Evaluation of Continuous Transverse Reinforcement

Applicability of current design provisions and detailing practices

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Recent advancements in automatic steel bar bending machines allow robotic prefabrication of steel reinforcement to form a rectilinear continuous transverse reinforcement (CTR) that can be used in lieu of conventional stirrups, ties, or hoops. Designed with a specific spacing (pitch) in a contiguous rectangular loop, such transverse reinforcement is engineered so that it can be condensed, shipped, and untied in the field, allowing it to spring into place with the desired spacing. To effectively "close" the cage, each end of a typical CTR is also supplied with four legs forming a hoop that is perpendicular to the longitudinal bars.

A main advantage of CTR is decreased construction time, which in turn reduces labor costs. The reduction in labor stems from the fact that the reinforcement is shipped in its compressed form (Fig. 1(a)) and it snaps to the intended pitch once untied at the construction site (Fig. 1(b)). (Note that safety training is required to avoid injury during release of the compressed CTR.) Upon expansion to the desired pitch and length, CTR is tied onto the longitudinal reinforcing bars to form a cage. In contrast, the time required for assembly of a cage comprising conventional stirrups is much greater because the spacing of conventional stirrups must be measured before they can be independently tied to the longitudinal reinforcement.

Other features of CTR include the options of:

- Varying the pitch along a segment; for example, gradually decreasing the pitch near the ends of the CTR;
- Creating a "dogleg" (refer to Fig. 1(b)) on each angled leg to assist with quick expansion when untied; and
- Bending either No. 3 or No. 4 (No. 10 and No. 13) bars. (Note that in the compressed state, a No. 4 [No. 13] CTR stores almost twice the energy as a No. 3 [No. 10] CTR, so safety training is particularly important when the larger bars are used in CTR.)

Although the Code (ACI 318-11[1]) does not explicitly permit the use of CTR, Section 1.4 of ACI 318 makes it possible to receive approval from a building official if adequacy can be shown by sufficient documentation. The documentation typically consists of successful applications, comprehensive analyses, test data, or a combination thereof. Recent research at the University of Cincinnati was focused on evaluating the performance of various types of members that included CTR and conventional transverse reinforcement to generate data that could facilitate the use of CTR.

Overview of Research

Thirty full-scale specimens were designed, tested, and evaluated. The main aspects of the specimens and variables are summarized in Table 1. All the specimens were proportioned according to the current code design provisions and other relevant recommendations.[1,2] Each group of specimens included a control specimen using conventional reinforcement.

The specimens allowed in-depth study of shear dominant flexural members; members subjected to pure torsion as well as to the combined actions of bending moment, shear, and torsion; short columns loaded in compression; and exterior beam-column connections subjected to cyclic loads simulating seismic events. In addition to generating basic data regarding the performance of members reinforced with CTR, the project

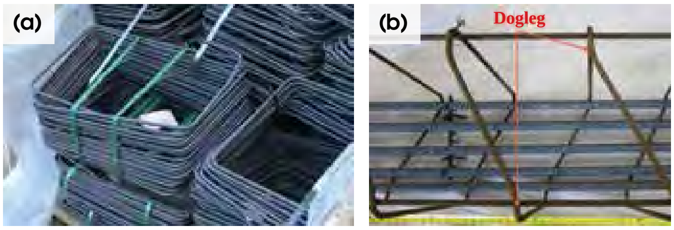

Fig. 1: Continuous transverse reinforcement (CTR): (a) in compacted and banded form prior to shipping; and (b) in expanded form (top view)

Table 1:
Summary of specimens and test variables

Member	Loading	Dimensions, width x height x length or diameter, in. (mm)	Transverse reinforcement	Pitch, in. (mm)	f'_c, psi (MPa)
Beam	Flexure and shear	16 x 24 x 174 (406 x 610 x 4420)	U stirrups	5 or 10 (127 or 254)	5000 or 10,000 (34.5 or 68.9)
			CTR†		
			CTR‡		
Beam	Pure torsion*	12 x 16 x 96 (305 x 406 x 2438)	Closed stirrups	5 (127)	5000 or 10,000 (34.5 or 68.9)
			CTR†		
			CTR‡		
Beam	Combined flexure, shear, and torsion	16 x 24 x 168 (406 x 610 x 4267)	Closed stirrups	8 (203)	5000 (34.5)
			CTR†		
			CTR‡		
Column	Axial	18 x 18 x 96 (457 x 457 x 2438)	Ties	10 (254)	5000 (34.5)
			CTR	10 (254)	
			CTR	3 (76)	
		20 x 96 (508 x 2438)	Spiral	2.5 (63)	
Exterior beam-column connection	Cyclic lateral	Column: 18 x 18 x 136 (457 x 457 x 3454)	Seismic ties	4 (102)	5000 (34.5)
		Beam: 16 x 24 x 144 (406 x 610 x 3658)	CTR§		

*Angle of twist was either in "spiral" direction of CTR or opposite to it.
†Angled legs on top/bottom.
‡Angled legs on sides.
§CTR in column and plastic hinge region of beam.
Notes: CTR is continuous transverse reinforcement. For beams subjected to flexure and shear or combined flexure, shear, and torsion, Grade 100 A1035 longitudinal reinforcement was used to prevent flexural failure. Conventional and continuous transverse reinforcement was fabricated from the same coil with average yield strength of 71,000 psi (489.5 MPa).

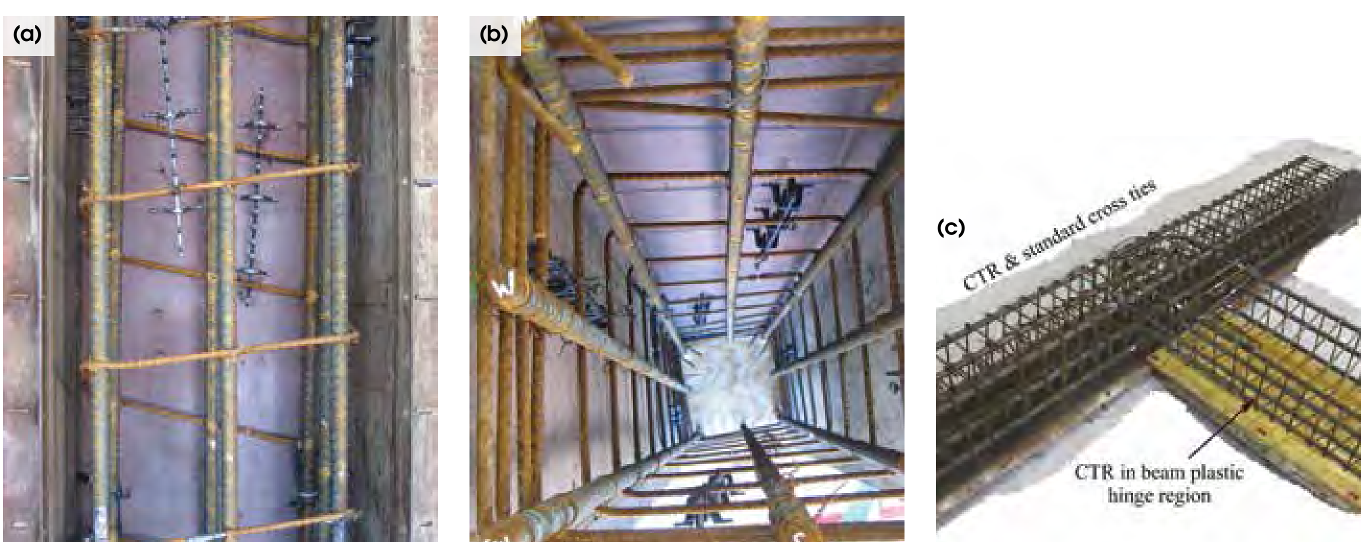

Fig. 2: Examples of reinforcing cages fabricated with CTR: (a) column elevation; (b) column cross section; and (c) exterior beam-column connection

allowed a number of issues unique to CTR to be studied. These issues included field modifications to CTR and whether a dogleg (Fig. 1(b)) can influence the development of transverse reinforcement. The test specimens consisted of a wide array of members and components subjected to various loading conditions. Examples of the tested reinforcing cages are shown in Fig. 2 through 4. Some of the test parameters are described in more detail in the following sections.

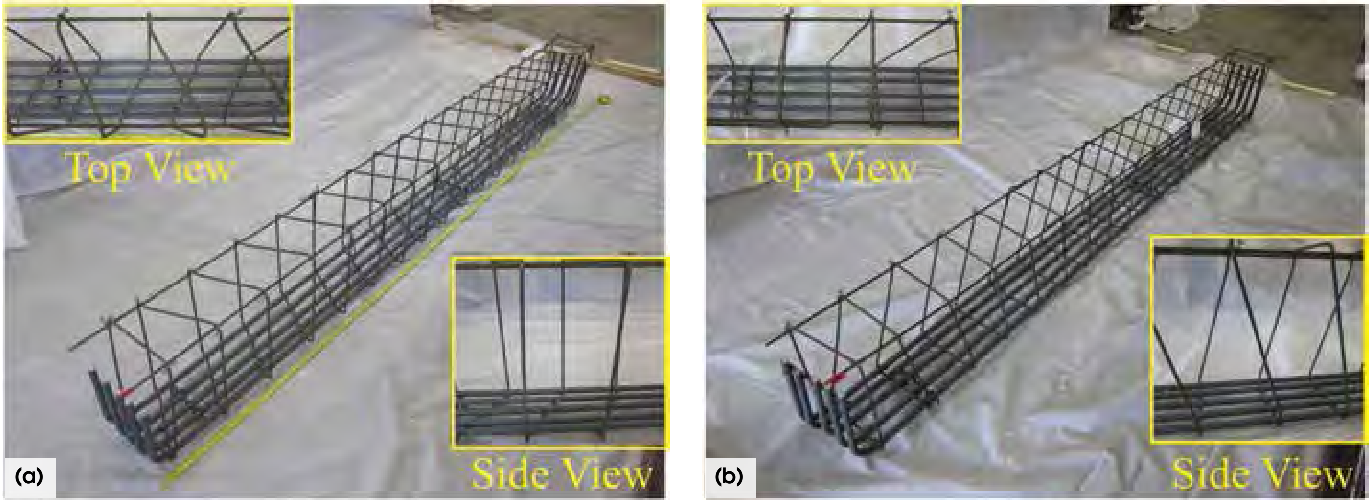

Fig. 3: Example of cages with CTR installed in two configurations: (a) angled legs on top and bottom faces of beam; and (b) angled legs on the sides of beam. Note that the CTR cages terminate in a complete hoop with all four legs of the rectangle in one common plane, perpendicular to the longitudinal bars

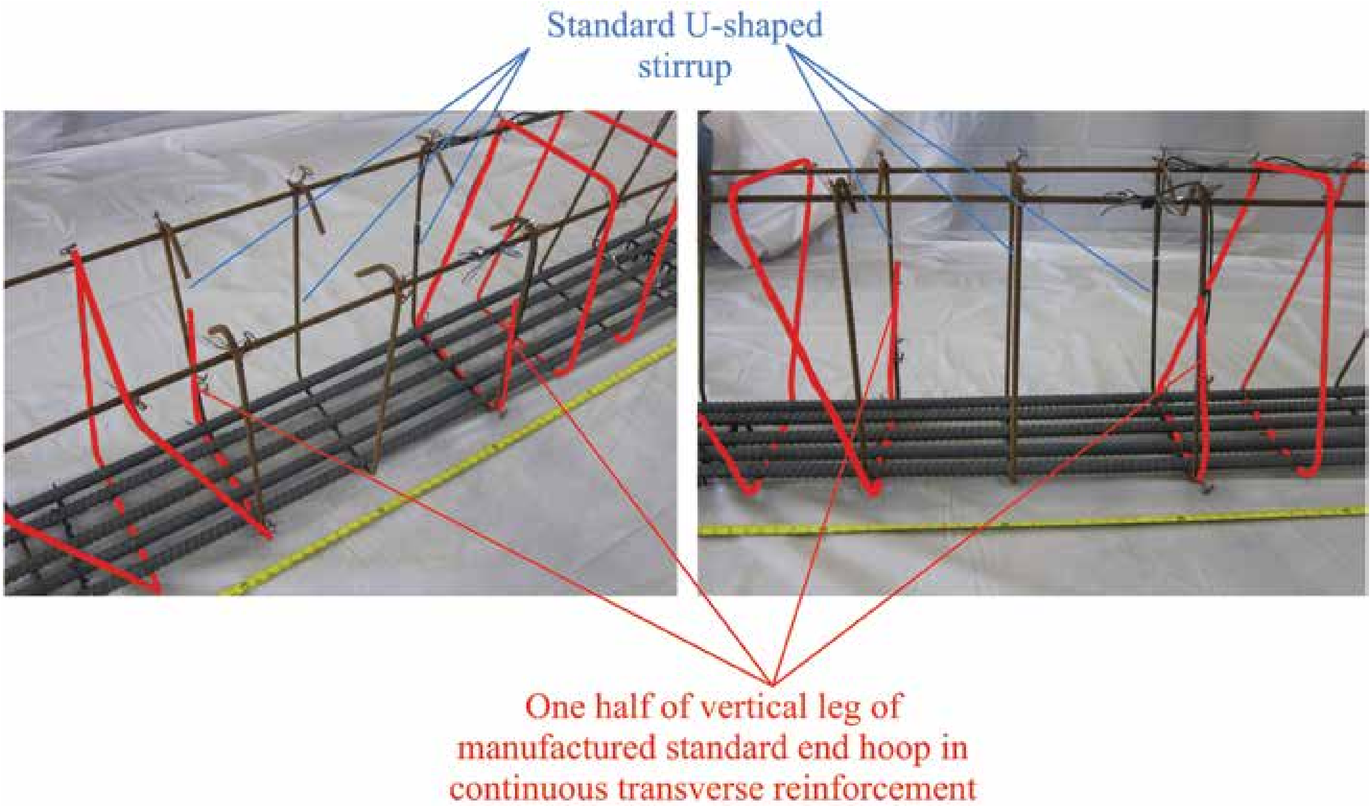

Fig. 4: Detail of test configuration for field modification of CTR cage. Because conventional transverse reinforcing can be tied to and replace the cut CTR, the CTR can be terminated at any leg. Additional conventional reinforcement can be added as required to complete the cage

Location of angled legs

To replicate the configuration of conventional stirrups, the vertical legs of the CTR should be on the sides of a beam, perpendicular to the longitudinal bars and in the plane of the loading. The angled legs should be on the top and bottom of a beam. Even if the construction documents include plan, side, and cross-section views to convey the geometry of the CTR, however, there is a possibility that the CTR will be installed with the angled legs on the sides of the beam. To evaluate the effect of the location of the angled legs, beams were tested with CTR installed with the angled legs at the top and bottom or on the sides of the beam (Fig. 3).

Using well-established principles,[3] the shear strength V_s attributed to CTR with angled legs on the sides is given as

$$V_s = \frac{2A_t f_{yt} d \sin\alpha}{s} \quad (1)$$

where A_t is the area of the bar used to fabricate the CTR (essentially, one leg); d is the effective depth of the beam; f_{yt} is the yield strength of the CTR; s is the center-to-center spacing of the transverse reinforcement (for CTR, this is the pitch); and α is the angle between the longitudinal reinforcement and an angled leg of the CTR.

The smallest value of α investigated in this project was 65 degrees (the angle was limited by the capability of the bar bending machine used to fabricate the CTR for the tests). Hence, the smallest value of V_s is $1.8A_t f_{yt} d/s$, which is 10% less than for a standard stirrup or a CTR with vertical legs on the sides (where α will be 90 degrees).

Job-site modification

One specimen was cast to evaluate a potential field correction if the delivered CTR didn't match the beam length but did have the correct pitch values and end closure hoops. The delivered CTR could be salvaged by cutting it into two sections and lap splicing conventional transverse reinforcement to the cut ends. Additional conventional transverse reinforcing could be installed if the delivered CTR was too short. For this test, the CTR had angled legs on the beam sides and conventional transverse reinforcing bars were spliced to the remainder of the cut leg (Fig. 4). The completed beam was tested so that the conventional bars were spliced to the CTR at a shear-critical zone.

Torsional resistance

Conventional transverse reinforcement required for torsion consists of four closed legs that are perpendicular to the member longitudinal axis. Pure torsion results in diagonal cracks that spiral around the member, and these cracks are arrested by transverse steel on all faces. In the case of CTR, however, the transverse reinforcement is angled on two faces (top/bottom or front/back). Therefore, the diagonal cracks on two faces may not be arrested by CTR if the direction of the applied torsional moment causes diagonal cracks that are parallel to the angled legs of the CTR (Fig. 5).

ACI 318 defines the nominal torsional strength of a beam T_n as

$$T_n = \frac{2A_t f_{yt} A_o \cot\theta}{s} \quad (2)$$

where A_o is the gross area enclosed by the shear flow path; A_t is the area of one leg of the transverse reinforcement resisting torsion; and θ is the angle between longitudinal reinforcement and diagonal cracks. Recognizing that with CTR, two of the four legs of the transverse reinforcing are angled at less than 90 degrees relative to the longitudinal bars,[3] Eq. (2) can be modified as

$$T_n = \frac{A_t f_v A_o \cot\theta\ (1+\sin\alpha)}{s} \quad (3)$$

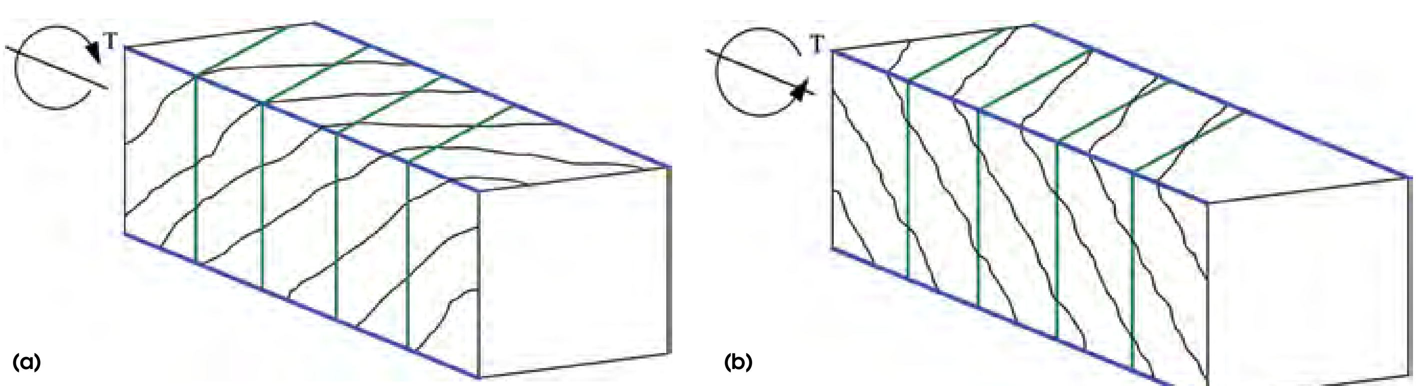

Fig. 5: The torsional resistance of beams with CTR will be affected by the direction of the torsional moment: (a) all legs of CTR will intercept diagonal cracks if the CTR and cracks spiral in opposite directions; and (b) angled legs may not intercept diagonal cracks if the CTR and cracks spiral in the same direction

For this study, the smallest value of α is 65 degrees, so the smallest value of T_n is $(1.9A_t f_{yt} A_o/s)\cot\theta$.

Major Results and Observations

A number of metrics were used to evaluate the performance of members reinforced with CTR. In Table 2, the ratio of the maximum measured load to the nominal capacity calculated per ACI 318 and Eq. (1) and (3) (Test:calc) are summarized, from which the following observations are made:

- With only a few exceptions, the specimens developed and exceeded the nominal capacity. The lowest measured load was 4% less than the computed nominal capacity. All specimens exceeded the design capacity—that is, all specimens failed at loads above ϕRn, where ϕ is the strength reduction factor and R_n is the nominal strength;

Table 2:
Summary of measured capacity (test) versus calculated capacity (calc) for CTR test program

Member/ component	Loading	Nominal f'_c, psi (MPa)	Transverse reinforcement	Pitch, in. (mm)	Test:calc
Beam	Flexure and shear	5000 (34.5)	U stirrups	10 (254)	1.50
			CTR (angled legs on top/bottom)		1.38
			CTR (angled legs on sides)		1.34
			Spliced CTR (angled legs on sides)		1.29
			U stirrups	5 (127)	1.18
			CTR (angled l egs on top/bottom)		1.25
			CTR (angled legs on sides)		1.14
		10,000 (68.9)	U stirrups	10 (254)	1.11
			CTR (angled legs on top/bottom)		1.11
			CTR (angled legs on sides)		0.96
			U stirrups	5 (127)	1.13
			CTR (angled legs on top/bottom)		1.11
			CTR (angled legs on sides)		1.20
	Pure torsion	5000 (34.5)	Closed stirrups	5 (127)	N/A*
			CTR (angled legs on top/bottom, CW)		1.15
			CTR (angled legs on sides, CW)		1.19
			CTR (angled legs on sides, CCW)		0.97
		10,000 (68.9)	Closed stirrups		0.99
			CTR (angled legs on top/bottom, CW)		1.21
			CTR (angled legs on top/bottom, CCW)		0.99
Column	Axial	5000 (34.5)	Tie	10 (254)	1.26
			CTR	10 (254)	1.26
			CTR	3 (76)	1.34
			Spiral	2.5 (63)	1.27
Exterior beam-column connection	Cyclic lateral	5000 (34.5)	Seismic tie	4 (102)	M+ : 1.06
					M– : 1.15
			CTR (angled legs on top/bottom)		M+ : 1.15
					M– : 1.14

*Due to servo-valve control issues, the specimen was damaged prior to collecting any data.

Notes: CTR is continuous transverse reinforcement; CW indicates cracking was opposite to "spiral" of CTR; CCW indicates cracking was in direction of "spiral" of CTR; M+ and M– indicates ratio relative to positive and negative flexural capacity of beam, respectively.

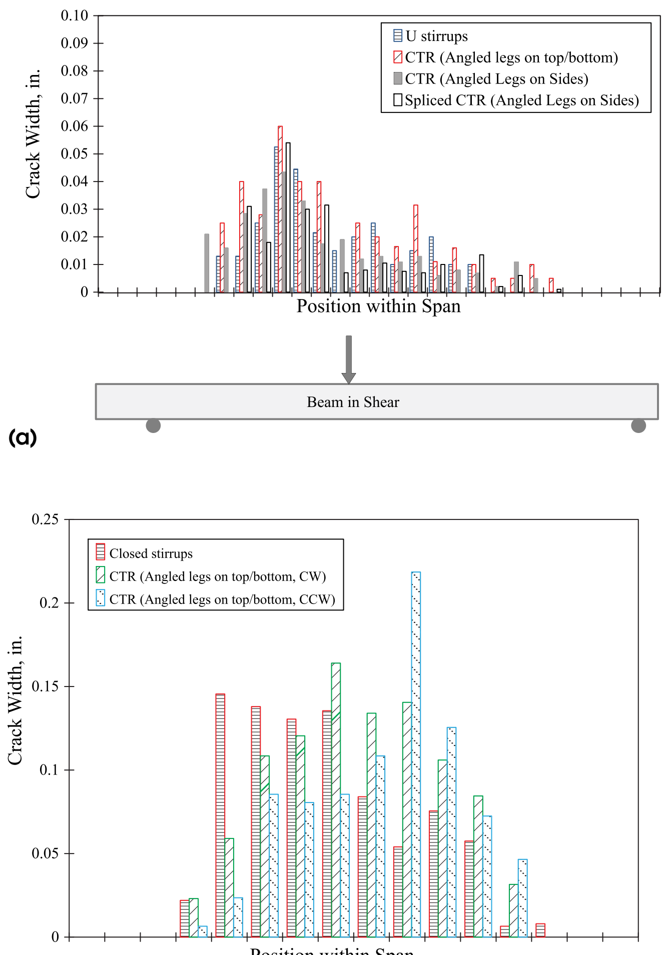

Fig. 6: Representative measured crack widths: (a) beams subjected to bending and shear; and (b) beams subjected to pure torsion, with CW indicating cracking in the opposite direction of spiral and CCW indicating cracking in the same direction as spiral (Note: 1 in. = 25 mm)

- The technique used to field modify CTR cages was successful in that it was simple to implement and the test beam developed the same shear capacity as a beam with a similar, unmodified cage;
- Torsional capacity is reduced when the torsion causes the diagonal torsional cracks to form in the same direction as the "spiral" of the CTR; the capacity was reduced by approximately 17% and 18% for the specimens made with 5000 and 10,000 psi (34.5 and 68.9 MPa) concrete, respectively; and
- The axial load resisted by columns using CTR or conventional transverse reinforcement (discrete ties or spiral reinforcement) was at least 26% larger than the calculated nominal capacity.

The specimens subjected to combined flexure, shear, and torsion were evaluated with reference to nondimensional interaction relationships,[4,5] but with particular emphasis on those proposed by Hsu.[5] Using the measured peak loads, the controlling values of the interaction equations were computed to be 0.91, 0.91, and 1.01 for conventional closed stirrups; CTR with the angled legs on the top and bottom; and CTR with the angled legs on the sides, respectively.[3] A value greater than 1 indicates that the member capacity was reached. The presence of angled legs on the sides (that is, in the plane of the shear load) reduced the capacity slightly. However, there are no differences between conventional closed stirrups and CTR placed as intended, with the angled legs on the top and bottom faces.

Representative crack widths at service load (approximately equal to ultimate load/1.50) are shown in Fig. 6. For all reinforcing schemes, the crack distribution is similar, and the widths are reasonably close. As expected for torsional loading, however, the crack widths are larger for the specimen where the "spiral" of CTR and the diagonal cracks are in the same direction. Considering the values and distribution of crack widths, no discernible differences could be identified between serviceability of the specimens with conventional transverse reinforcement and those using CTR.

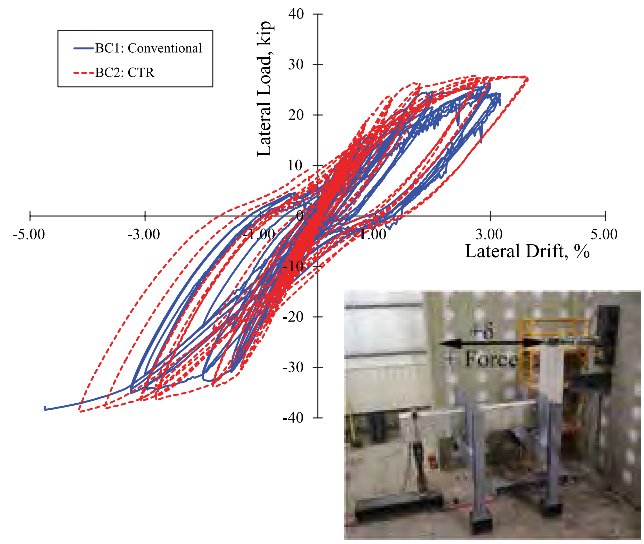

Fig. 7: Comparison of hysteretic responses of exterior beam-column connections with conventional seismic ties and CTR (Note: 1 kip = 4.45 kN)

As is evident from Fig. 7, the hysteretic responses of exterior beam-column connections with standard seismic ties and CTR are nearly identical, indicating similar levels of energy dissipation and rates of degradation.

Summary and Recommendations

The test data presented herein and in Reference 3 clearly indicate that current design provisions and detailing practices are applicable to CTR. In terms of serviceability, strength, and ductility, the test results confirm that CTR can be used in lieu of conventional transverse reinforcement. The following recommendations are made to account for slight differences between CTR and standard stirrups or ties:

1. V_s can conservatively be taken as $1.8A_tf_{yt}d/s$ for CTR when α is limited to at least 65 degrees;

2. T_n can conservatively be taken as $(1.9A_tf_{yt}A_o/s)\cot\theta$ for CTR when α is limited to at least 65 degrees;

3. If the direction of the torsional loading is known a priori—for example, when the member is subjected to gravity loads only—CTR must be placed such that the orientation in which the CTR "spirals" will be in the opposite direction of the diagonal cracks from the applied torque. For cases where the direction of torque could change, the capacity of the member needs to be limited to the torsional cracking capacity (computed based on the current Code[1]) multiplied by an additional factor of 0.75; and

4. In lieu of isometric drawings, plan, side, and cross-sectional views should be used to convey the geometry of CTR.

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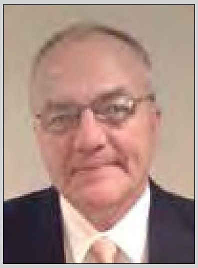

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