in./sec [0.13 mm/sec]) to determine the residual axial strength. These tests were conducted until there was a greater than 50% drop in axial load capacity from the peak residual strength.

In addition to the internal crosshead displacement measurement from the testing machine, four linear variable displacement transducers with 8.00 in. (203 mm) gauge length and ±1.00 in. (25.4 mm) stroke were placed symmetrically about the midheight on each column face to measure the axial shortening displacements (Fig. 5). To prevent damage due to cover spalling, these sensors were removed during the first loading stage by pausing the test at 50% of the nominal column axial strength.

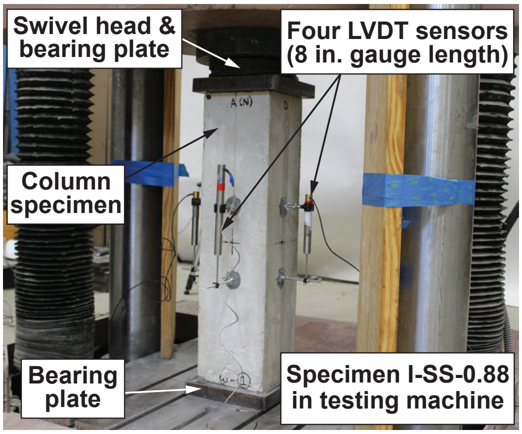

Figure 5. Phase I test setup and instrumentation. Note: For specimen labels, the first term denotes test phase (I or II), the second term denotes confinement reinforcement type and layout (RH = reinforcing bar hoops, SS = strip spiral, SH = strip hoops, 2SS = two strip spirals, and UNC = unconfined), and the third term denotes confinement volumetric ratio as a percentage. LVDT = linear variable displacement transducer.

Phase II test program

Summary of phase II columns The larger-scale columns evaluated as part of phase II provided important benefits in determining the effectiveness of the strip confinement. Specifically, it was possible to use strip reinforcement (t_s of 0.060 in. [1.5 mm] and w_s of 2.00 in. [50.8 mm]) with an area equivalent to no. 3 (10M) reinforcing bar without violating the minimum clear spacing requirements in ACI 318-19 for confinement. An intermediate longitudinal reinforcing bar (Fig. 4) was added to each column face to be more representative of full-scale column reinforcing bar layouts (eight no. 4 [13M], Grade 60 [414 MPa] ASTM A615 bars). This resulted in a longitudinal reinforcement ratio ρ_{sl} of 1.60%, slightly larger than the 1.20% ρ_{sl} for the phase I columns. A larger cover of 0.750 in. (19.1 mm) was used for the phase II columns (Fig. 3).

In phase I, concrete cover crushing or spalling generally initiated at either the top or bottom of the column adjacent to the bearing plates of the testing frame rather than near the midheight. To mitigate potential end loading effects, enlarged end-cap regions were added at the top and bottom of the column test height in phase II (Fig. 3). These end-cap regions had twice the cross-sectional area within the column test height. As an added benefit, the spiral strip confinement was continuous over the column test height region and fully embedded and developed within the end-cap volumes.

The following parameters were varied in phase II:

- confinement type (strip reinforcement versus reinforcing bar)
- confinement reinforcement ratio (by changing strip cross-sectional area or strip spacing)
- strip confinement layout (hoops, single spiral, or two spirals [Fig. 4])

The control column (II-RH-2.07) in Fig. 3 was designed to be a baseline representation of a state-of-practice reinforced concrete column in special moment frames. Based on the phase II column dimensions and design material properties, Grade 100 (690 MPa) no. 3 (10M) reinforcing bar hoops with an s_t of 2.50 in. (63.5 mm) and anchored with 135-degree seismic hooks were selected for the lateral confinement reinforcement (corresponding to layout 2 in Fig. 4). The resulting volumetric steel ratio ρ_{st} was 2.07%, exceeding the minimum of 1.15% specified in ACI 318-19 for rectilinear hoops (Table 2). The intermediate longitudinal bars on the column faces did not need to be supported by crossties or seismic hooks per the ACI 318-19 requirements; however, recent research[33] has recommended that every longitudinal bar in the columns of special moment frames be supported by a hoop corner or a seismic hook to improve ductility and toughness under seismic loading. Column II-RH-3.11 (layout 3 in Fig. 4) was detailed to account for this potential code change through the addition of no. 3 (10M) reinforcing bar crossties between the two sets of intermediate longitudinal bars.

Columns II-SH-2.07 and II-SS-2.07 represented baseline strip-confined columns with individual strip hoops and continuous single strip spiral layouts, respectively (layouts 4 and 5 in Fig. 4). A column with individual strip hoops was included to evaluate the effectiveness compared with the spiral configuration. In both cases, the spacing and volumetric ratio of the strip confinement matched the details for the control column II-RH-2.07 with reinforcing bar hoop confinement. These three columns satisfied the ACI 318-19 confinement design requirements (Table 2). For column II-SH-2.07, the steel strip hoops were anchored in the concrete (layout 4 in Fig. 4) in a similar manner to the start of the strip spirals in phase I (initial 135-degree hook and then wrapping 1.5 times around the longitudinal bars).

The strip width w_s of 2.00 in. (50.8 mm) combined with the center-to-center spacing s_t of 2.50 in. (63.5 mm) resulted in a small clear spacing between the hoops or spiral legs of 0.500 in. (12.7 mm). This clear spacing was small compared with that of 2.13 in. (54.1 mm) for the control column with reinforcing bar hoop confinement. As such, a concrete mixture with nominal coarse aggregate size equal to 0.375 in. (9.53 mm) was selected to allow for proper concrete consolidation between the confinement layers per ACI 318-19 requirements. For columns II-SS-2.07 through II-SS-1.04 (layout 5), the spacing of the single strip spirals s_t was increased from 2.50 to 5.00 in. (127 mm) with the corresponding volumetric steel ratios ρ_{st} decreasing from 2.07% to 1.04%. This range of ρ_{st} and s_t allowed for the minimum reinforcement ratios and maximum spacing requirements in chapter 18 of ACI 318-19 to be evaluated for strip confinement (Table 2).

Layout 6 in Fig. 4 was detailed to provide support for every longitudinal bar using a strip double spiral layout consisting of an inner circular spiral within an outer square spiral. This layout was selected because the large width of the strip steel does not allow for the use of crossties (layout 3). Further, the continuous spirals and circular geometry of the inner spiral would likely be more effective in confining the core concrete. Column II-2SS-1.64 featured layout 6 details with spacing of both the outer and inner spirals equal to 2.50 in. (63.5 mm). For column II-2SS-1.35, the spacing of the inner strip spiral was increased to 5.00 in. (127 mm), which exceeds $s_{t,max}$ recommendations in ACI 318-19 (Table 2), to determine whether larger inner spiral spacing would still provide adequate support to the intermediate longitudinal bars. A smaller strip with a thickness t_s of 0.040 in. (1.0 mm) and width w_s of 1.50 in. (38.1 mm) was used for these columns to not provide an overly large volumetric confinement ratio. The confinement ratios for columns II-2SS-1.64 and II-2SS-1.35 were 1.64% and 1.35%, respectively, and exceeded the minimum ratios required by ACI 318-19 (both the minimum reinforcement ratio for rectilinear hoops [Eq. 1] and for spiral and circular hoops [Eq. 2]) for the phase II column geometry (Table 2).

Phase II test setup and instrumentation Due to the increased column cross-sectional area in phase II (56% larger), a different testing frame (**Fig. 6**) with a larger axial

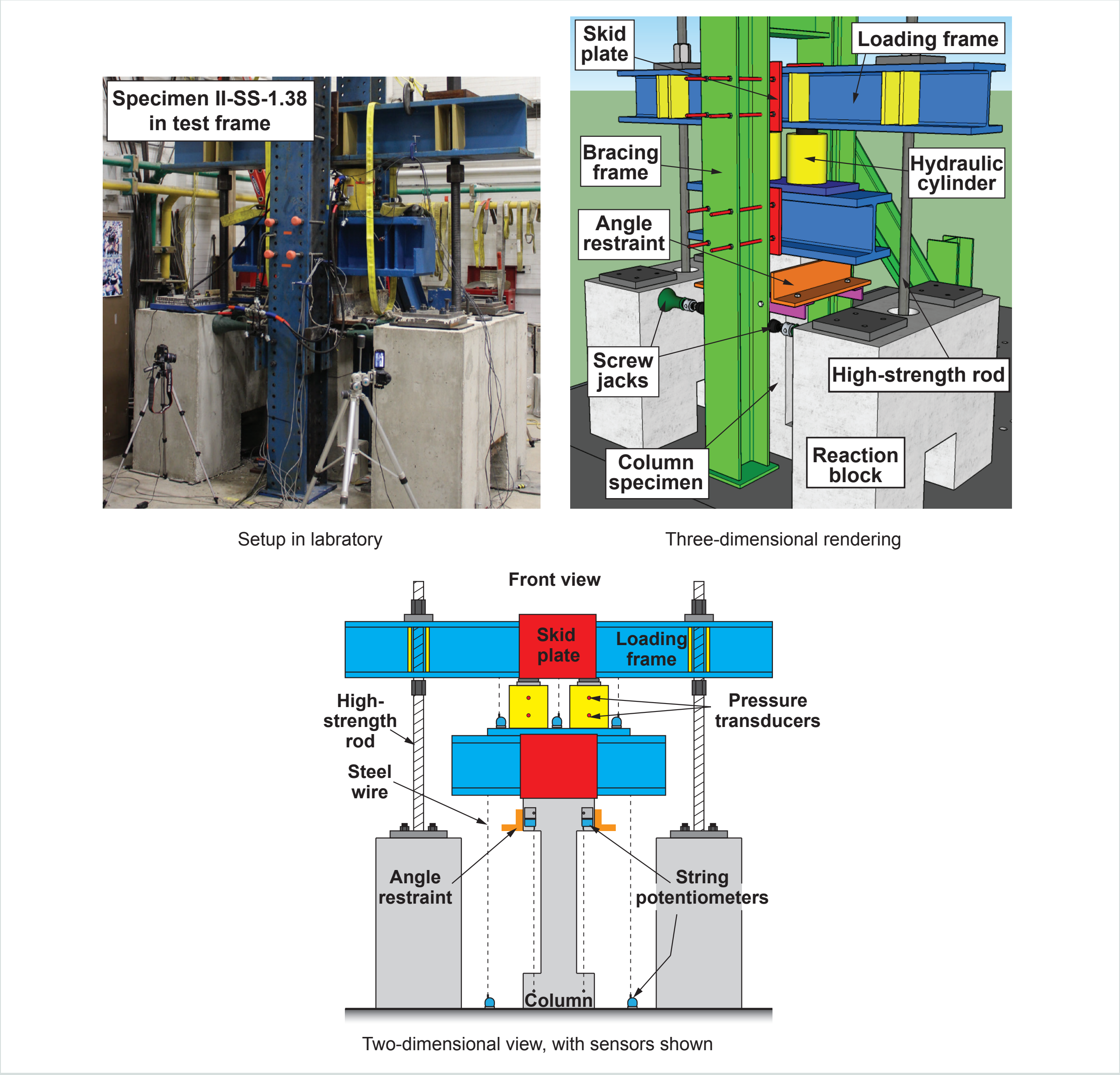

Figure 6. Phase II test setup and instrumentation. Note: For specimen labels, the first term denotes test phase (I or II), the second term denotes confinement reinforcement type and layout (RH = reinforcing bar hoops, SS = strip spiral, SH = strip hoops, 2SS = two strip spirals, and UNC = unconfined), and the third term denotes confinement volumetric ratio as a percentage.

compression load capacity (about 750 kip [3340 kN]) was designed and built in the laboratory. For clarity, Fig. 6 shows a three-dimensional rendering of the phase II testing frame with individual components annotated. The axial load was applied through a pair of 500 kip (2220 kN) hydraulic cylinders with a maximum piston stroke of 6.00 in. (152 mm). A large steel beam was placed on top of the test specimen to evenly distribute the applied axial load over the area of the column end-cap region. The two hydraulic cylinders were placed between this steel beam and a longer reaction beam above (Fig. 6). Swivel caps at the top of each hydraulic cylinder were used to accommodate any rotation between the top of the column specimen and the reaction beam. The applied loads from the vertical extension of the hydraulic cylinder pistons were equilibrated through two high-strength 2.50 in. (63.5 mm) diameter threaded steel tension rods. The bottom end of each rod was connected to a steel rocking plate mechanism that reacted against a separate reinforced concrete block fixed to the laboratory strong floor. The rocking plate allowed for the out-of-plane rotation of the rod due to any asymmetry in the applied axial loading.

To limit eccentricity in the applied axial loads, an external steel bracing frame (green-shaded members in Fig. 6) was constructed around the primary loading frame and fixed to the strong floor. The bracing frame included two sets of steel plates (red components in Fig. 6) to restrain out-of-plane movement of the top steel reaction beam and the shorter steel beam at the top of the column specimen. A set of steel angle restraints was also bolted to the bracing frame to confine and restrain the top end-cap region of the test specimen. Four steel screw jacks were included to provide further restraint of the bracing frame against lateral movement in the direction of the top steel reaction beam. These screw jacks were placed between the vertical bracing columns and the adjacent reinforced concrete reaction blocks.

During testing, the hydraulic cylinders were operated in load control up to an initial axial load of 250 kip (1110 kN) followed by displacement control through failure. The loading and displacement rate of the cylinders could not be actively controlled via a servo valve. Instead, the input and output valves on the hydraulic pump were closed as much as possible to limit the oil flow, resulting in a slow, pseudostatic loading rate (measured after the test at about 0.008 in./sec [0.2 mm/sec]).

Figure 6 shows the instrumentation for the phase II column tests. A total of 15 displacement sensors were used to measure displacements at discrete locations on each specimen and the loading frame. Four string potentiometers (with 2.00 in. [50.8 mm] travel) at the corners of the column specimens measured the average axial shortening displacement over the column test height. The individual measurements from these sensors captured any asymmetry in the axial loading of the columns as well. Three displacement sensors recorded the vertical extension of the hydraulic cylinders (two sensors with 2.00 in. and one with 10.0 in. [254 mm] travel), while the remaining sensors were used to track any vertical movement of the concrete reaction blocks (1.50 in. [38.1 mm] travel) and the steel beam at the top of the column specimen (2.00 in. travel). The applied axial loads were measured using four 10,000 psi (69,000 kPa) pressure transducers, two on the input and output ports of each hydraulic cylinder.

Specimen construction

The construction sequence for each strip-confined column consisted of three primary tasks:

1. Bend the strip spirals and hoops.

2. Assemble the reinforcing bar cages using a rotating template.

3. Place the cages inside the cells of preassembled plywood formwork beds.

The bending of the steel strip spirals is intended to be automated for expedited construction in precast concrete facilities; however, in the current laboratory application, the strip spirals and hoops were bent manually using an arbor press to the specified dimensions, including the bend and pitch angles. The strip was spiraled outward with each bend of the press at the specified angle until the required overall length of the strip spiral was achieved. The corners of the strip confinement were bent to inside radii matching the radii of the column longitudinal bars. For comparison, the inside bend radius was 0.250 in. (6.35 mm) for the strip confinement versus 1.13 in. (28.7 mm) for the corners of the reinforcing bar hoops in column II-RH-2.07.

Once the strip spiral was completed, it was wrapped around a rotating template containing the longitudinal reinforcing bars for the column cage. The strip steel was tied at every intersection with the corner longitudinal bars and at every other intersection along the intermediate longitudinal bars (in phase II only) and then removed from the template. The finished reinforcing bar cages (**Fig. 7**) were then placed inside individual cells within an oiled plywood formwork assembly. The column specimens were cast in the horizontal position to be representative of the typical column casting configuration in precast concrete plants. For each phase, the columns were cast in a single concrete placement to limit any variability in the concrete within each phase of testing. The only exceptions were specimens II-RH-2.07 and II-RH-3.11, which were cast on a different day from the other phase II specimens.

Concrete properties

Table 3 summarizes the concrete mixture designs and measured 28-day material properties, and Table 1 provides the test-day properties. The target design compressive strength for the concrete f'_{dc} in phase I was 6.00 ksi (41.3 MPa). This was selected in conjunction with the column cross-section dimensions to ensure that the capacity of the testing frame would not be exceeded by the column axial strength and to be

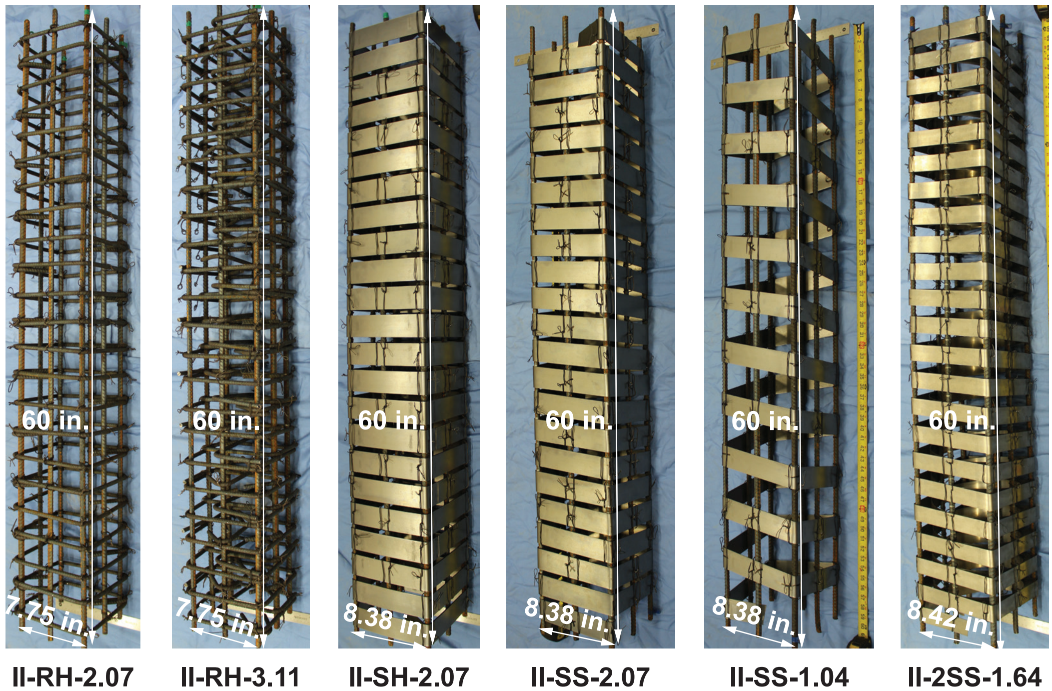

Figure 7. Phase II (10.0 × 10.0 in. [254 × 254 mm] cross section) column reinforcement cages prior to casting. Note: For specimen labels, the first term denotes test phase (I or II), the second term denotes confinement reinforcement type and layout (RH = reinforcing bar hoops, SS = strip spiral, SH = strip hoops, 2SS = two strip spirals, and UNC = unconfined), and the third term denotes confinement volumetric ratio as a percentage. 1 in. = 25.4 mm.

Table 3. Concrete mixture designs and properties

Concrete constituent or property	Phase I	Phase II	
Type I/II portland cement, lb/yd³	182	323	
Slag cement, lb/yd³	437	107	
Crushed limestone,*† lb/yd³	1745	1775	
Sand,* lb/yd³	1346	1480	
Water,* lb/yd³	250	271	
High-range water-reducing admixture (fl. oz/cwt)	5.0	9.0	
Water-to-cement ratio	0.40	0.63	
Slump, in.	8.75	7.25	
f'_c at 28 days, ksi	7.59	3.47‡	4.91§
E_c at 28 days, ksi	5620	4680‡	5050§

Note: E_c = concrete elastic modulus (3 × 6 in. cylinders); f'_c = measured concrete compressive strength (3 × 6 in. cylinders). 1 in. = 25.4 mm; 1 ksi = 6.895 MPa; 1 lb/yd³ = 0.593 kg/m³; 1 fl. oz/cwt = 65.3 mL/100 kg.

* Based on saturated surface dry (SSD) condition of aggregates.

† Indiana Department of Transportation no. 11 gradation.

‡ From concrete placement for reinforcing-bar-confined specimens in phase II.

§From concrete placement for strip-confined specimens in phase II.

representative of strengths used in the precast concrete industry. All phase I specimens were cast from the same batch of concrete and tested on the same day. An alternative concrete mixture design with lower target compressive strength f'_{dc} of 5.00 ksi (34.5 MPa) was developed for the phase II columns (Table 3). The lower target f'_{dc} was selected to ensure that the axial strength of the phase II columns did not exceed the load capacity of the testing frame in Fig. 6. Workability of the concrete was an important mixture design parameter to ensure proper concrete consolidation around the confinement reinforcement. As such, the high-range water-reducing admixture dosages in Table 3 were selected to result in large slump measurements. For both mixtures, the measured concrete compressive strength f'_c was determined in accordance with ASTM C39[34] using standard 3 × 6 in. (76 × 150 mm) cylinder samples (average of three). To determine the concrete elastic modulus E_c, an averaging axial extensometer with 2.00 in. (50.8 mm) gauge length measured the concrete compression strains in the linear-elastic range on all three samples. The modulus of elasticity was then calculated using the method prescribed in section 7 of ASTM C469.[35] Column specimens II-RH-2.07 and II-RH-3.11 were cast on a different day from the other phase II specimens. Despite trying to maintain the same mixture design, these specimens had an average test-day concrete compressive strength that was 31.1% lower than the average strength for the specimens with strip confinement (Table 1). As will be discussed in the "Test Results" section, this variation in concrete compressive strength may have implications when comparing the measured responses of the column specimens.

Steel properties

Table 4 summarizes and **Fig. 8** illustrates the measured stress-versus-strain behaviors for the column reinforcing bars and coiled strip steel. Steel testing was performed following ASTM A370.[36]

The reinforcing bar samples were tested over an 8 in. (200 mm) length between the tensile grips in the crossheads of a universal testing machine. The bar strains up to peak strength f_u were measured using an extensometer with 2.00 in. (50.8 mm) gauge length attached to the middle of the 8 in. bar length between the grips. The incremental strains beyond f_u up to the steel rupture strain ε_r were approximated using the relative change in displacement between the testing machine crossheads over the initial distance between the testing machine crossheads.

To have a width compatible with the available extensometer, the strip samples were machined to have a dog-bone shape with a reduced width of 0.5 in. (13 mm) over a length of 3 in. (76 mm) in accordance with ASTM A370. The strains up to 0.04 were measured using an extensometer with 2 in. (50 mm) gauge length attached to the middle of the length between the grips. The strains beyond 0.04 up to the steel rupture strain ε_r were approximated using the relative change in displacement between the testing machine crossheads over the reduced cross-section length.

The yield strength f_y and strain ε_y for the no. 4 (13M) ASTM A615 bars were determined from the initiation of the distinctive yield plateau on the stress-strain curves per ASTM A370. Because the no. 3 (10M) ASTM A1035 bars and the DP 980/700 steel strip did not have a distinctive yield plateau, the yield strength and strain were determined using the 0.2% offset method.[36] The steel elastic modulus E_s was determined using a linear regression of the measured stress-strain curve between 20.0 and 50.0 ksi (138 and 345 MPa) per ASTM E111.[37]

Test results

Phase I columns

Table 5 summarizes the peak measured axial strength P_m and the residual strength P_{res}. The residual strength P_{res} is defined as the highest measured load after the column achieved the peak load (when the concrete cover spalls) and started carrying load again. For phase I specimens, this residual strength was determined in the later displacement-controlled stage of the loading protocol. These strengths are both compared with the nominal axial strength P_0 predicted by ACI 318-19 (Eq. [3]).

$$P_0 = 0.85 f'_c \left(A_g - A_{st} \right) + f_{yl} A_{st} \tag{3}$$

where

A_{st} = total cross-sectional area of the longitudinal reinforcement

Figure 9 shows the measured axial force P (normalized with respect to P_0) compared with the column axial shortening. The data shown here include both the data from the first test that captured the peak strength and the later displacement-controlled test that focused on the residual strength.

Prior to reaching the peak strength, all seven of the tested specimens exhibited similar initial stiffness (Fig. 9). Importantly, the peak strength P_m of all six of the strip-confined columns exceeded the ACI 318-19 axial strength prediction P_0. The average ratio of measured peak strength to predicted strength

Table 4. Column reinforcement properties

Property	Confinement reinforcement			Longitudinal reinforcement	
				Phase I	Phase II
Specification	DP 980/700	DP 980/700	ASTM A1035	ASTM A615	ASTM A615
Size	0.04 × 1.50 in.	0.06 × 2.00 in.	No. 3	No. 4	No. 4
f_{sy}, ksi	100	100	100	60	60
f_y, ksi	93.3	108	150	65.9	64.5
ε_y, %	0.575	0.627	0.700	0.296	0.236
E_s, ksi	24,800	25,400	30,000	27,000	28,000
f_u, ksi	132	142	187	103	98.7
ε_u, %	8.93	6.90	5.70	10.5	12.4
ε_r, %	12.6	10.5	7.26	14.7	18.0

Note: E_s = steel elastic modulus; f_{sy} = specified yield strength; f_u = peak strength; f_y = measured yield strength; ε_r = rupture strain; ε_u = strain at peak strength; ε_y = strain at yield; no. 3 = 10M; no. 4 = 13M. 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

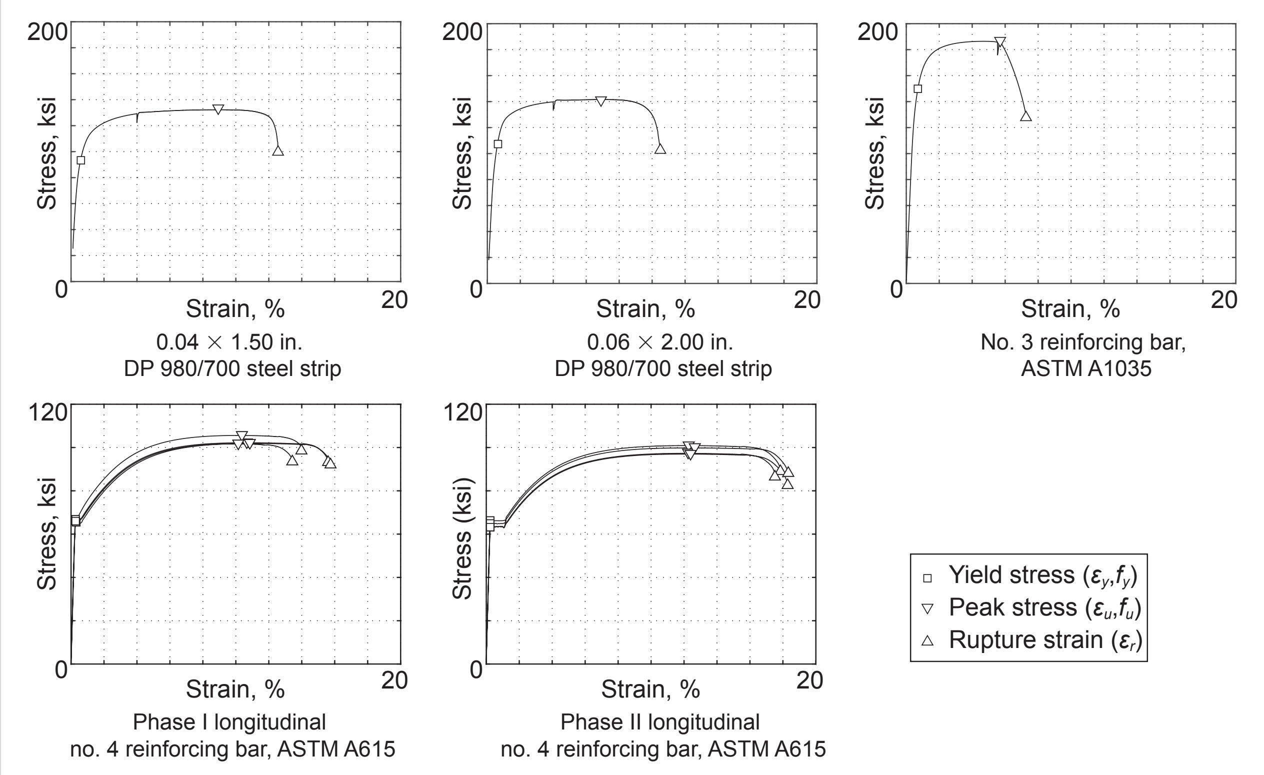

Figure 8. Measured reinforcing steel stress versus strain behavior. Note: f_u = peak steel strength; f_y = yield strength; ε_r = steel rupture strain; ε_u = steel strain at peak strength; ε_y = steel strain at yield. No. 3 = 10M; no. 4 = 13M; 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

(P_m/P_0) among these six specimens is 1.08. Experimentally tested square columns using conventional reinforcing bar confinement in the literature have exhibited peak strengths less than P_0. For example, Sheikh and Uzumeri[38] tested 24 square columns with varying longitudinal bar and tie layouts. Of their specimens, seven did not achieve $P_m/P_0 > 1$ but the average value of P_m/P_0 was 1.06. Razvi and Saatcioglu[39] tested nine square columns using a similar reinforcing bar layout to the phase I specimen layout (four longitudinal bars confined with conventional reinforcing bar hoops). Only one achieved $P_m/P_0 > 1$, and the average was 0.93. Of the 24 conventionally confined square columns tested by Saatcioglu and Razvi,[40] 11 did not have a peak strength exceeding P_0, and the average ratio of measured peak strength to predicted strength (P_m/P_0) of those 24 columns was 1.02. This was attributed to premature spalling of the concrete cover combined with the high compressive stresses developed, particularly for the specimens using high-strength concrete (f'_c of 18.0 ksi [124 MPa]).

The average strength of these six strip-confined columns exceeded the strength of the unconfined column (I-UNC) by 15%. No clear trend emerged relating the peak strength to the confinement reinforcement ratio ρ_{st} or the strip spacing s_t.

The failure of all strip-confined specimens was brittle and explosive, with a large load drop that triggered the end of testing (a drop of greater than 50% in load from the peak). Failure initiated with concrete cracking and spalling at either the top or bottom end of the specimen (**Fig. 10**). To avoid this local behavior in the phase II specimens, large end caps were used. Although longitudinal reinforcing bar buckling was observed in all specimens, the bar buckling was much more pronounced for the specimens with the greatest strip spacing s_t (I-SS-0.69, I-SS-0.55, and I-SS-0.44). None of the strip confinement ruptured or unwound during this (load-controlled to peak P_m) loading of the columns. This brittle failure mode was observed even in specimen I-SS-0.88*, which was tested in displacement control (as opposed to load control for the other specimens in phase I), indicating that the loading protocol did not affect specimen behavior.

The brittle response is indicative of the reinforcement layout used in the small-scale specimens (only four longitudinal bars located at the column corners with perimeter confinement). Saatcioglu and Razvi[40] demonstrated similar brittle behavior with their square column tests using a four-bar layout with perimeter hoops compared with the more ductile behavior observed in a 12-bar layout with overlapping hoops. The small scale of the phase I specimens necessitated this four-bar layout. The larger phase II specimens were designed with an eight-bar configuration with varying strip confinement layout to further investigate the effect of the strip confinement on column ductility.

The most significant differences in behavior among the strip-confined specimens is observed in the postpeak region

Table 5. Test results

Column specimen†	P_m, kip	ε_m, %	P_{res}, kip	P_o, kip	P_m/P_o	P_{res}/P_m
Phase I (8 × 8 in.)						
I-SS-0.88	511	0.512	179	475	1.08	0.35
I-SS-0.75	498	0.533	157	475	1.05	0.32
I-SS-0.69	498	0.498	134	475	1.05	0.27
I-SS-0.55	543	0.553	121	475	1.14	0.22
I-SS-0.44	514	0.540	102	475	1.08	0.20
I-SS-0.88*	519	0.526	196	475	1.09	0.38
I-UNC	445	0.448	n/a	475	0.94	n/a
Phase II (10 × 10 in.)						
II-RH-2.07	466	0.270	438	426	1.09	0.94
II-RH-3.11	491	0.324	481	419	1.17	0.98
II-SH-2.07	611	0.225	310	552	1.11	0.51
II-SS-2.07	578	0.224	369	547	1.06	0.64
II-SS-1.38	617	0.249	277	571	1.08	0.45
II-SS-1.04	600	0.233	184	582	1.03	0.31
II-2SS-1.64	627	0.258	514	564	1.11	0.82
II-2SS-1.35	614	0.235	336	580	1.06	0.55

Note: P_m = maximum axial strength; P_{res} = residual axial strength (after concrete cover spalling); P_o = nominal axial strength from ACI 318-19; ε_m = axial strain at maximum axial strength. 1 in. = 25.4 mm; 1 kip = 4.448 kN.

*Alternative anchorage.

† The first term denotes the test phase (I or II), the second term denotes confinement reinforcement type and layout (RH = reinforcing bar hoops, SS = strip spiral, SH = strip hoops, 2SS = two strip spirals, and UNC = unconfined), and the third term denotes confinement volumetric ratio as a percentage. Figure 4 lists corresponding column cross-section layouts.

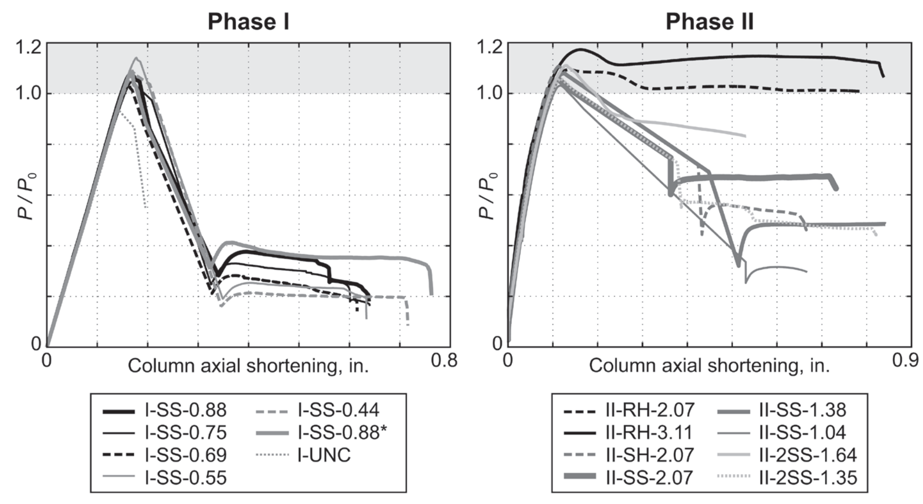

Figure 9. Measured column axial force versus axial shortening behavior. Note: For specimen labels, the first term denotes test phase (I or II), the second term denotes confinement reinforcement type and layout (RH = reinforcing bar hoops, SS = strip spiral, SH = strip hoops, 2SS = two strip spirals, and UNC = unconfined), the third term denotes confinement volumetric ratio as a percentage, and an asterisk indicates alternative anchorage. P = measured axial strength; P_o = nominal axial strength from ACI 318-19. 1 in. = 25.4 mm.

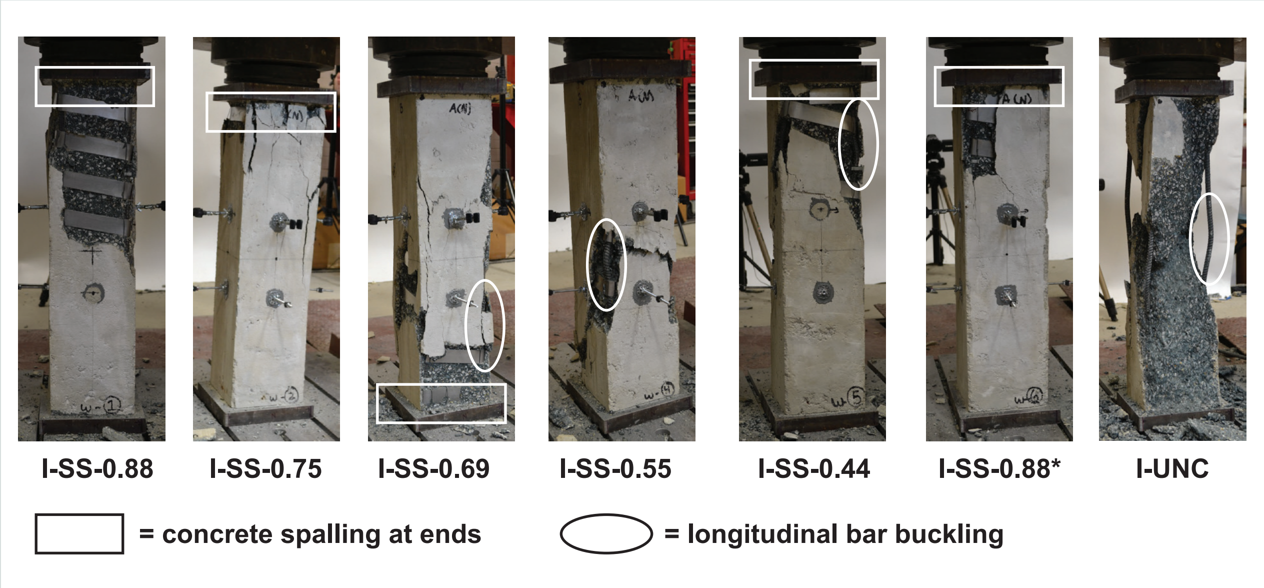

Figure 10. Phase I damage states after peak load but prior to residual load testing. Note: For specimen labels, the first term denotes test phase (I or II), the second term denotes confinement reinforcement type and layout (RH = reinforcing bar hoops, SS = strip spiral, SH = strip hoops, 2SS = two strip spirals, and UNC = unconfined), the third term denotes confinement volumetric ratio as a percentage, and an asterisk indicates alternative anchorage.

where the residual strength P_{res} is measured. In this region, the cover has spalled and the effect of the confinement is important. As expected, the residual strength P_{res} decreases with decreasing confinement reinforcement ratio ρ_{st} (or increasing strip spacing s_t). More pronounced bar buckling is observed after this phase of testing (**Fig. 11**). The strip ruptured for each of the strip-confined specimens toward the end of this second phase of loading.

Between specimens I-SS-0.88 and I-SS-0.88*, which featured the same reinforcement layout but varying confinement anchorage, there was negligible difference in peak strength P_m or residual strength P_{res}, indicating that the different anchorage details did not affect the behavior of these specimens. The steel rupture in the displacement-controlled phase of loading occurred near the midheight of the columns, away from the anchorage regions at the top and bottom. This indicates that

Figure 11. Phase I final column damage states after residual load testing. Note: For specimen labels, the first term denotes test phase (I or II), the second term denotes confinement reinforcement type and layout (RH = reinforcing bar hoops, SS = strip spiral, SH = strip hoops, 2SS = two strip spirals, and UNC = unconfined), the third term denotes confinement volumetric ratio as a percentage, and an asterisk indicates alternative anchorage.

either anchorage approach would be sufficient for this loading and specimen configuration, but additional anchorage testing should be performed in the future.

Phase II columns

Table 5 summarizes the peak measured axial strength P_m, the measured residual strength P_{res}, and the nominal axial strength P_0 predicted by ACI 318-19. In phase II, each test was conducted continuously and the measured residual strength P_{res} refers to the highest load carried after peak. Figure 9 shows the axial force versus axial shortening behaviors of these columns.

The prepeak behavior of all eight columns is similar, demonstrating that the strip confinement did not affect the initial stiffness of the specimens.

Like the phase I specimens, all eight specimens had a peak strength P_m that exceeded the nominal axial strength P_0. The average value of P_m/P_0 for the six strip-confined specimens was 1.08 compared with 1.13 for the two specimens confined by conventional reinforcing bar. Even specimen II-SS-1.04, which had approximately half of the confinement reinforcement of the conventionally confined II-RH-2.07, had $P_m/P_0 > 1$.

All of the strip-confined specimens, with the exception of specimen II-2SS-1.64 (to be discussed later), featured a rapid, large drop in load after peak before maintaining a residual strength to about 10 times the strain at peak load. In contrast, the reinforcing-bar-confined specimens did not exhibit the rapid, large drop in load and had a higher postpeak residual strength P_{res} (Fig. 9). The reinforcing-bar-confined specimens were cast at a different time and inadvertently with a lower concrete compressive strength f'_c of 3.86 ksi (26.6 MPa) for II-RH-2.07 and 3.77 ksi (26.0 MPa) for II-RH-3.11, whereas the average concrete compressive strength f'_c for the strip-confined columns was 5.54 ksi (38.2 MPa). As a result, the concrete cover for the reinforcing-bar-confined specimens spalled at a lower peak load. (The average peak strength P_m for the reinforcing-bar-confined specimens was 479 kip [2130 kN] compared with 608 kip [2700 kN] for the strip-confined specimens.) Furthermore, the average relative contribution of the longitudinal reinforcement to the nominal axial strength P_0 in Eq. (3) increased from 18.2% for the strip-confined specimens to 24.4% for the reinforcing-bar-confined specimens.

Specimens II-RH-2.07, II-SH-2.07, and II-SS-2.07 had the same reinforcement ratio and similar confinement layout, with the only difference being that specimen II-RH-2.07 used conventional reinforcing bar hoops, specimen II-SH-2.07 used strip hoops, and specimen II-SS-2.07 used strip spirals. In specimen II-RH-2.07, both the corner and middle longitudinal bars buckled, whereas only the middle longitudinal bars noticeably buckled in specimen II-SH-2.07 and specimen II-SS-2.07, with the corner bar buckling being less evident (**Fig. 12**). While the reinforcing-bar-confined specimens showed better residual strength and ductility, the strip confinement (in either a hoop or spiral configuration) was better able to support corner longitudinal bars from buckling in an eight-bar configuration where confinement is only provided on the exterior of the longitudinal bars (no crossties are provided). This improved support can be attributed to the wider width of strip that is in contact with the longitudinal bars compared with conventional reinforcing bar. In other words, the clear spacing, or unbraced length, of the longitudinal bars is reduced when using the strip confinement in lieu of reinforcing bar. This effect is likely more pronounced on the corner longitudinal bars, as opposed to the middle bars, because a greater part of the circumference of the longitudinal bars is in contact with the strip. The residual strength of specimen II-SS-2.07 with strip spiral is higher than the residual

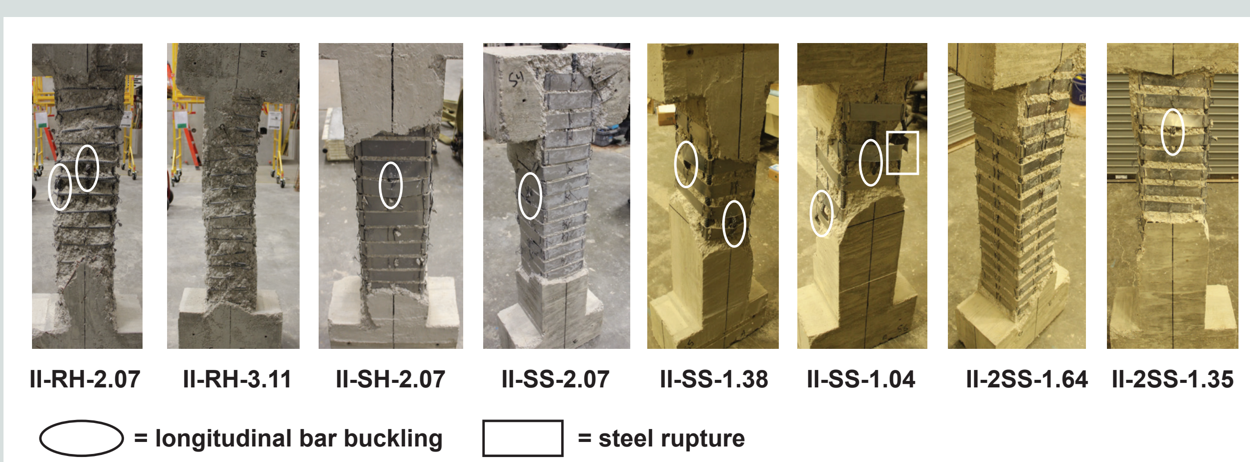

Figure 12. Phase II final column damage states. Note: For specimen labels, the first term denotes test phase (I or II), the second term denotes confinement reinforcement type and layout (RH = reinforcing bar hoops, SS = strip spiral, SH = strip hoops, 2SS = two strip spirals, and UNC = unconfined), and the third term denotes confinement volumetric ratio as a percentage.

strength of specimen II-SH-2.07 with strip hoop, indicating superior performance of the spiral configuration compared with hoops, as expected.

When the lateral reinforcement ratio is decreased by increasing the strip spiral spacing from 2.07% to 1.04% in specimens II-SS-2.07, II-SS-1.38, and II-SS-1.04 while maintaining the same confinement layout (layout 5 in Fig. 4), the residual strength P_{res} decreases as the lateral reinforcement ratio decreased. The peak strength P_m, however, is not affected. Specimen II-SS-2.07 meets the ACI 318-19 requirements for center-to-center spacing, clear spacing, and reinforcement ratio (calculated as either Eq. [1] or Eq. [2]). As discussed, the strip spiral was able to provide sufficient support to the corner longitudinal bars to prevent buckling. In contrast, in specimen II-SS-1.38, which violates the center-to-center spacing requirement, buckling of both the corner and middle longitudinal bars was observed (buckled corner bars are not shown in Fig. 12). Specimen II-SS-1.04 violates the center-to-center spacing, clear spacing, and minimum reinforcement ratio for rectilinear hoops (Eq. [1]) but not the minimum reinforcement ratio for spiral and circular hoops (Eq. [2]). In this specimen, buckling of the corner and middle longitudinal bars was observed, as well as core degradation and rupture of the steel strip (Fig. 12). This indicates that the ACI 318-19 requirements related to center-to-center spacing, clear spacing, and minimum reinforcement ratios for deformed reinforcing bar confinement are likely applicable for strip confinement as well.

In contrast to the specimens where confinement was only provided on the exterior of the longitudinal bars, specimens II-RH-3.11, II-2SS-1.64, and II-2SS-1.35 provide additional confinement supporting the middle longitudinal bars. Specimen II-RH-3.11 used deformed bar, hoops, and crossties, whereas specimens II-2SS-1.64 and II-2SS-1.35 use two independent spiral strips. In specimen II-RH-3.11 and II-2SS-1.64, the additional restraint prevented any of the longitudinal bars from noticeable buckling (Fig. 12). Specimen II-2SS-1.64 provided this restraint using just 53% of the reinforcement of specimen II-RH-3.11. It was not possible to test a specimen with deformed bar hoops and ties with a smaller lateral reinforcement ratio, as smaller sized deformed bars are not available. Of all the strip-confined specimens, specimen II-2SS-1.64 had the highest residual strength and largest ductility after concrete cover spalling, even with 21% less lateral reinforcement than specimen II-SS-2.07. This demonstrates that for an eight-bar configuration, a two-strip spiral layout is preferred, as all longitudinal bars are supported. Specimen II-2SS-1.64 meets the center-to-center, clear spacing, and minimum reinforcement ratios (both Eq. [1] and Eq. [2]) of ACI 318-19. In specimen II-2SS-1.35, the inner spiral spacing was increased and violated the center-to-center and clear spacing requirements of ACI 318-19. As a result, the middle longitudinal bars were not adequately restrained and buckled. The specimen also did not have the more gradual postpeak load drop that specimen II-2SS-1.64 exhibited. This further demonstrates that the ACI 318-19 requirements for center-to-center spacing and clear spacing are applicable for strip confinement.

Conclusion

This paper presents results from monotonic concentric axial compression tests of 15 square columns not subjected to length effects. The behavior of reinforced concrete columns confined using dual-phase high-strength (100 ksi [690 MPa] yield strength) steel coiled strips is compared with the behavior of unconfined and deformed reinforcing-bar-confined (using 100 ksi yield strength ties) specimens. In the two phases of testing, the varied parameters included confinement type (strip versus deformed bar), confinement reinforcement ratio, strip confinement configuration (strip hoops, single spiral, or two spirals), and strip anchorage.

The major findings are as follows:

- All strip-confined columns had a peak strength exceeding the nominal axial strength P_0 predicted by ACI 318-19 by an average of 8%. This is important because some square column tests reported in the literature that used similar reinforcement layout and reinforcement ratios did not have peak strengths exceeding P_0.
- Specimens tested with strip spiral reinforcement were able to achieve similar ratios of peak strength P_m to nominal axial strength P_0 and prepeak stiffness as specimens tested with deformed reinforcing bar ties.
- In an eight-bar configuration, single strip spiral confinement results in a rapid load drop after peak before maintaining a residual strength. Deformed reinforcing bar hoop confinement without crossties had a behavior where a more gradual load drop occurred and had a higher residual strength. Therefore, single strip spirals are not recommended for an eight-bar configuration.
- In an eight-bar configuration, two strip spirals are preferred over a single exterior spiral as the two strip spirals prevented a large rapid drop in load after peak, resisted noticeable buckling of all longitudinal bars, and resulted in a higher residual strength even with a reduced lateral reinforcement ratio. The two-strip spiral layout in an eight-bar configuration will be the focus of future research.
- In an eight-bar configuration, a column confined by two strip spirals can achieve approximately 80% of the P_{res}/P_m ratio of that of a conventionally reinforced column (with reinforcing bar hoops and ties) despite having half as much confinement reinforcement.
- Increased strip spiral spacing results in lower residual strength P_{res} but does not change the maximum load capacity.
- In an eight-bar configuration where confinement is only provided on the exterior of the longitudinal bars, the following was found:

– Based on posttest observations, steel strip (in either a hoop or spiral configuration) appears to be better able to support corner longitudinal bars from buckling compared with deformed reinforcing bar hoops.

– Continuous strip spirals provide higher residual strength than individual strip hoops.

- ACI 318-19 column confinement requirements related to center-to-center spacing, clear spacing, and minimum reinforcement ratios may be appropriate for strip confinement.

The experimental tests in this paper are a pilot study focused on investigating the axial load behavior of short, square reinforced concrete columns with steel strip confinement as a first step in evaluating this confinement approach. Research, which is already ongoing, investigating the behavior of strip-confined columns under combined axial and reversed-cyclic lateral (flexural) loads is necessary to evaluate the strips for earthquake-resistant design. The focus of the combined axial and reversed-cyclic lateral tests is on the two-strip spiral layout in an eight-bar configuration because this layout was shown to be the most promising in this pilot study.

Additional future research into developing analytical and numerical models that can predict the behavior of these columns would also be important for this strip reinforcement concept to be used by designers. As concrete cover spalling may be more likely with the strip confinement, additional design considerations may need to be developed.

This research focused on short square columns. This strip steel concept was aimed toward adoption by the precast concrete industry, where square or rectangular columns are more common than circular columns. The nature of coiled steel strips could be applied to circular columns, which is also an area of future research.

Ultimately, steel strip confinement reinforcement is a potentially disruptive technology that can have a major impact on the concrete industry.

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Notation

A_{ch} = cross-sectional area of concrete core measured to the outside edges of the confinement reinforcement

A_g = gross area of column cross section

A_{st} = total cross-sectional area of the longitudinal reinforcement

b_c = cross-section width

d_b = reinforcing bar diameter

d_c = cross-section depth

E_c = concrete elastic modulus

E_s = steel elastic modulus

f'_c = measured concrete compressive strength

f'_{dc} = design concrete compressive strength

f_{sy} = specified yield strength

f_u = peak steel strength

f_y = yield strength

f_{yl} = measured longitudinal steel yield strength

f_{yt} = measured confinement steel yield strength

f_{syt} = specified confinement steel yield strength

h_{ct} = column height

n_b = number of longitudinal bars

P = measured axial strength

P_m = peak measured axial strength

P_0 = nominal axial strength from ACI 318-19

P_{res} = residual axial strength (after concrete cover spalling)

s_t = confinement steel center-to-center spacing (pitch)

$s_{t,max}$ = maximum center-to-center confinement spacing

s_{tc} = clear spacing of confinement steel

$s_{tc,max}$ = maximum clear spacing of confinement steel

$s_{tc,min}$ = minimum clear spacing of confinement steel

t_s = steel strip thickness

w_s = steel strip width

ε_m = axial strain at maximum axial strength

ε_r = steel rupture strain

ε_u = steel strain at peak strength

ε_y = steel strain at yield

ρ_{sl} = longitudinal steel reinforcement ratio

ρ_{st} = volumetric reinforcement ratio of confinement steel

$\rho_{st,min1}$ = minimum volumetric confinement ratios for rectilinear hoops

$\rho_{st,min2}$ = minimum volumetric confinement ratios for circular spirals and hoops

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Abstract

This paper experimentally investigates the axial load behavior of square reinforced concrete columns confined using dual-phase high-strength (100 ksi [690 MPa] yield strength) steel coiled strips. Two phases of testing were conducted on reduced-scale specimens (8 × 8 in. and 10 × 10 in. [203 x 203 mm and 254 x 254 mm]). Varied parameters include confinement type (strip versus reinforcing bar), confinement reinforcement ratio, confinement layout (hoops and ties, single spiral, two spirals), and strip anchorage. Although the reinforcing-bar-confined columns demonstrated better postpeak residual strength and ductility, important findings include the following: strip-confined columns had peak strengths exceeding the nominal axial strength predicted by code, strip-confined columns were able to achieve similar normalized peak strengths and prepeak stiffness as columns with reinforcing bar hoop confinement, two strip spirals are necessary to achieve the desired postpeak residual strength and ductility for an eight-bar layout, and strip spirals and hoops may provide better restraint against buckling of corner bars compared with reinforcing bar hoops.

Keywords

Axial load, column, confinement, high-strength steel, reinforced concrete column, strip reinforcement.

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