BEHAVIOR OF HIGH-PERFORMANCE FIBER-REINFORCED CEMENTITIOUS COMPOSITES FOR RC COUPLING BEAMS IN EARTHQUAKE-RESISTANT STRUCTURAL WALL SYSTEMS

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Background Information and Project Overview

- Coupled shear walls are a popular reinforced concrete (RC) structural system for medium-rise structures in areas of moderate to high seismicity.
- Building code specifications for RC coupling beams typically require substantial longitudinal, transverse, and sometimes even confined diagonal reinforcement; the result can often be reinforcement congestion accompanied by costly operations and time delays.
- The next generation of reinforced concrete structures could utilize ductile cementitious materials in critical shear and/or moment regions, rather than extensive reinforcement detailing.
- High-performance fiber-reinforced cementitious composites (HPFRCC) can increase coupling beam damage tolerance through a ductile response obtained by the tensile strain-hardening and confined compressive behavior of the material.
- Additionally, HPFRCC is being investigated as a replacement for some steel confinement reinforcement and to provide an additional shear resistance mechanism.
- The reported experimental program at the University of Illinois has been conducted to further understand the behavior of HPFRCC under general uniaxial and biaxial stress states, such as would be expected at various key locations in a coupling beam.
- Failure envelopes were developed for each type of composite, and their stress-strain behaviors as well as failure mechanisms were observed.
- Concrete plate specimens comprising mixes containing from 1 to 2 percent fiber volume fraction of hooked steel fibers and Spectra (polyethylene) fibers were tested to gain an understanding of the possible energy dissipating behavior of HPFRCC for uses in structural elements for seismic design.


Figure 1. Spectra Fibers

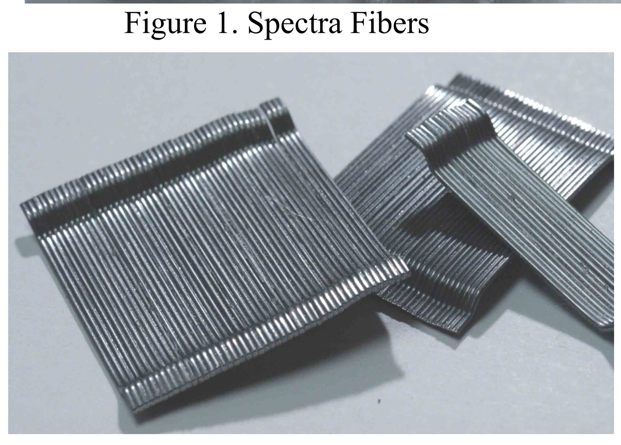
Figure 2. Hooked Steel Fibers

Research Program

Testing Program

- Hooked steel fiber, Spectra fiber, and plain concrete mixes were investigated.
- Individual and loaf specimens were cast. Loaf specimens were cut to match individual specimen size at 5.5 x 5.5 x 1.5 in., a size similar to historical concrete biaxial tests by Kupfer et al. (1969).
- Two concrete mixtures were explored: Mortar Mix (MM) and NEES Mix 4 (NM4)
- MM specimens had Spectra fibers, hooked steel fibers, or no fibers, and NM4 had either hooked steel fibers or no fibers.
- 1.0, 1.5, and 2.0 percent fiber volume fractions were investigated for both fiber types.
- Upon visual inspection, it could seen that the fibers were adequately and randomly dispersed in the loaf specimens.
- Six to ten specimens of each mixture and fiber type were tested for the individually cast specimens, and six specimens were tested for each mixture of the loaf specimens, for a total of 133 specimens.

Table 1. Mixture Proportions by Weight of Cement

Matrix Type		Mortar	NEES Mix 4
Cement type 3 (Early age)		1	1
Aggregates	Silica Sand (Flint)	1	2.5
	Coarse Aggregate	-	1.25
Fly Ash Class C		0.15	0.875
Chemical Admixtures	Super-Plasticizer	*	0.0055
	VMA	-	0.065
Water		0.4	0.84
Fibers	Types of Fibers	Hooked, Spectra	Hooked
	Percent Volume	1.0, 1.5, and 2.0	1.0, 1.5, and 2.0
28-Day Compressive Strength, ksi		8 (55.2)	5.1 (35.2)

Test Specimens / Test Procedure

- The hooked steel fibers were Dramix® RC-80/30-BP, and they had a length of 1.2 in., a diameter of 0.0217 in., and a tensile strength of 334 ksi.
- The Spectra® fibers had a length of 1.5 in., a diameter of 0.0015 in., and a tensile strength of 375 ksi.
- Loaf specimens were cut from 6.5 x 6.5 x 18 in. loaves with a diamond precision saw to the aforementioned individual specimen size.
- The four sides of each specimen were ground to achieve flat edges and right-angle corners for a uniform biaxial stress state.
- A closed-loop system in displacement control using INSTRON controllers was used to capture the post-peak response of the specimens, and all of the biaxial compressive loads were applied simultaneously.
- Pin-connected brush-type loading platens were used to minimize frictional confinement of the test specimens, with simple guide-ways to ensure planar loading of the specimens.
- Standard applied strain rate was 0.01 in./min for compression.
- Strain and displacement measurements were obtained using the non-contact Krypton K600 Dynamic Measuring Machine (DMM).
- Krypton DMM can obtain the 3D location of many small light-emitting diodes (LEDs) to an accuracy of +/- 0.0008 in. at a sampling rate of up to 1000 readings per second.
- LEDs were placed on an overall 3 in. x 3 in. grid (with 1.5 in. spacings) centered on the specimen.
- Out-of-plane data was obtained by two 0.25 in. stroke LVDTs, positioned on special frames and placed such that they were touching the center of each face of the specimen.

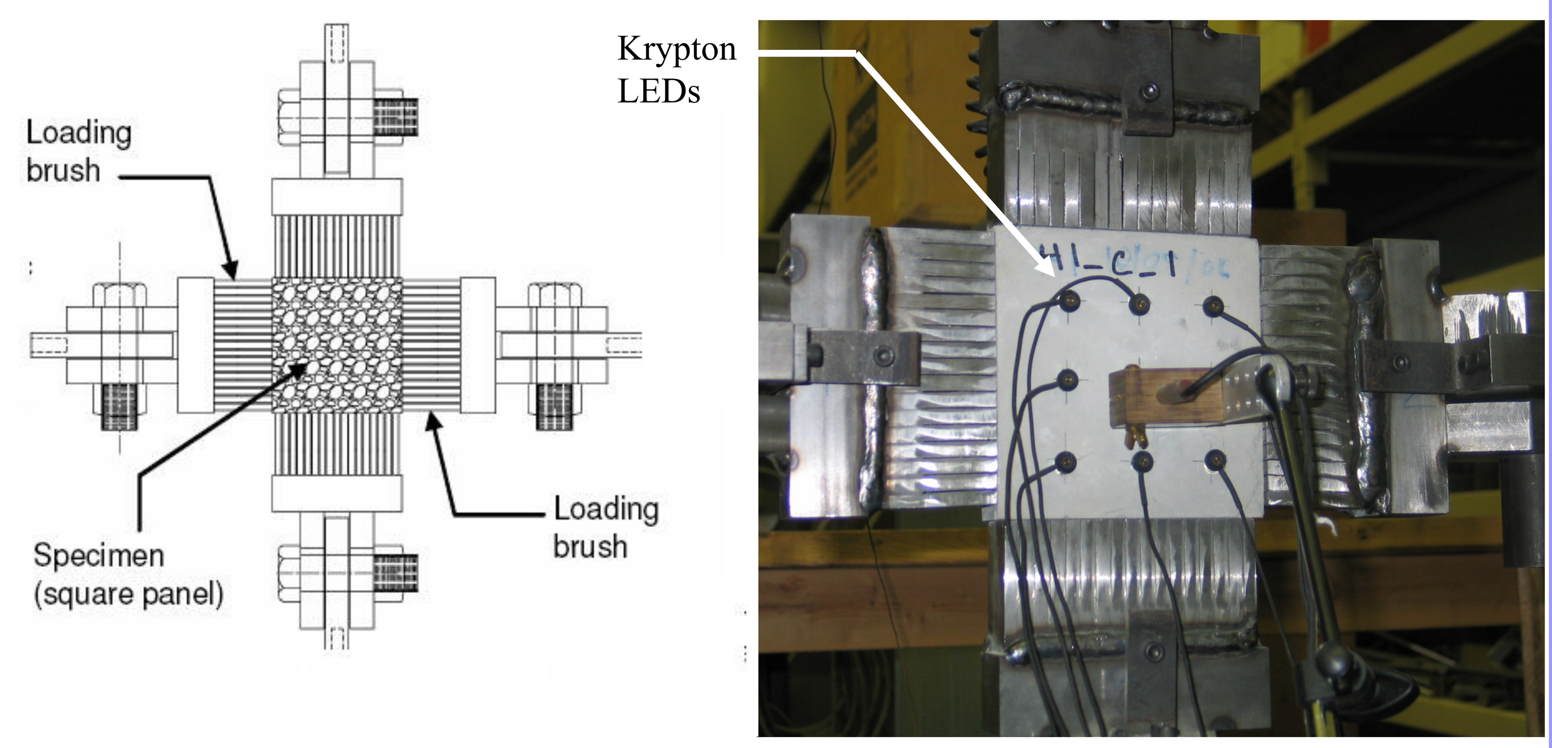

Figure 3. Experimental Test Setup

Results and Conclusions

Ultimate Strength:

- Table 2 displays the average uniaxial compressive plate strengths for the respective concrete mix and fiber type.
- Within each mix and specimen type, a general trend was that, as the fiber volume fraction increased from 1 to 2 percent, the unconfined uniaxial compressive strength from cylinder tests slightly decreased.
- Individual specimens (all fiber and mix types) benefited between 2 and 6 percent from being subjected to equal biaxial compression stresses, with a maximum strength increase of between 12 and 20 percent at a stress ratio of about 0.5 (Figure 4).
- Due to the more random orientation of fibers, loaf specimens experienced a strength increase of greater than 50 percent more than their respective uniaxial strengths under equal biaxial loading (Figure 4).
- At a stress ratio of about 0.5, a greater increase in strength for the average loaf hooked steel fiber specimens was observed than from Yin et al (1989), as shown in Figure 5.
- The envelope predicts an inferior performance at a stress ratio around 0.2, but this is likely due to a paucity of data points at lower stress levels (Figure 5).
- Compared to previous tests on plain specimens, the plain MM had a stronger normalized biaxial strength than from most previous research except that observed by Yin et al (1989). NM4 results align quite well with the other historical tests, and nearly duplicate the result obtained by Nelissen (1972), as seen in Figure 6.

Table 2. Uniaxial Compressive Strength

Mix	Specimen Type	Fiber Type	Average Plate Compressive Strength, ksi
Mortar Mix	Individual	Hooked	10.2
		Spectra	8.8
		Plain	8.6
	Loaf	Hooked	6.6
		Spectra	5.8
NEES Mix #4	Individual	Hooked	6.3
		Plain	7.6

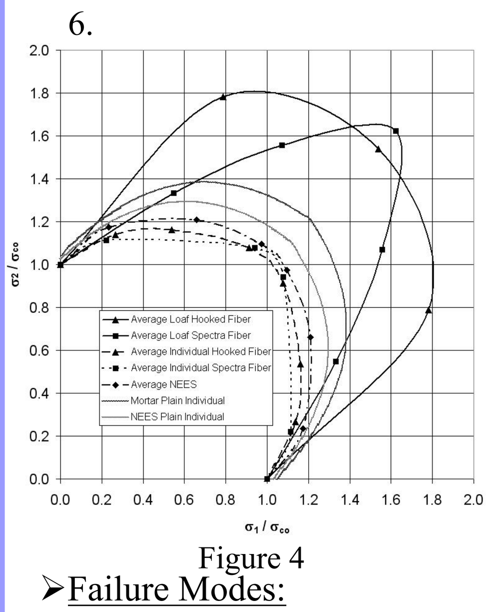
Figure 4

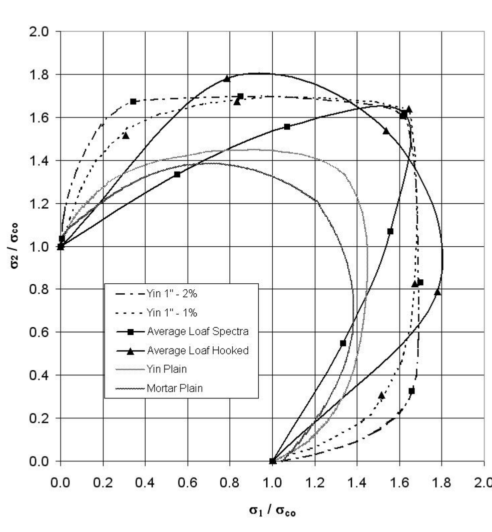
Figure 5

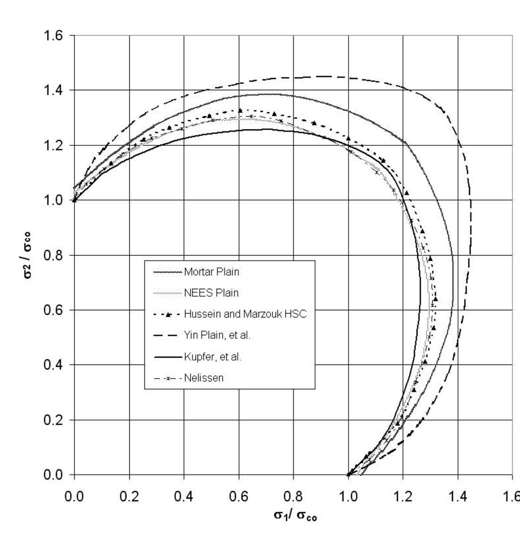
Figure 6

Failure Modes:

- The typical failure mechanism of plain concrete specimens was by tensile splitting. Under biaxial loading, the origination of a failure surface along a plane parallel to the plane of the test specimen resulted in an abrupt failure of the specimen, while the uniaxial tests experienced fracture formation along a plane parallel to the applied load and perpendicular to the unloaded out-of-plane surface of the specimen.
- The failure mechanisms experienced by the loaf fiber specimens were a faulting or shear failure due to the formation of multiple fault planes in the specimen, as described in previous research by Yin et al. (1989), also shown in Figure 7.


Figure 7

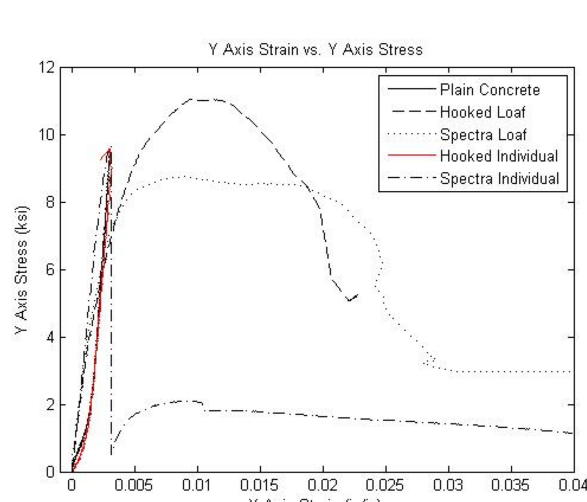

Figure 8

- Individually cast specimens experienced an explosive event at their maximum strength with some residual strength due to the predominantly in-plane orientation of the fibers (Figure 8).
- Loaf specimens obtained a random orientation of fibers and a significantly increased ductility.
- For loaf specimens, the strain at the maximum loading was nearly 0.01 in both directions of applied stress, and a significant residual stress was maintained to a strain of nearly 0.025 (Figure 8).
- Figure 9 illustrates the effect of fibers on the ductility of the specimens, as well as the influence of the application of a secondary biaxial stress on the compressive response of the specimen.
- Biaxial stress states were found to significantly increase the compressive strength of the material, as well as magnitude of the residual strength, as shown in Figure 9.
- Also, a marked improvement in the strength and ductility was experienced at intermediate stress ratios.

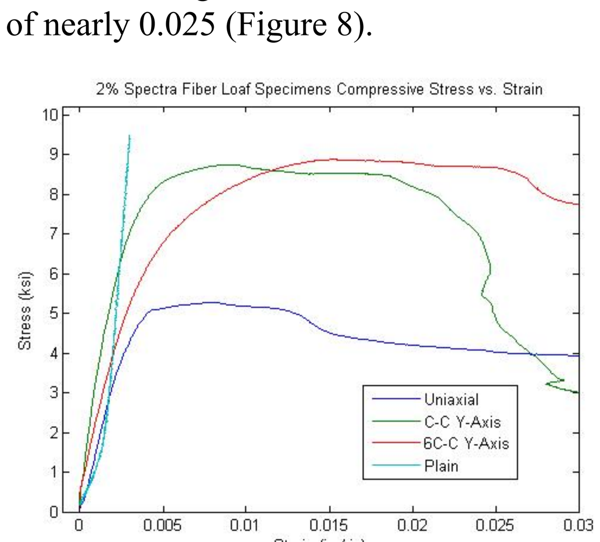

Figure 9

Current Progress and Future Direction

Current Progress and Future Directions

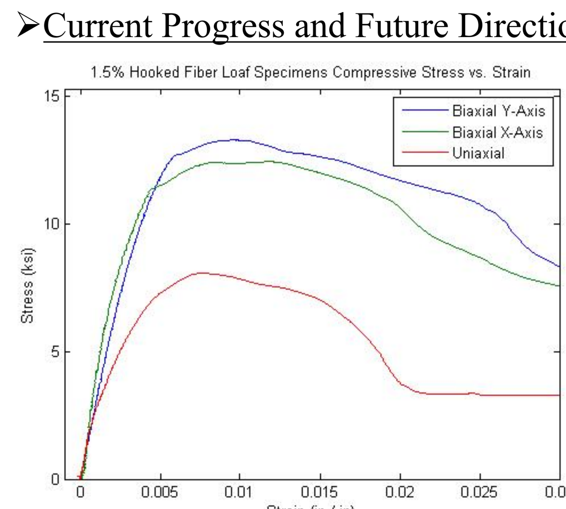

Figure 10

- Further loaf specimens have shown the importance of random fiber orientation to achieving the ductile and energy dissipating potential of the HPFRCC specimens (Figure 10)
- Substantial residual strengths have been observed at as much as 3% strain.
- Future specimen tests are to include uniaxial and biaxial tensile response for the complete biaxial behavior of HPFRCC.
- Large-scale coupled shear wall tests utilizing HPFRCC coupling beams are to be conducted at the University of Michigan.
- Another application being explored includes single-panel and double-panel infill panels for seismic retrofitting of steel moment frames.

Target Applications

- A comprehensive database of reinforced concrete coupling beam test specimens exhibiting four major modes of failure has been constructed.
- Conventionally and diagonally steel reinforced specimens were the the predominant types of steel reinforcement arrangement/layout (Figure 11).
- Some of the recorded data from each experimental specimen includes the reinforcement ratios, span-to-depth ratio, aspect ratio, concrete compressive strength, and major points characterizing the hysteretic (shear stress vs. displacement) response (Figure 12).
- The dominant governing failure modes were shear tension, shear compression, flexure, and buckling of compression bars.
- By employing a Bayesian parameter estimation probabilistic method, such as used by Kim et al. (2007) and Kim and LaFave (2008), several key influence parameters on shear capacity have been found, and an overall capacity prediction model was developed based on shear failure governed conventional steel reinforced specimens.
- Ongoing work includes the verification of the prediction capacity model with previous models found in literature. Further work also includes modifying the probabilistic method to develop a prediction capacity model for non-shear failure governed specimens of non-conventionally reinforced specimens (diagonally reinforced coupling beams) with HPFRCC.

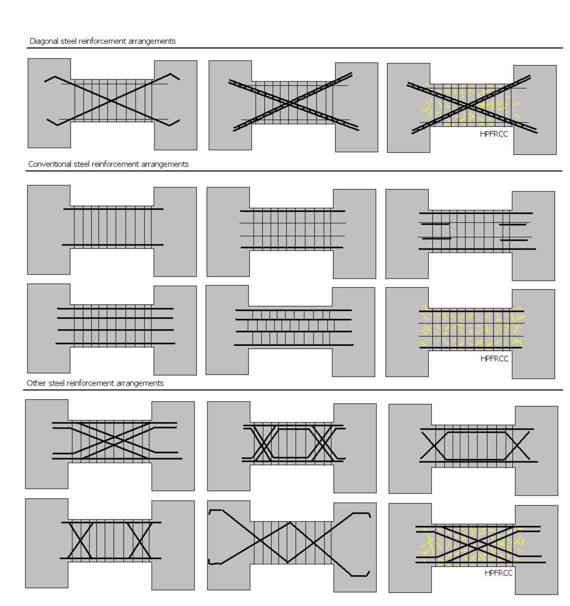
Figure 11

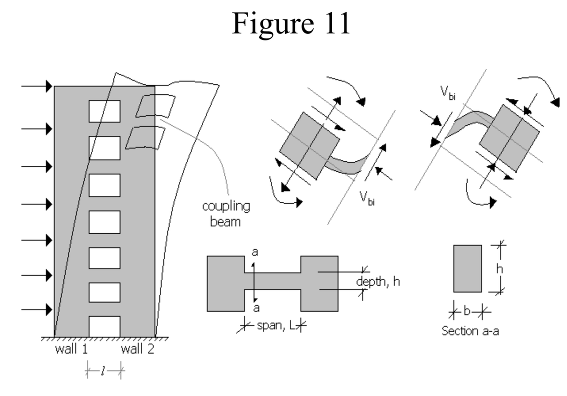

Figure 12

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NEES
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