Seismic Behavior of Coupling Beams with Double-Hook Steel Fiber Reinforced Concrete

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ACI/JCI 6th Joint Seminar
Part 3 of 4

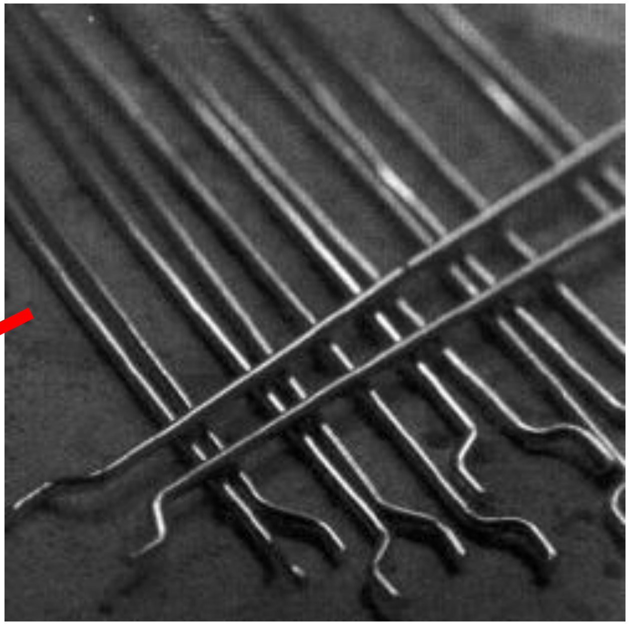
COUPLING BEAMS

- Concrete walls are usually pierced with openings to accommodate doors and windows, resulting in short, deep elements referred to as ***coupling beams***

- Coupled shear wall systems are preferred over single cantilever walls for their increased lateral strength and stiffness due to the coupling action provided by coupling beams

FIBER REINFORCED CONCRETE

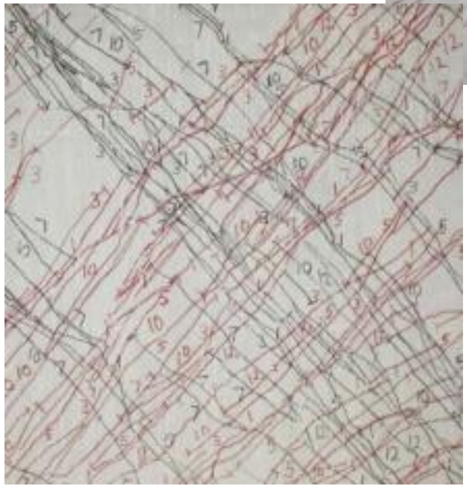
- Concrete reinforced with discontinuous fibers
- Commonly used steel fibers have deformations to improve bond with surrounding concrete
- Single-hook steel fibers are expected to pullout without yielding, while double-hook steel fibers are expected to yield without pulling out



HIGH-PERFORMANCE FRC (HPFRC)

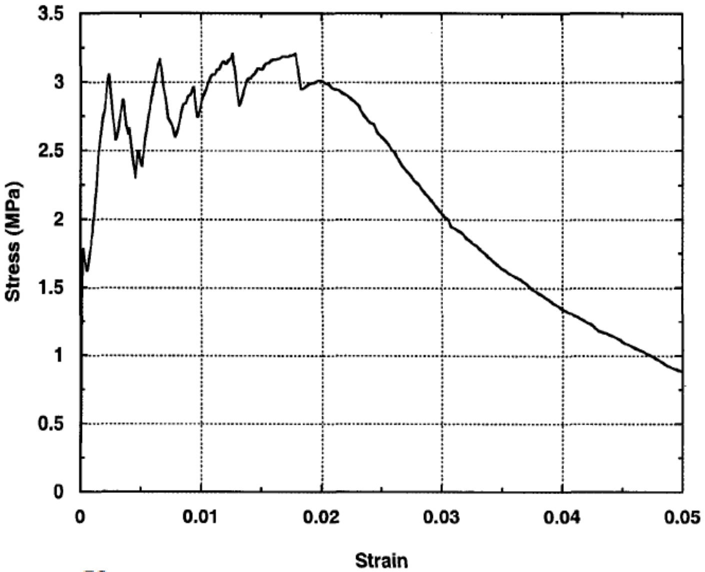
Fiber reinforced concrete with tensile strain-hardening behavior and compression behavior similar to that of well-confined concrete

RC

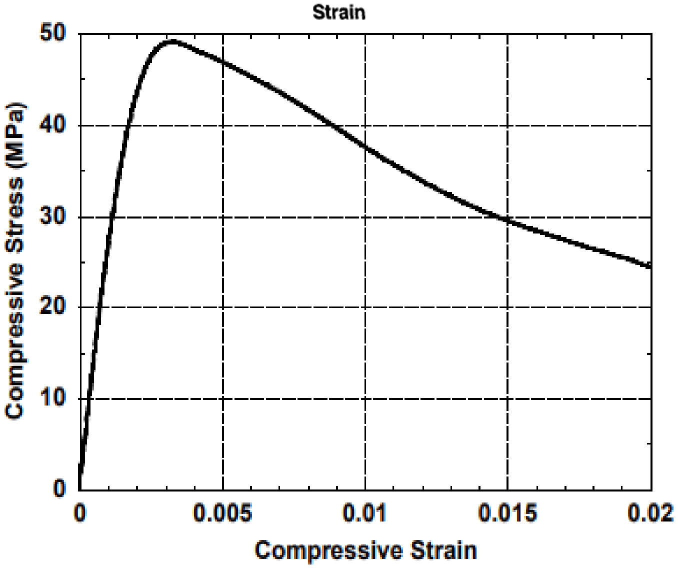


HPFRC

Tension



Compression



(Canbolat, 2005)

ACI 318-19 COUPLING BEAM PROVISIONS

- Coupling beams with $2 \le L_n/h \le 4$ and shear stress greater than $4\sqrt{f_c}$ (psi) must be designed with either diagonal reinforcement or as beams of special moment frames. However, most designers use diagonal reinforcement because of higher shear stress limit and increased deformation capacity

- Maximum shear stress in diagonally-reinforced coupling beams $= 10\sqrt{f_c}$ (psi)

- Column-type special confinement reinforcement required either around diagonal bars or confining entire coupling beam

CURRENT COUPLING BEAM DESIGN PRACTICE

Courtesy of Remy Lequesne

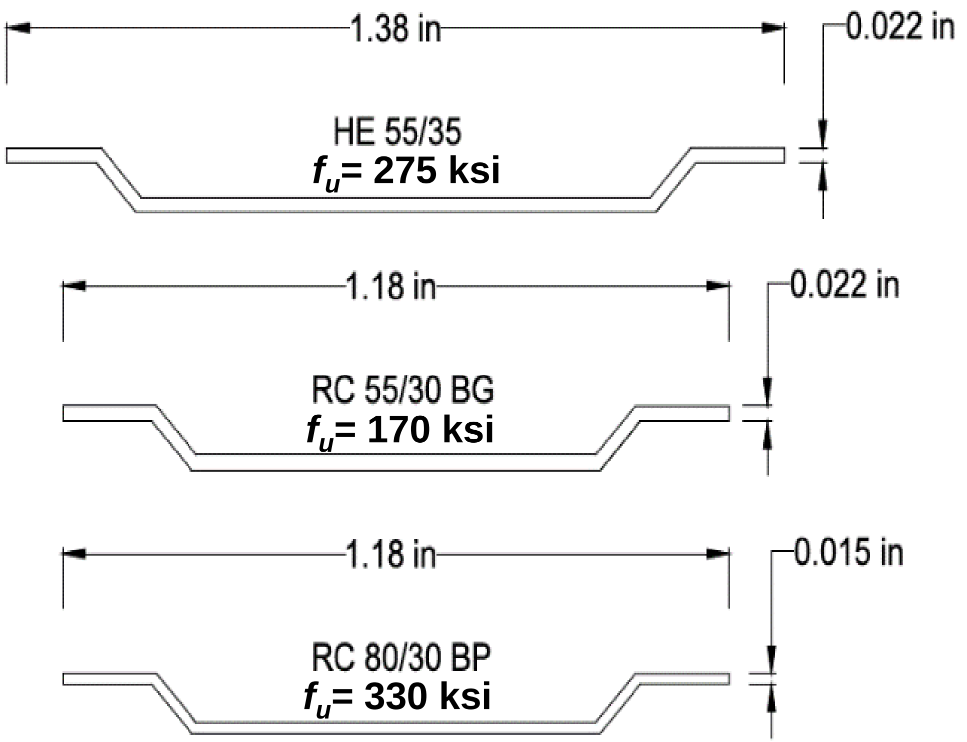
MOTIVATION

- Diagonal and transverse reinforcement requirements for coupling beams lead to severe reinforcement congestion, with associated increase in labor, construction time, and costs

- Use of a material with large tension deformation capacity and confined concrete-like behavior should allow for substantial simplification in transverse confinement reinforcement without compromising seismic behavior

PREVIOUS WORK

- Three types of single-hook steel fibers
- Fiber volume content between 1.0% and 1.5%
- Test results showed diagonal reinforcement can be eliminated in SFRC coupling beams with $L_n/h \geq 2.0$
- Several high-rise structures have been constructed with SFRC coupling beams in state of Washington



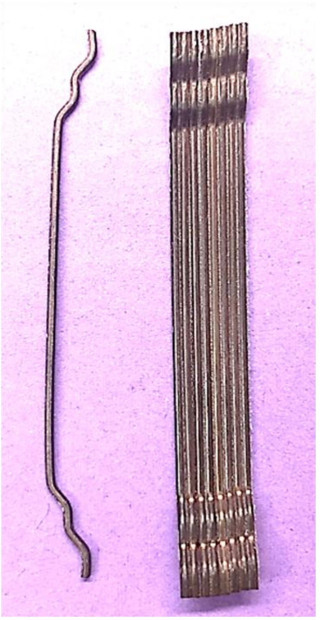
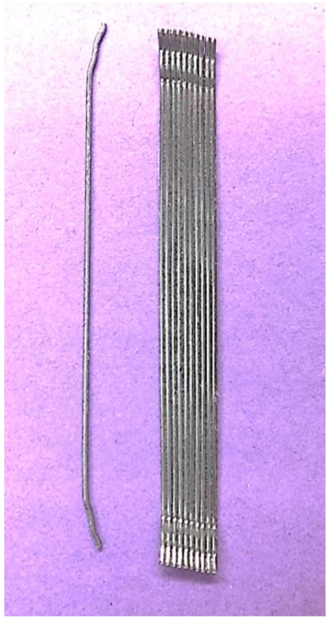
EXPERIMENTAL PROGRAM

- Twelve coupling beam specimens tested under large displacement reversals
- Aspect ratio (L_n/h) between 2.0 and 3.0
- Target peak average shear stress: $6 \text{ to } 10\sqrt{f'_c}$ (psi)
- Target concrete compressive strength: 8 ksi
- Two types of double-hook steel fibers evaluated in two dosages. Three SFRC mixtures evaluated

DOUBLE-HOOK STEEL FIBERS

Two types of double-hook steel fibers evaluated:

- 5D 65/60 at fiber volume fraction (V_f) of 1.0% and 1.25%
- 4D 80/60 used at V_f = 1.25%

	
L_f = 2.4 in. d_f = 0.04 in. f_u = 335 ksi	L_f = 2.4 in. d_f = 0.03 in. f_u = 260 ksi

5D 65/60 @ V_f=1.25%

TEST SPECIMENS

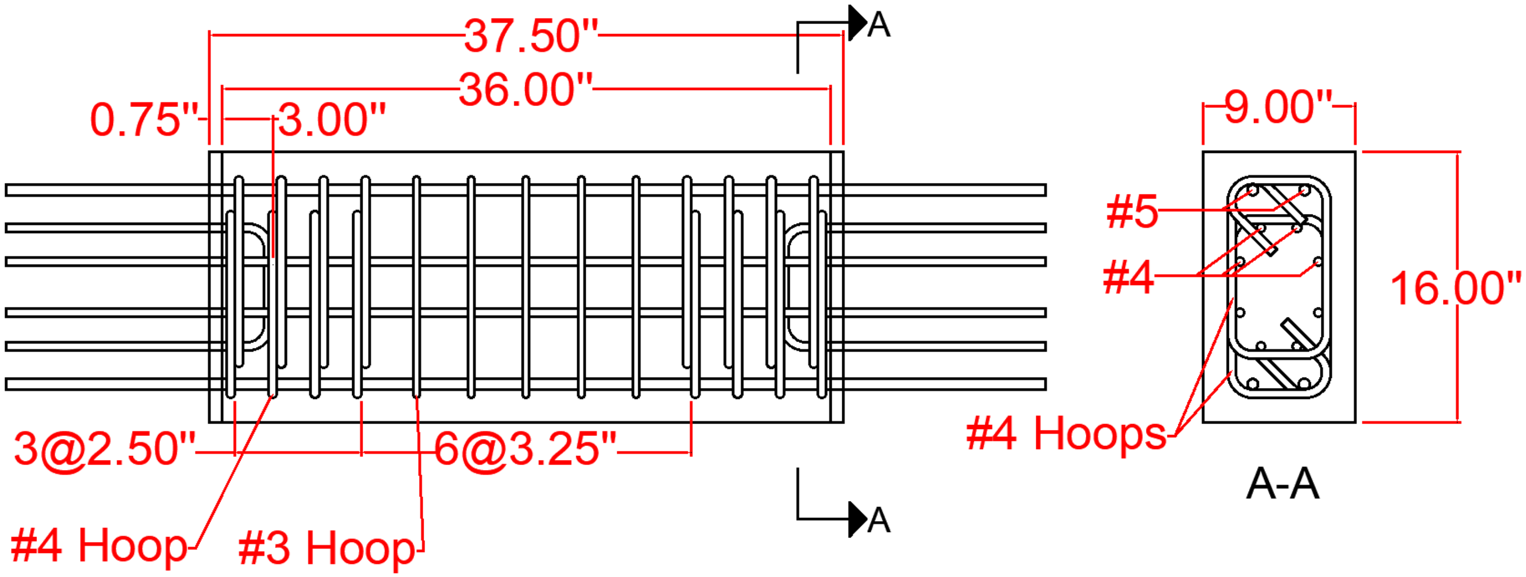
*Designed with 30% of required diagonal reinforcement

** Designed in accordance with ACI 318-14

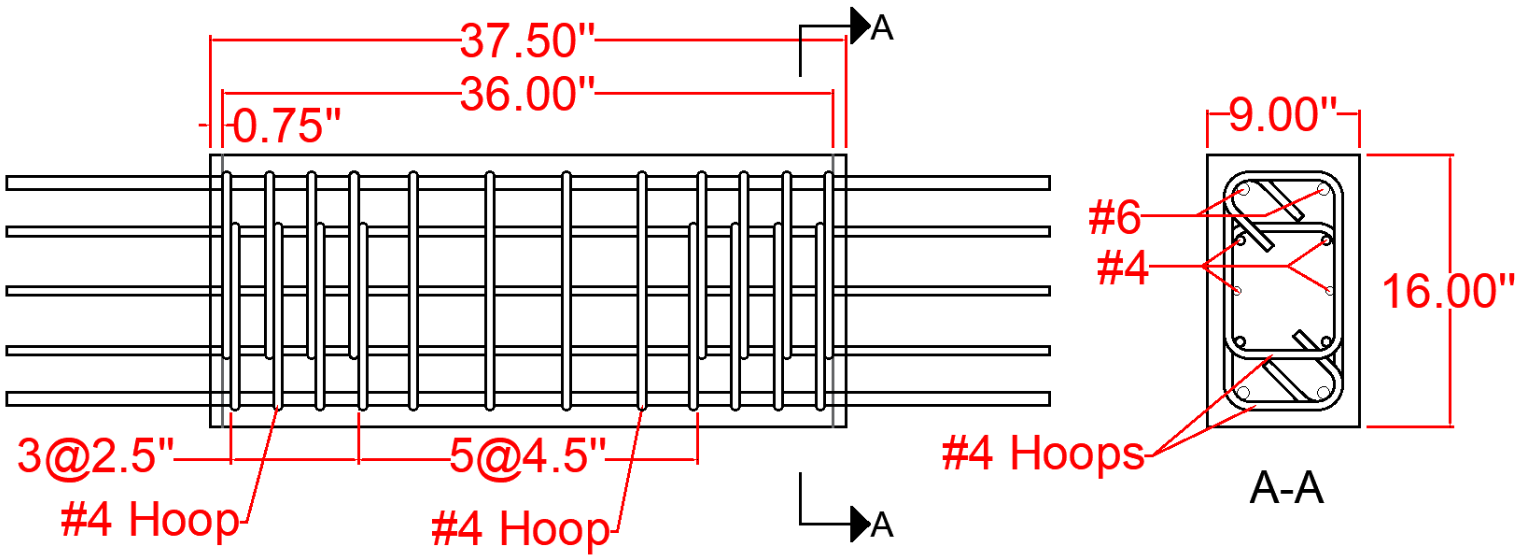
† Without U-Shaped dowels

Specimen	L_n/h	Fiber Type	V_f	Target v_u
CB3	2.0	5D 65/60	1.25%	$8\sqrt{f_c}(psi)$
CB4*	2.0	5D 65/60	1.25%	$8\sqrt{f_c}(psi)$
CB5	2.0	5D 65/60	1.25%	$6\sqrt{f_c}(psi)$
CB1	2.25	5D 65/60	1.0%	$8\sqrt{f_c}(psi)$
CB2**	2.25	N/A	N/A	$8\sqrt{f_c}(psi)$
CB8	2.25	4D 80/60	1.25%	$8\sqrt{f_c}(psi)$
CB12†	2.25	5D 65/60	1.25%	$8\sqrt{f_c}(psi)$
CB6	3.0	5D 65/60	1.0%	$8\sqrt{f_c}(psi)$
CB7	3.0	4D 80/60	1.25%	$8\sqrt{f_c}(psi)$
CB9	3.0	5D 65/60	1.25%	$8\sqrt{f_c}(psi)$
CB10	3.0	5D 65/60	1.25%	$8\sqrt{f_c}(psi)$
CB11†	3.0	5D 65/60	1.25%	$10\sqrt{f_c}(psi)$

COUPLING BEAM DETAILS



Coupling beam details with U-shaped dowels

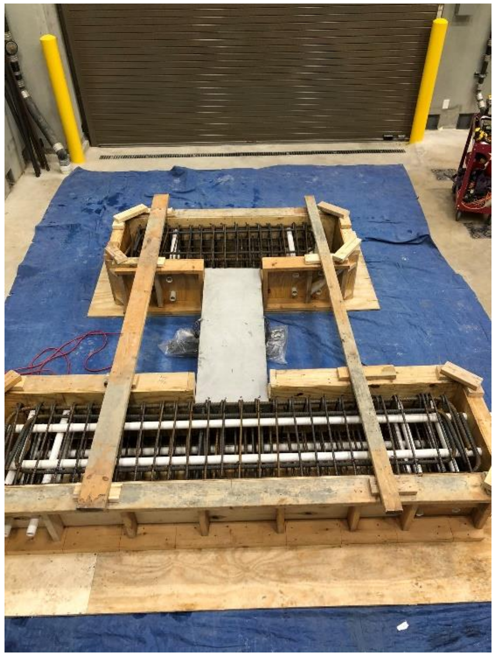


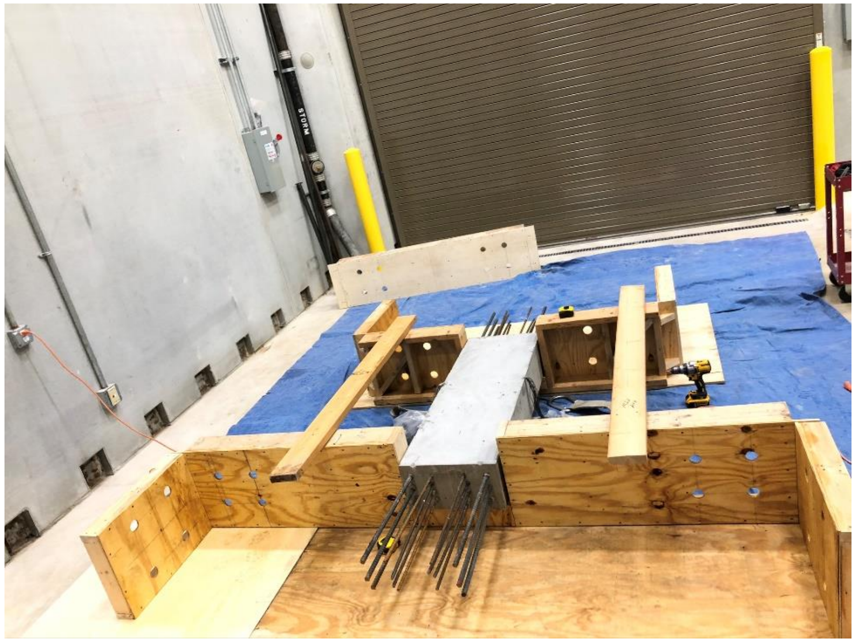
Coupling beam details without U-shaped dowels

COUPLING BEAMS W/ AND W/O U DOWELS

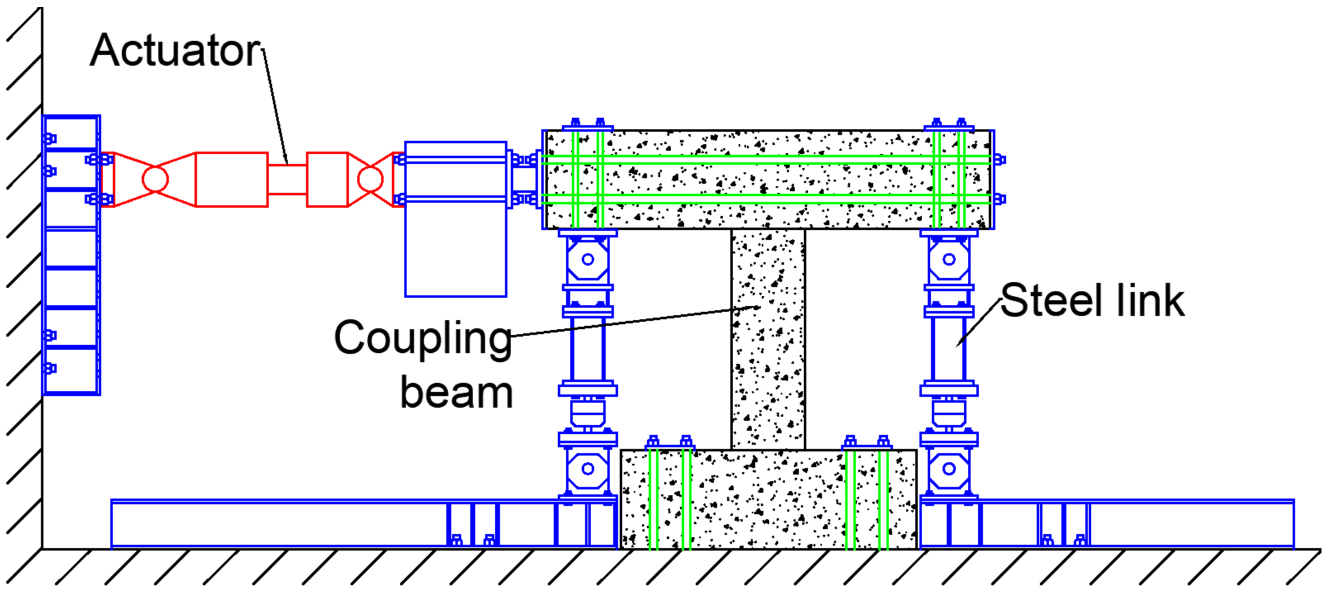
	Specimen	*U dowels?*	Fiber Type	V_f	Target v_u
$L_n/h = 2.25$	CB1	Yes	5D 65/60	1.0%	$8\sqrt{f_c}(psi)$
	CB12	No	5D 65/60	1.25%	$8\sqrt{f_c}(psi)$
$L_n/h = 3.0$	CB9	Yes	5D 65/60	1.25%	$8\sqrt{f_c}(psi)$
	CB11	No	5D 65/60	1.25%	$10\sqrt{f_c}(psi)$

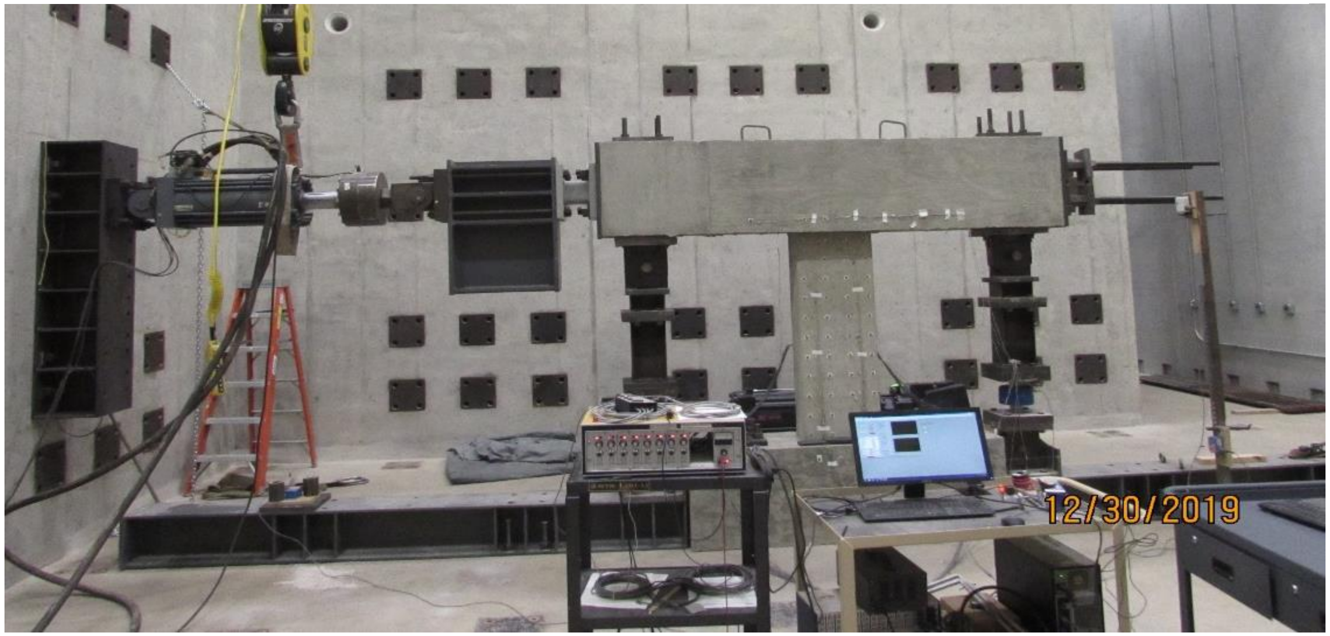
PRECAST COUPLING BEAM



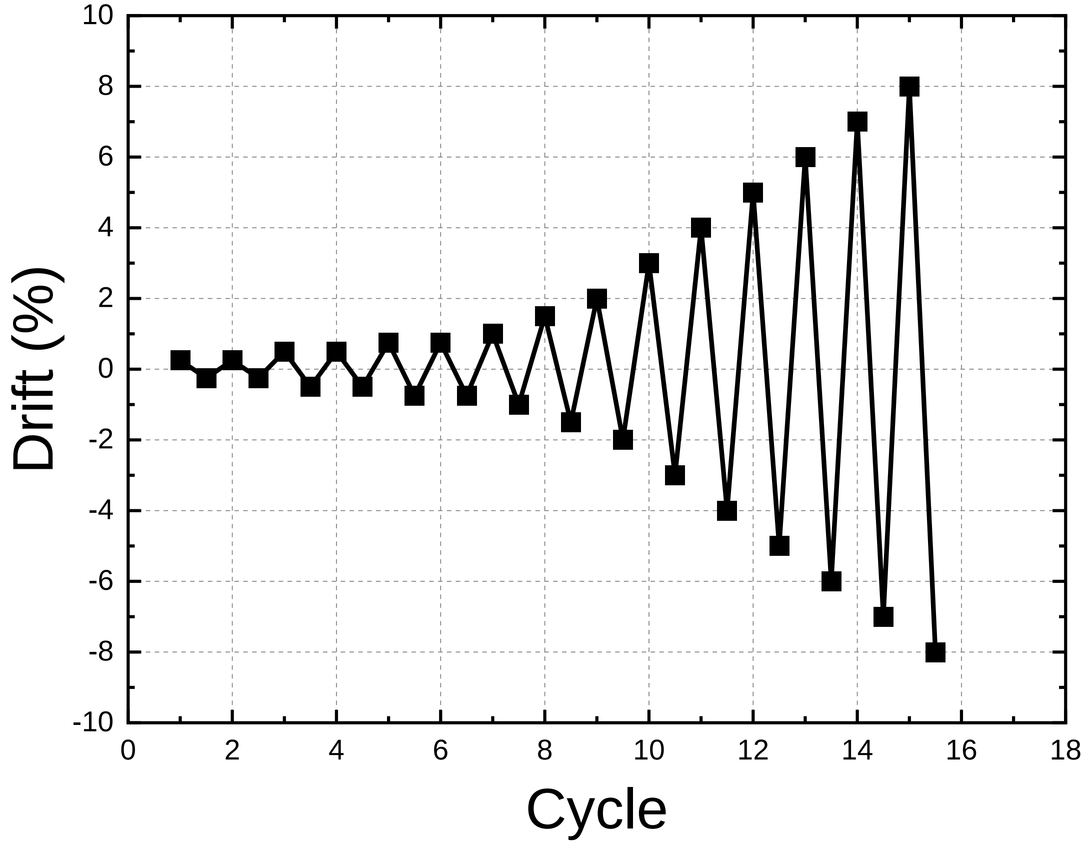


TEST SETUP

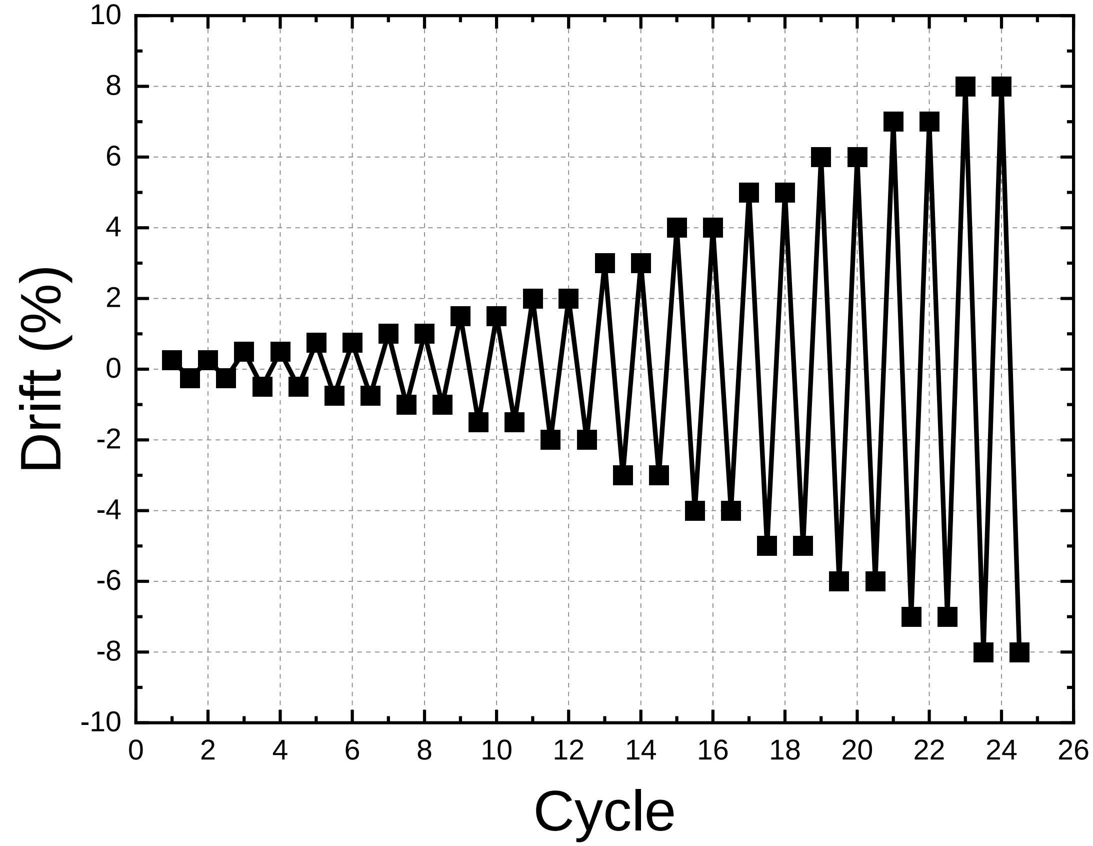




LOADING PROTOCOL

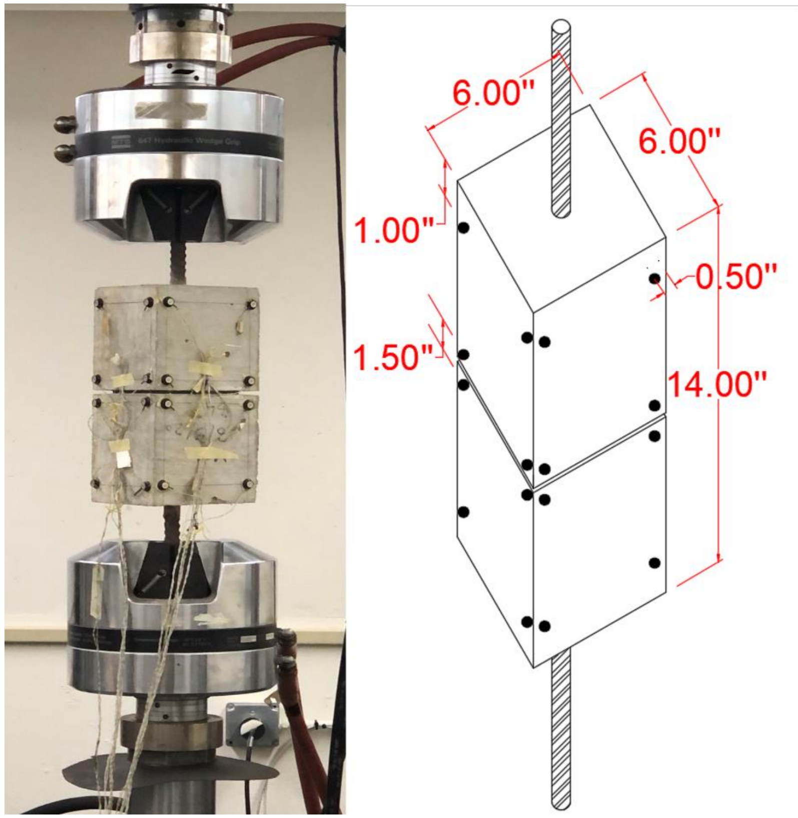


Specimens CB1 through CB10

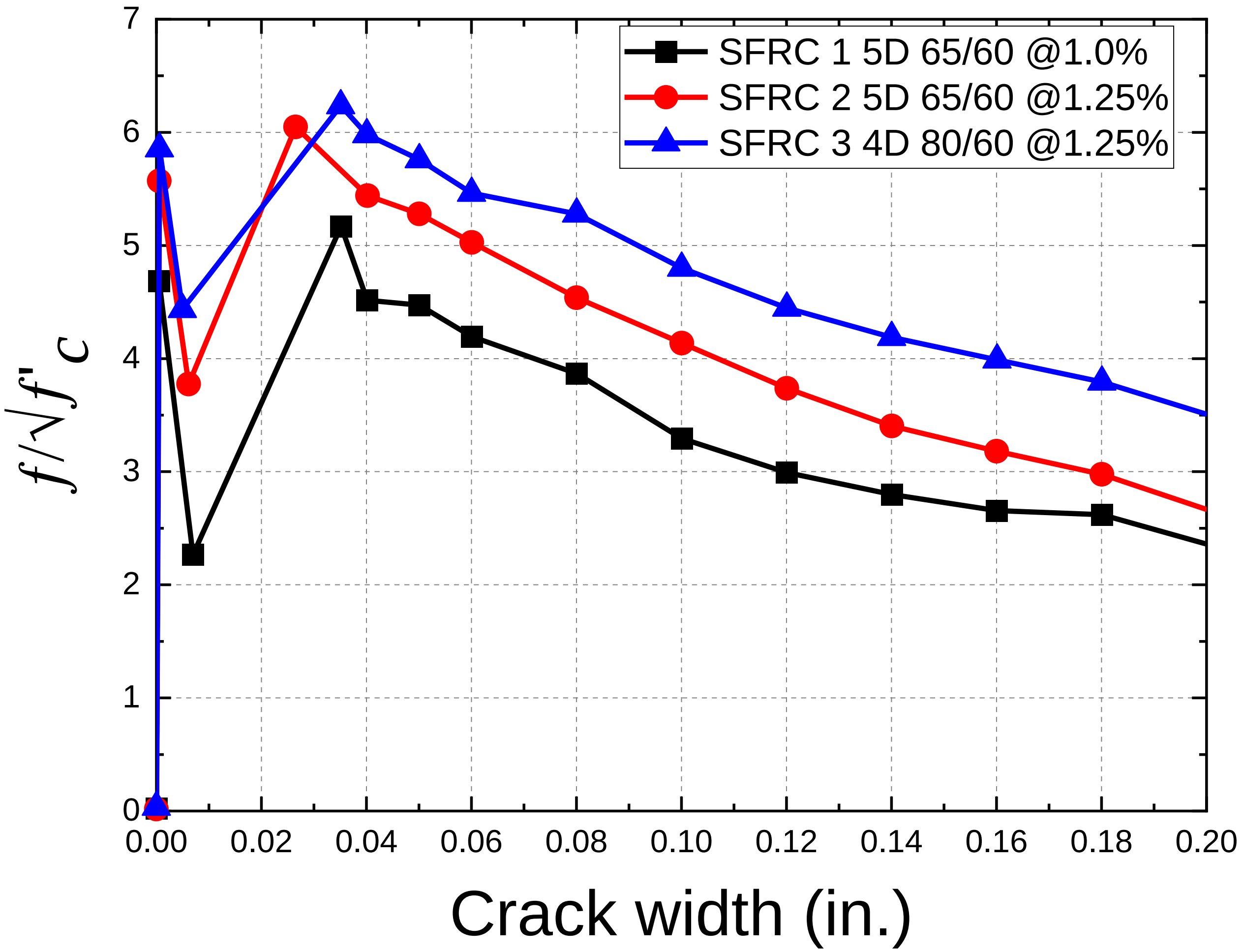


Specimens CB11 and CB12

SFRC MATERIAL TESTS – DIRECT TENSION

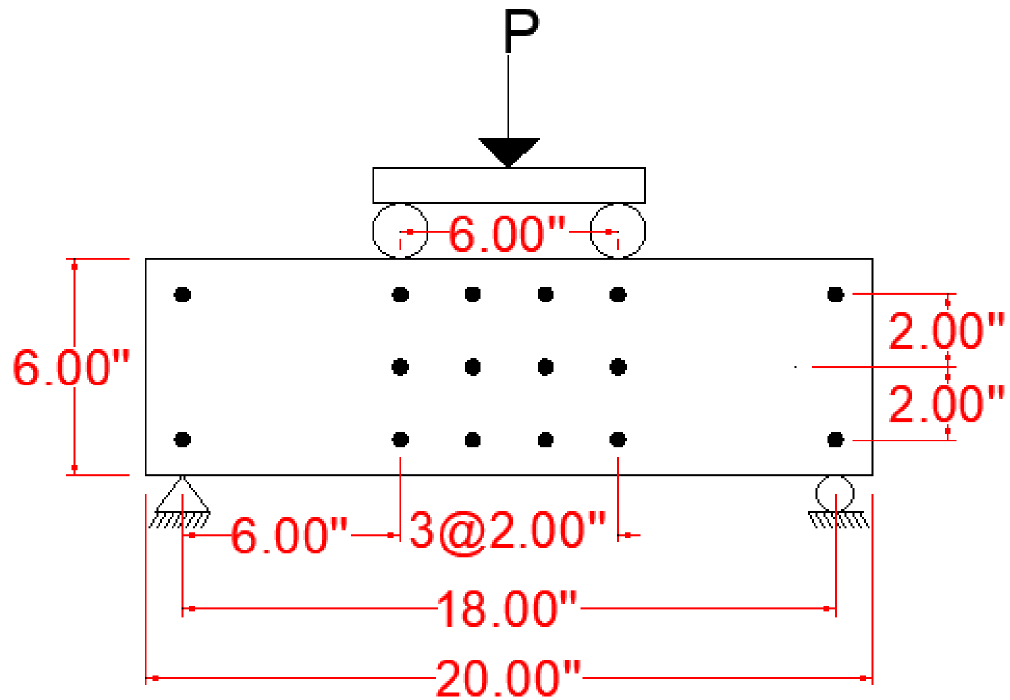


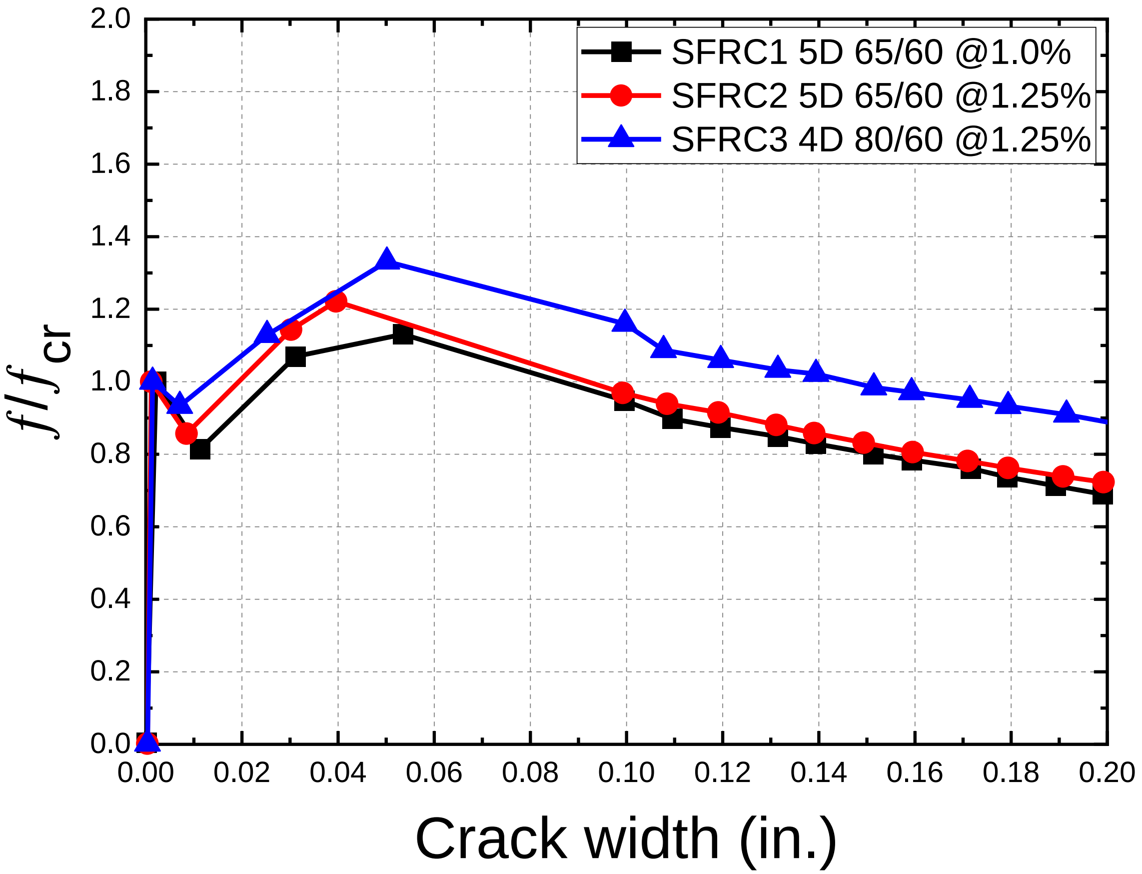
Direct tension tests



SFRC MATERIAL TESTS – BENDING

ASTM C1609 four-point bending tests

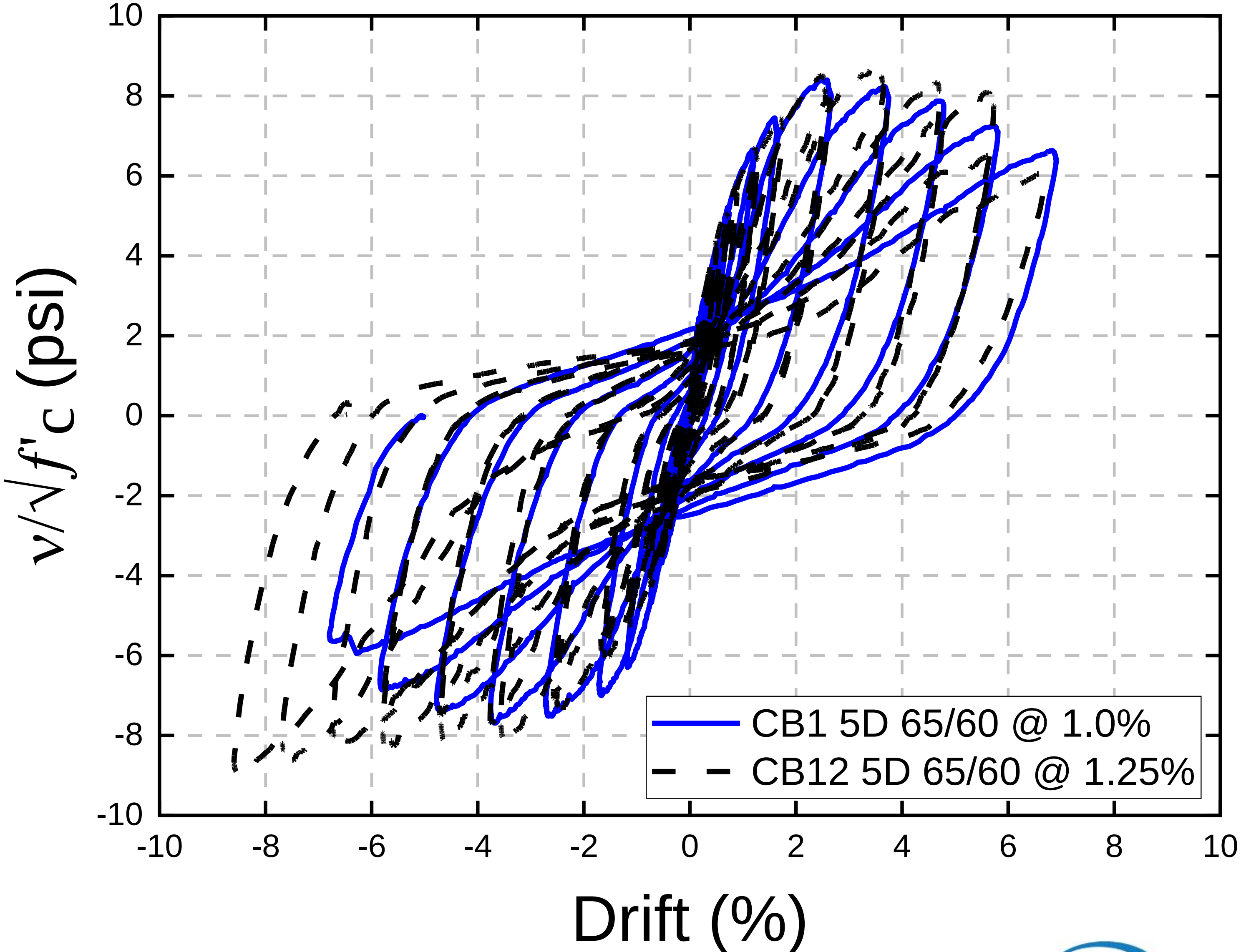




COUPLING BEAM BEHAVIOR

$L_n/h = 2.25$

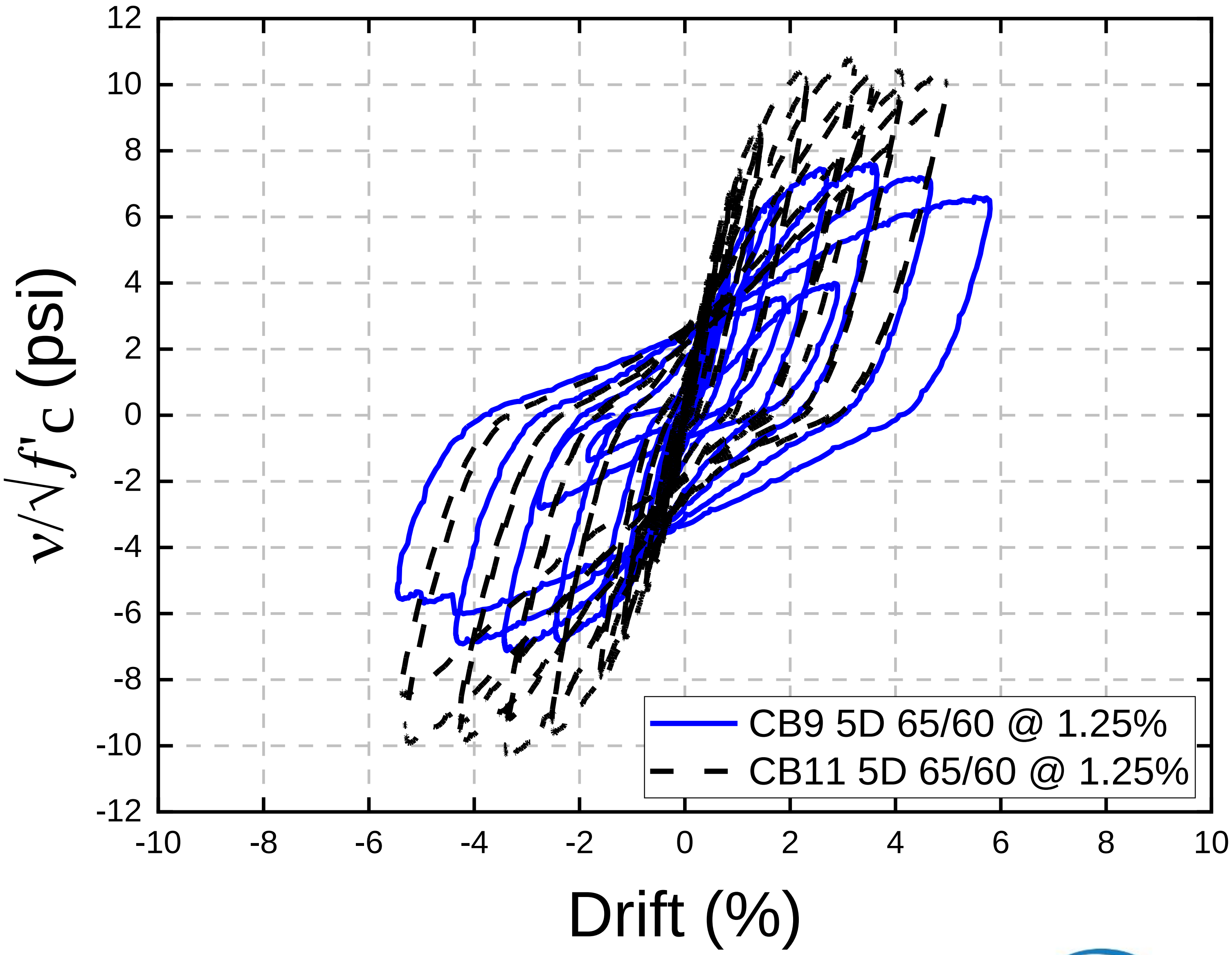
- Specimen CB12 was constructed without U dowels



COUPLING BEAM BEHAVIOR

$L_n/h = 3.0$

- Specimen CB11 was constructed without U dowels



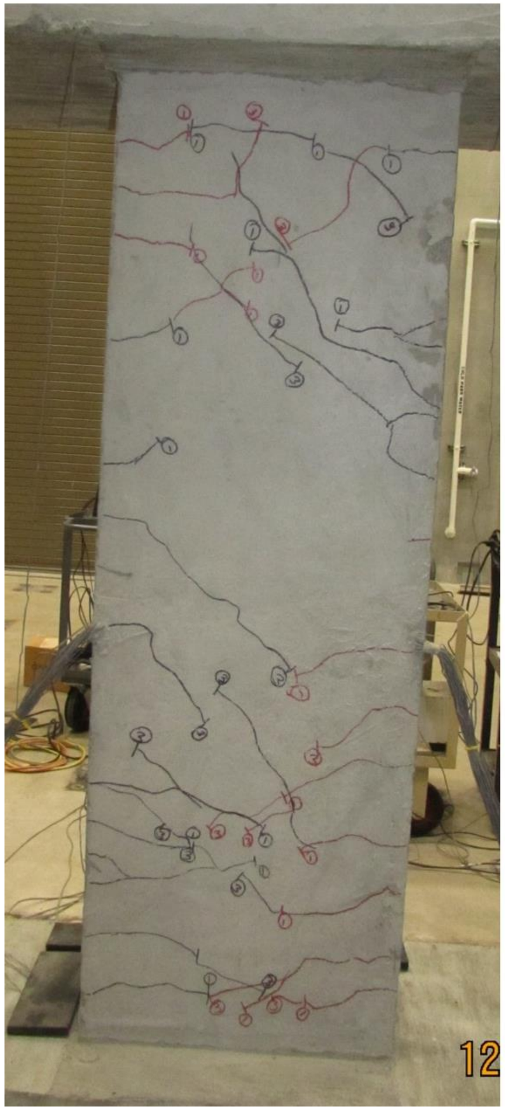
TEST RESULTS

- Coupling beams with no diagonal reinforcement exhibited a stable hysteresis response
- Maximum shear stress achieved ranged between $7.1 \text{ and } 10.8\sqrt{f'_c}$ (psi)
- Peak axial force measured was, on average, $0.1f'_cA_g$
- Coupling beams maintained at least 80% of their peak strength at 5.0% drift ratio
- Behavior of coupling beams was dominated by flexural rotations at the beam ends
- Lateral strength and stiffness decay was directly related to initiation of sliding displacements

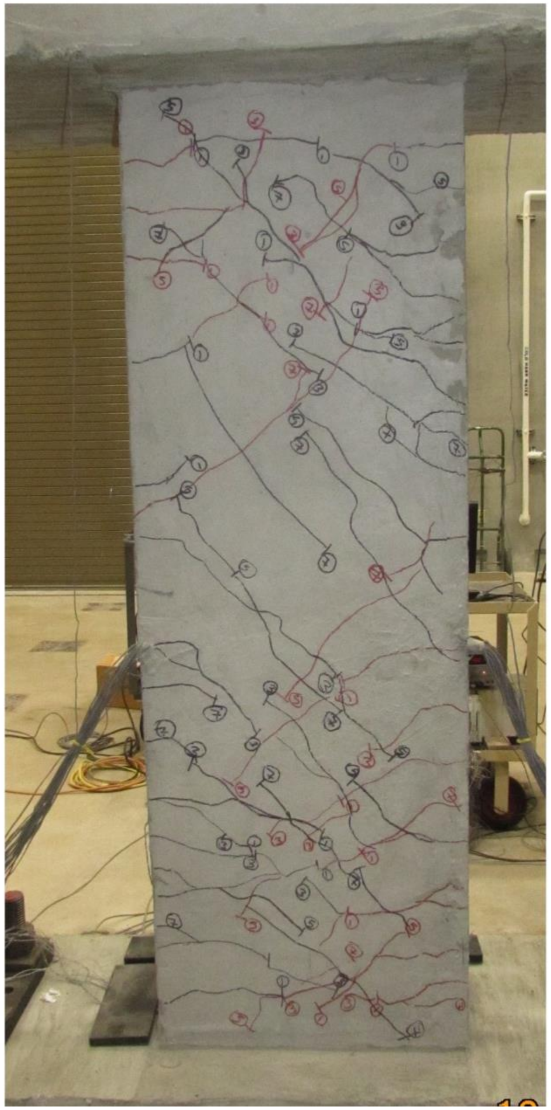
DAMAGE PROGRESS

- L_n/h = 3.0; 5D 65/60 fibers at 1.25% volume content

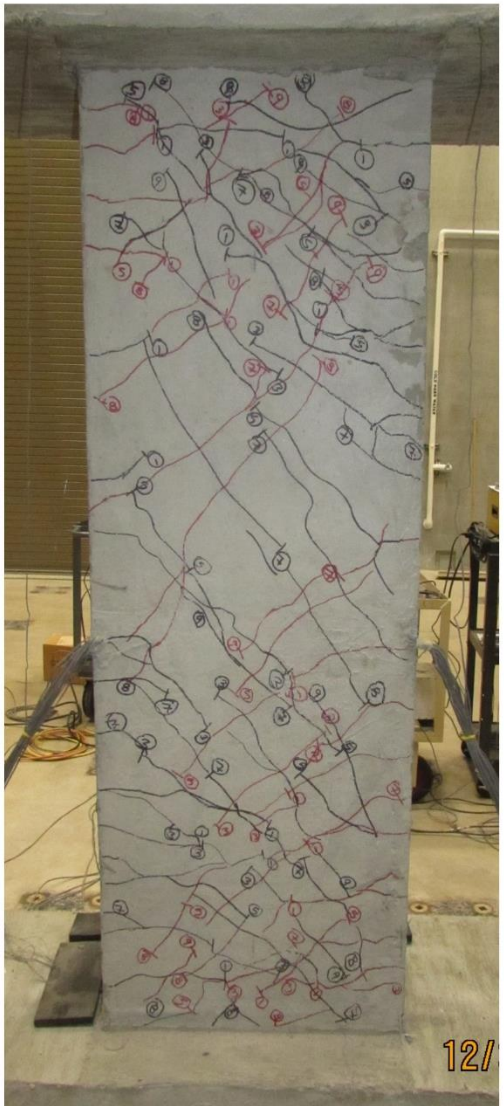
0.5% drift



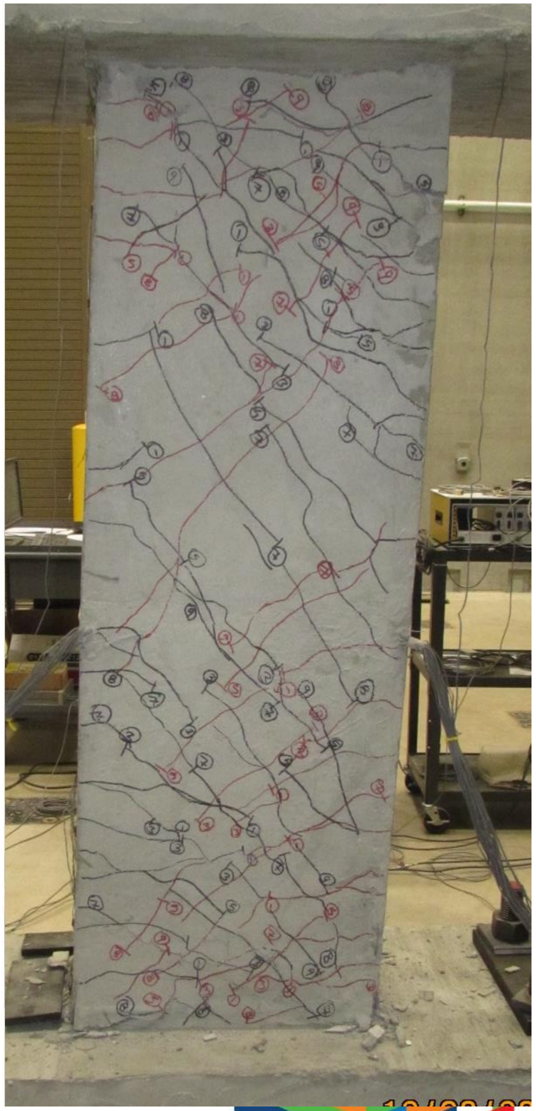
1.0% drift



2.0% drift



4.0% drift



EFFECTIVE FLEXURAL STIFFNESS AT YIELD

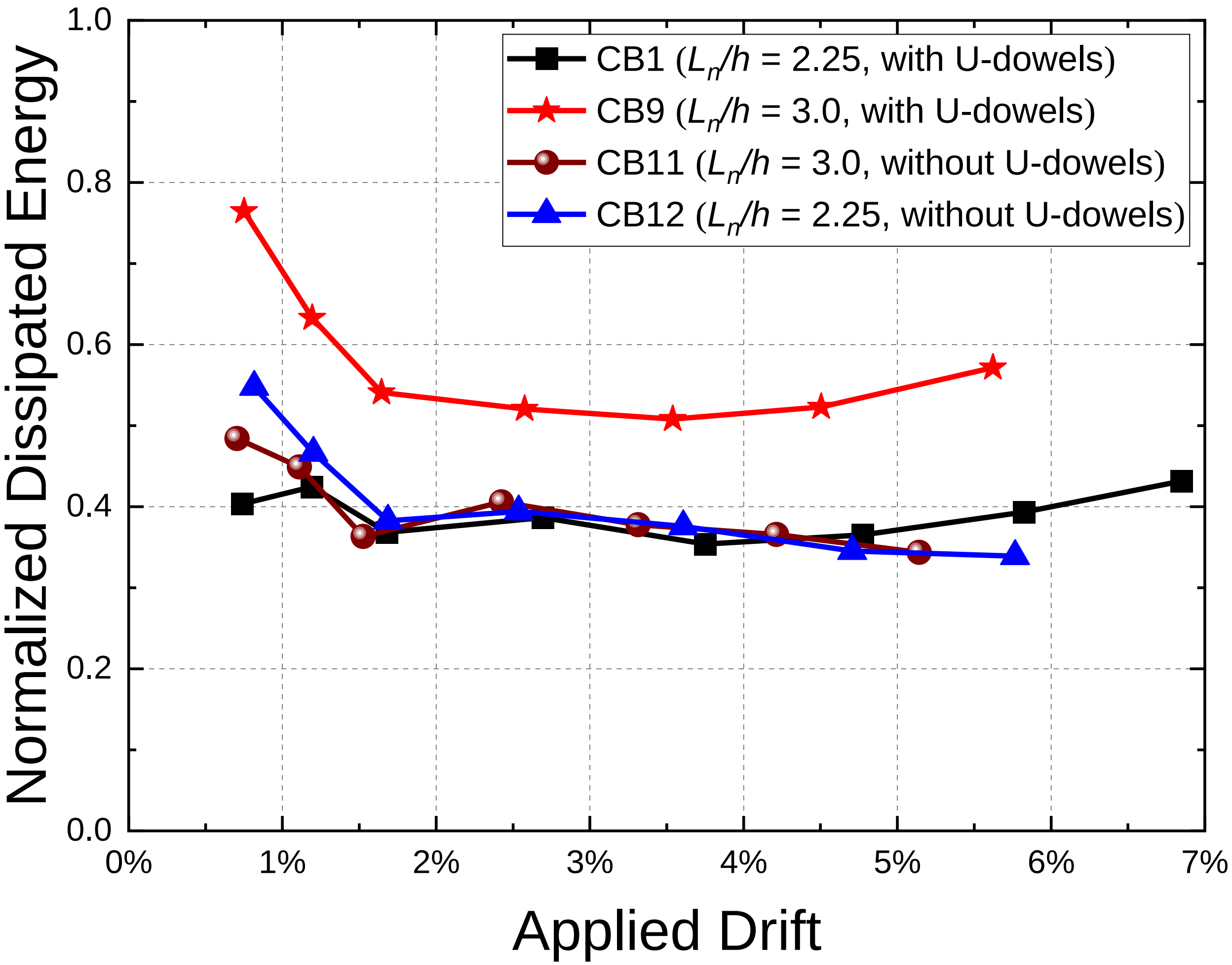
- On average, estimated EI_{eff} at yield was 65% of the flexural stiffness recommended by the ACI 318-19

Specimen	L_n/h	EI_{eff}/EI_g	EI_{eff}/EI_g (318-19 Table A.8.4)
CB1	2.25	0.09	0.16
CB12	2.25	0.11	0.16
CB9	3.0	0.13	0.21
CB11	3.0	0.21	0.21

ENERGY DISSIPATION

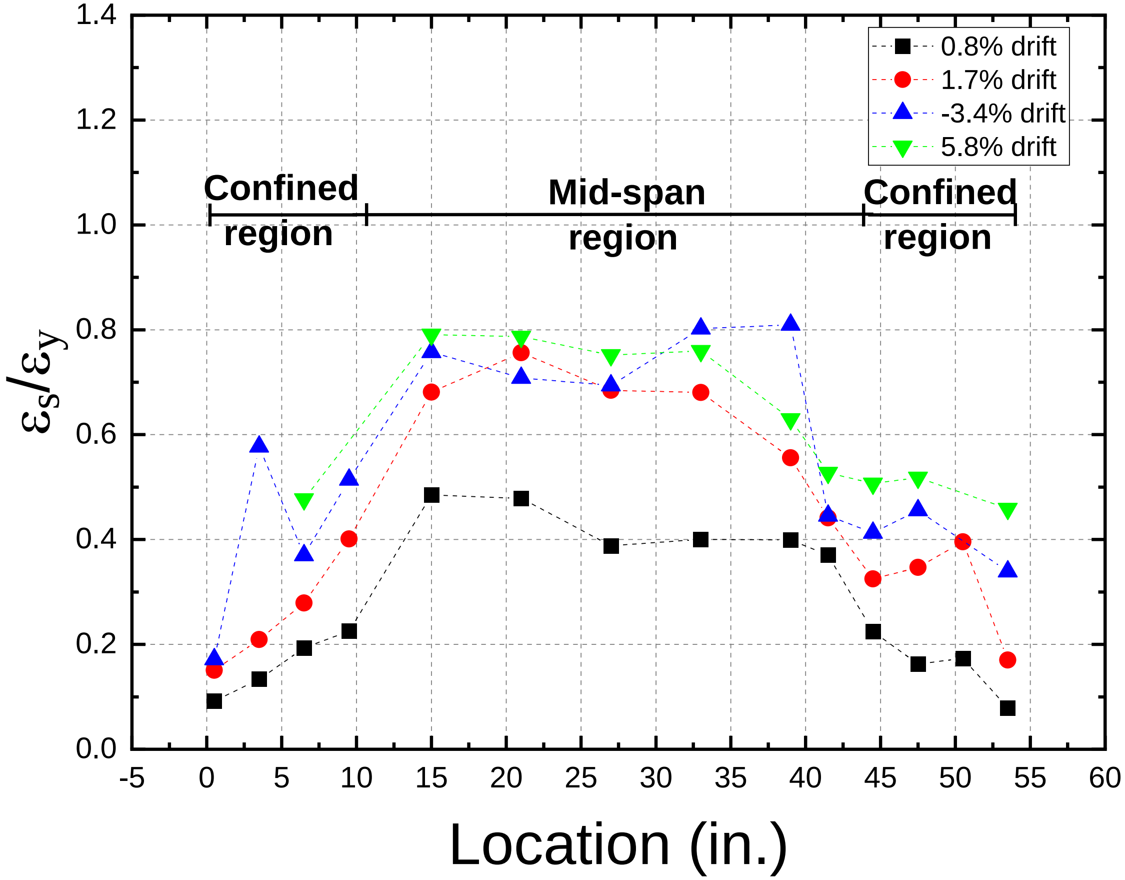
- All SFRC coupling beams exhibited energy dissipation capacity comparable to that of well-detailed diagonally-reinforced concrete coupling beams

- For same shear stress level, removal of dowels did not affect energy dissipation capacity

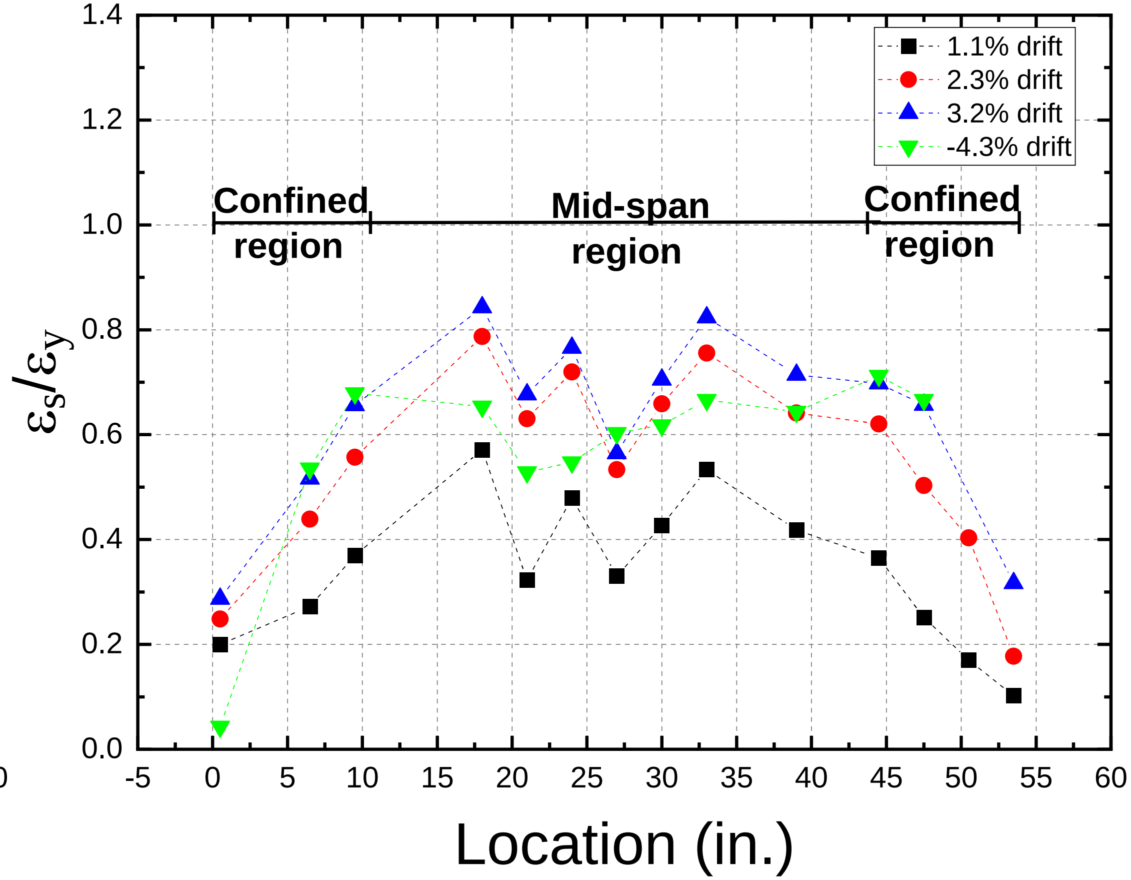


TRANSVERSE REINFORECEMENT STRAIN

- Transverse reinforcement in the mid-span and the confined regions remained elastic



Specimen CB9 (L_n/h =3.0)
5D 65/60 @1.25%
With U dowels



Specimen CB11 (L_n/h =3.0)
5D 65/60 @1.25%
Without U dowels

CONCLUSIONS

- Strain-hardening SFRC coupling beams with $L_n/h \geq 2.0$ exhibited stable, flexurally-dominated behavior while undergoing shear stress reversals ranging from 8 to $10\sqrt{f'_c}$ (psi)
- Drift capacity in test specimens was at least 5%
- Column-type confinement reinforcement only required at beam ends
- Shear stress contribution by the SFRC greater than $4\sqrt{f'_c}$ (psi)
- Coupling beams constructed without U-shaped dowels showed similar behavior to those constructed with U-shaped dowels

ACKNOWLEDGMENTS

- Bekaert Corporation
- University of Wisconsin-Madison