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

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ABSTRACT :

Coupled shear walls are a popular reinforced concrete (RC) structural system for medium-rise structures in areas of moderate to high seismicity. Since current 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. As a design alternative, use of High Performance Fiber Reinforced Cementitious Composites (HPFRCC) has been considered. Use of HPFRCC may allow for a simplified reinforcement detailing, especially when located in critical shear and/or moment regions where extensive reinforcement is usually required. It is expected that the use of 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. Concrete plate specimens comprising mixes containing from one to two percent volume fraction of hooked steel fibers and Spectra (polyethylene) fibers were tested. Using the knowledge and behavioral trends gained through laboratory tests of these HPFRCC materials, it may be possible to extrapolate the energy dissipating behavior of HPFRCC to potential uses in structural elements for seismic design.

KEYWORDS: Fiber-Reinforced Concrete, Coupling Beams, Earthquake Resistant Design, Shear Strength, Damage Tolerance, Biaxial Loading

1. INTRODUCTION

Interest in the development of high performance fiber-reinforced cementitious composites (HPFRCCs) as a design alternative to alleviate reinforcement congestion in critical shear and/or moment regions of reinforced concrete coupled shear walls has recently been considered. HPFRCC materials can achieve a damage tolerant response through a ductile tensile strain-hardening behavior and a "confined" compressive behavior. Thus, the use of HPFRCC materials in large-scale structural applications could significantly reduce the amount of reinforcement required to ensure adequate performance in areas of inelastic deformation demands, while also potentially reducing costly labor demands and construction time delays (Parra-Montesinos 2005). Due to increased costs associated with using HPFRCC, the material has been targeted for critical regions where substantial reinforcement detailing is required for adequate behavior during earthquake loading. Canbolat et al. (2005) investigated the use of HPFRCC coupling beams without transverse reinforcement around the main diagonal reinforcing bars. The result indicated that a reduction in reinforcement may be achieved in HPFRCC coupling beams without compromising the shear strength due to the additional diagonal tensile strength of the fibers. Since cast-in-place HPFRCC coupling beams could present constructability issues, the use of precast HPFRCC beams in combination with conventional reinforced concrete structural walls has been proposed. To further understand the behavior of HPFRCC under general uniaxial and biaxial stress states, for possible use in various earthquake-resistant applications, an experimental program investigating the full range of biaxial material behavior has been employed. The study was conducted on HPFRCC using two different types of fiber: hooked steel fibers and Spectra (polyethylene) fibers. Failure envelopes were developed for each type of composite, and their stress-strain behaviors as well as failure mechanisms were observed. Currently, only the compressive biaxial behavior of HPFRCC has been examined; however, future tests including application of tensile stresses will also be explored.

2. EXPERIMENTAL PROGRAM

2.1 Testing Program

Hooked steel fiber, Spectra fiber, and plain concrete mixes were investigated. Figure 1 shows examples of the Spectra fibers and hooked steel fibers. The Spectra fibers are strong and durable white polyethylene fibers made by Honeywell. The mixes were first cast individually as 5.5 x 5.5 x 1.5 in. specimens, a size similar to historical concrete biaxial tests (Kupfer et al. 1969). Two concrete mixtures were explored, to be called the Mortar Mix (MM) and NEES Mix 4 (NM4) (Liao et al. 2006). Specimens were cast with Spectra fibers, hooked steel fibers, or without fibers for the MM, while only hooked steel fiber and plain concrete mixes were batched for NM4. To explore the influence of specimen type on orientation of the fibers (and therefore also on biaxial behavior), large 6.5 x 6.5 x 18 in. loaves of the MM were also cast to ensure a random orientation of the hooked steel and Spectra fibers. These loaves were then cut and trimmed to the aforementioned specimen size using a diamond precision saw. Upon visual inspection, it could be easily seen that the fibers were adequately and randomly dispersed in the loaf specimens. For both the Spectra fiber and hooked fiber specimens, 1.0, 1.5, and 2.0 percent fiber volume fractions were used. 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.

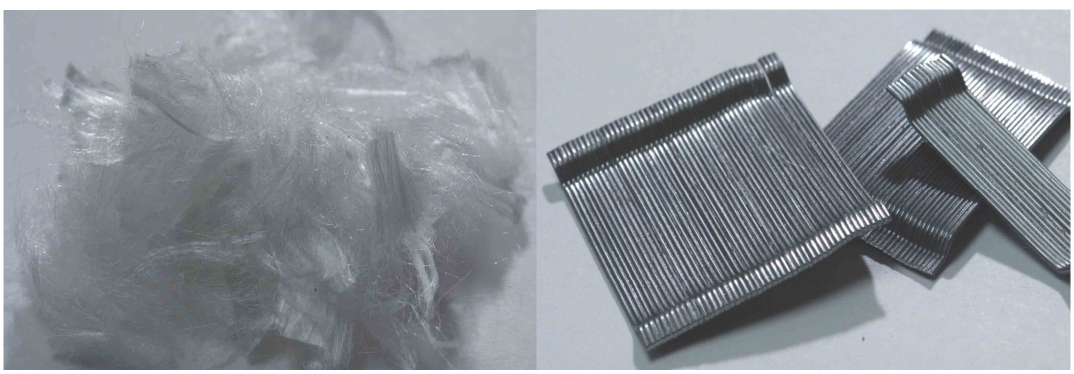

Figure 1. Spectra Fibers (left) and Hooked Steel Fibers (right)

2.2 Test Specimens

All concrete test specimens were made of Type III Portland cement. Table 1 displays the mixture proportions of each concrete by weight of cement. The coarse aggregate used in NM4 had a maximum aggregate size of ½ in., and the fine aggregate for both mixes was #16 flint silica sand supplied by the U.S. Silica Company. The hooked steel fibers were Dramix® RC-80/30-BP, and 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.

The mixing protocol outlined by Liao et al. (2006) was followed when batching the specimens, which took place under the supervision of project partner colleagues at the University of Michigan. During the addition of fibers, special attention was made to ensure that the fibers did not clump, especially for the Spectra fibers. Also, once the specimens were cast into a plastic mold, they were placed on a vibrating table to achieve sufficient compaction. After each pour, the specimens were kept in their molds and covered with plastic sheets for about 24 hours. They were removed from the molds and placed into a water tank for curing for at least another 28 days. All specimens were allowed to dry for at least 48 hours prior to testing. As previously mentioned, specimens cast as loaves were then also cut with a diamond precision saw to 5.5 x 5.5 x 1.5 in. In an effort to ensure uniform biaxial stress and strain fields, the four sides of each specimen were then ground to achieve flat edges and right-angle corners.

Table 1. Mixture proportions by Weight of Cement

Matrix Type		**Mortar Mix**	**NEES Mix 4**
Cement Type III (High Early Strength)		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 Fraction	1.0, 1.5, and 2.0	1.0, 1.5, and 2.0
28-day Cylinder Compressive Strength, ksi		8.0	5.1

2.3 Testing Procedures

The experiments were displacement controlled, with the ratio of principal strains varied in an effort to obtain a comprehensive understanding of the biaxial behavior. Testing was conducted using a 112 kip INSTRON biaxial servo-controlled hydraulic frame. A closed-loop system in displacement control was used to capture the post-peak response of the specimens, and all of the biaxial compressive loads were applied simultaneously. Displacement control was provided by AC linear variable displacement transducers (LVDTs) attached to each hydraulic actuator. Each axis of loading had one actuator slaved to a master actuator through digital line connections. The closed-loop control of the actuators was executed using INSTRON 8500 and INSTRON 8800 controllers. Similar to previous researchers (Kupfer et al. 1969, Nelissen 1972, and others), frictional confinement of the test specimens by the loading platens was minimized by using brush-type loading platens. The brush platens were pin-connected to the fixtures (including simple guide-ways to ensure planar loading), which were in turn mounted on the load cell of each actuator. For compression (and equal biaxial compression), the standard applied strain rate was 0.01 in./min. For intermediate targeted stress ratios, the standard applied strain rate was simply reduced in the horizontal direction to try to achieve the desired stress ratio. Figure 2 shows both a line drawing and a picture of the typical test setup.

All strain and displacement measurements were obtained using the non-contact Krypton K600 Dynamic Measuring Machine (DMM). The Krypton DMM can obtain the three-dimensional 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. For these tests, LEDs were placed on an overall 3 in. x 3 in. grid (with 1.5 in. spacings) centered on the specimen. To obtain the out-of-plane data, two 0.25 in. stroke LVDTs were positioned on special frames and placed such that they were touching the center of each face of the specimen, as shown in Figure 2. (Early tests were conducted using 9 LEDs on the front of the specimen, with a single LVDT touching the center of the back of the specimen; however, it was later found that the out-of-plane data was less noisy when two LVDTs were used to capture the lateral behavior.) The analog output signals from the measuring devices were connected to different input channels of the data acquisition system. Four-axis control of the system was synchronized with a PC using Labview. This allowed the synchronization of the start of each test, as well as of the load, displacement, and LVDT data collection with time. In addition, several two-axis plots were displayed with real-time updates to monitor the performance and behavior of the specimens during testing. The Krypton measuring system had its own data acquisition software, so the two sets of data were synchronized during post-processing. Once a specimen was secured in the testing frame, it was preloaded to about 224 lbs in the direction(s) of loading to remove any excess flexibility in the system and to ensure proper contact with the specimen.

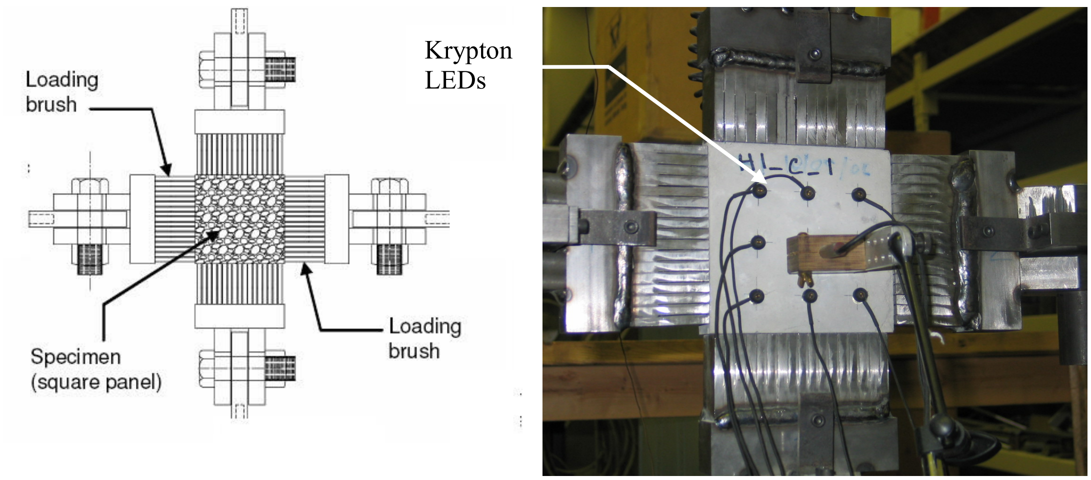

Figure 2. Experimental Test Setup

3. EXPERIMENTAL RESULTS

3.1 Ultimate Strength

Non-dimensionalized ultimate strength data are shown as biaxial stress envelopes, as depicted in Figure 3. Stresses are reported as fractions of the average unconfined uniaxial compressive plate strength of the specimens for the particular concrete mixture and fiber volume fraction, σ_{co}. The average uniaxial compressive plate strength of the MM individual hooked steel specimens, individual Spectra specimens, and individual plain specimens were about 10.2, 8.8, and 8.6 ksi, respectively, while the average uniaxial compressive plate strength for the MM loaf hooked steel specimens and loaf Spectra specimens was significantly lower (6.6 and 5.8 ksi, respectively). NM4 was intentionally created with a lower concrete matrix strength; the average uniaxial plate strengths for NM4 hooked fiber specimens and plain specimens were 6.3 and 7.6 ksi, respectively. Within each mix and specimen type, a general trend was that, as fiber volume fraction increased from 1 to 2 percent, the unconfined uniaxial compressive strength from cylinder tests slightly decreased.

Figure 3 shows the biaxial strength envelopes from the conducted tests and a comparison between the results of the loaf specimens and those obtained by Yin et al. (1989) (also from loaves). The left figure illustrates the effect of a more random fiber orientation by plotting the average result for each tested type of fiber, concrete mixture, and specimen. The averaged curves were obtained first by normalizing each specific concrete batch by its average uniaxial value, and then the data points that had a similar failure stress ratio for a particular specimen, mix, and fiber type were averaged to create the data points for the curve. For example, the average loaf Spectra curve was made by first normalizing the 1.0, 1.5, and 2.0 percent fiber volume fraction results by their respective average uniaxial values, and then data points with similar failure stress ratios were averaged together. The fibers were 1.2 to 1.5 in. long, and since the individually cast specimens were only 1.5 in. thick, it was unlikely that many fibers would be oriented in the out-of-plane direction to arrest the tendency for tensile splitting failure in a plane parallel to the test specimen. Each plot has been normalized by its average uniaxial compressive performance, so the individual specimens were not actually weaker than the loaf specimens; they just did not benefit as much from the addition of a second principal confining stress. In fact, the individual specimens had about a 50 percent higher uniaxial strength than the loaf specimens for both the hooked steel fibers and the Spectra fibers; however, under equal biaxial compressive stress, the individual specimens and the loaf specimens were within 3 percent of each other, in an absolute (ksi) sense, for each fiber type. The individual specimens of the hooked steel fiber, Spectra fiber, and NEES hooked steel fiber mixes benefited between 2 and 6 percent from being subjected to equal biaxial compression stresses, and each set of specimens had a maximum strength increase of between 12 and 20 percent at a stress ratio of about 0.5. Somewhat anomalously, the individual plain concrete specimens experienced both a higher concrete strength and a greater increase in strength under biaxial loading than the individual fiber specimens. This could most likely be attributed to the nature of the failure mechanism of the individual specimens. Due to the thickness of the plate specimen, the fibers in the individually cast specimens had a tendency to align themselves in the plane of the specimen. Thus, the combination of the interference of the fibers within the concrete matrix and the lack of fibers in the transverse direction (to prevent a tensile-splitting failure) resulted in an inferior performance of the individually cast specimens. The loaf hooked specimens and the loaf Spectra specimens experienced a much greater benefit under biaxial loading due to the passive confinement provided by the randomly oriented fibers; in fact, both types of loaf specimens experienced a strength increase of greater than 50 percent more than their respective uniaxial strengths under equal biaxial loading.

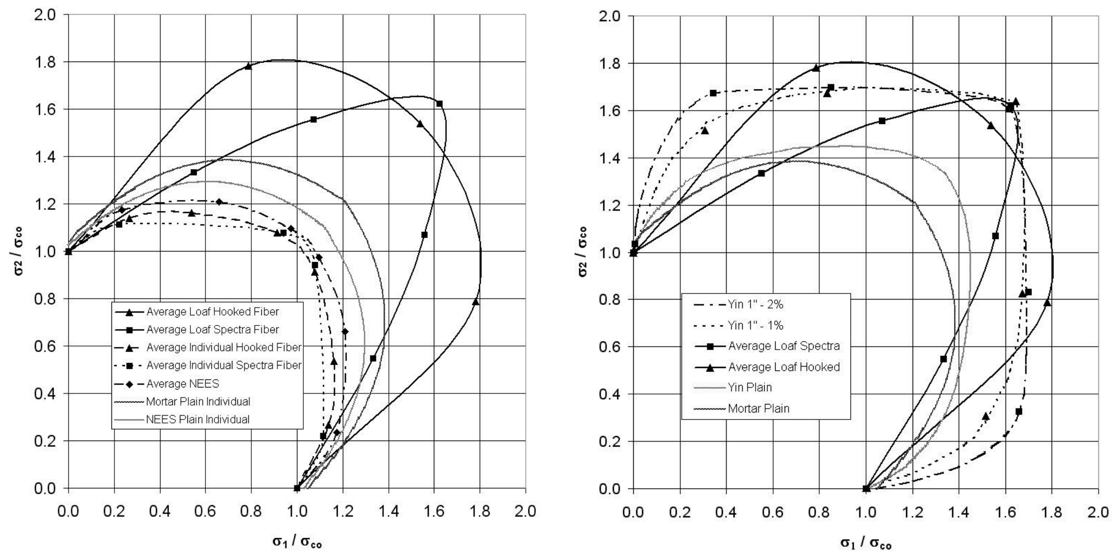

Figure 3. Biaxial Strength Envelopes from Experimental Test Results (left) and Comparison of Loaf Specimens with Yin et al. (right)

In Figure 3, the right graph shows a comparison of the average loaf specimen results with those obtained by Yin et al (1989). The plate specimens tested by Yin et al. were cut from a concrete loaf to a specimen size comparable to the present study, and they contained a 1 or 2 percent volume fraction of 1 in. long carbon steel fibers. The figure shows that the strength benefit of equal biaxial compression due to the addition of fibers was similar to the findings from Yin et al. However, some disparities arise when comparing the results from intermediate stress ratios. The present investigation experienced a greater increase in strength for the average loaf hooked steel fiber specimens than did Yin et al. at a stress ratio of about 0.5; however, the average curve predicts a performance perhaps much less than Yin et al. at a stress ratio of about 0.2. This may be partly explained by the lack of tests performed in this study at such a low stress ratio, as evidenced by the location of the average data points. When examining the average behavior of the loaf Spectra fiber specimens, the strength envelope values were very similar for equal compression, yet the values were significantly less for all other intermediate stress ratios. This may be attributed to differences between the Spectra fibers and the hooked steel fibers used by Yin et al. and perhaps to differences between the concrete mixes themselves. The left plot of Figure 4 displays biaxial strength envelopes of the plain concrete mixes used in the investigation, as well as some plain concrete results from previous researchers. The test results presented in Figure 4 are from tests of plain concrete using similarly sized specimens and brush-type loading platens. It can be seen that the plain MM had a stronger normalized biaxial strength than from any of the previous research except that observed by Yin et al., whose increased strength was mostly attributed to the use of crushed quartz and flint as the coarse aggregate. The plain MM had an average uniaxial strength of 8.6 ksi, and it can be seen that its normalized biaxial compressive strength exceeds the strength achieved by the high strength concrete reported by Hussein and Marzouk (2000). NM4 results align quite well with the other historical tests, and nearly duplicate the result obtained by Nelissen (1972).

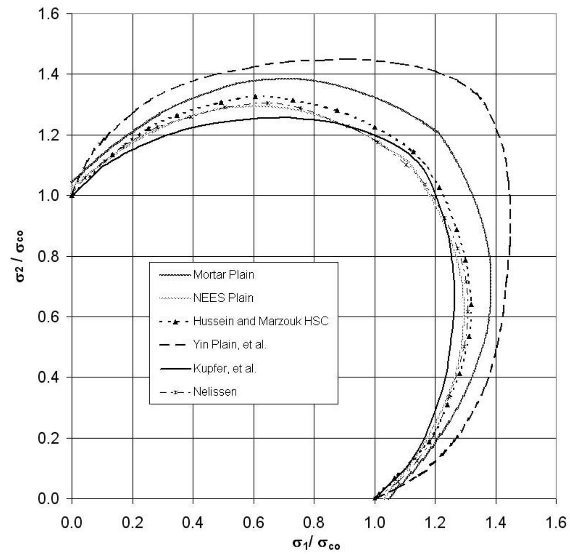

Figure 4. Comparison of Biaxial Strength Envelopes for Various Plain Concrete Mixes (left) and Failure Mode of Hooked Steel Fiber Specimen Subjected to Biaxial Compressive Stresses (right)

3.2 Failure Modes

The typical failure mechanism of the plain concrete specimens was by tensile splitting of the concrete. 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 considerably different. As also described in previous research (Yin et al. 1989), these specimens experienced a faulting or shear failure due to the formation of multiple fault planes in the specimen, as shown on the right in Figure 4.

Figure 5 depicts the stress-strain curves of plain and 2 percent volume fraction fiber-reinforced MM specimens subjected to a compressive stress ratio of 1.0. The figure on the left displays the vertical stress-strain response, and the figure to the right depicts the horizontal stress-strain result, as well as including the out-of-plane strain versus the horizontal stress. It can be seen that the addition of fibers into the concrete seems to slightly reduce the initial stiffness of the concrete under equal biaxial compression in the loaf specimens, while the stiffness of the individually cast specimens seemed to be somewhat less affected. Figure 5 also clearly illustrates the importance of a random orientation of the fibers within the concrete. The individually cast fiber reinforced concrete specimens experienced a significantly more explosive event at their maximum strength; although these fiber specimens still had some residual post-peak strength, the Krypton LEDs used to measure the strain were typically disturbed and unable to give any further reliable results. The dramatic strength loss followed by some residual strength of the individual specimens can be seen in Figure 5 for the Spectra individual specimen. In contrast, the loaf fiber specimens did obtain a random orientation of fibers, and the significantly increased ductility of these specimens can also be observed from Figure 5. Both types of loaf specimens remained fairly linear until a strain of about 0.005. The strain at the maximum loading was approximately 0.01 in both directions of applied stress, and a significant residual strength was maintained to a strain of nearly 0.025.

Since the tests were displacement controlled, modest differences between the stresses in each direction can be attributed to anisotropy in the specimens.

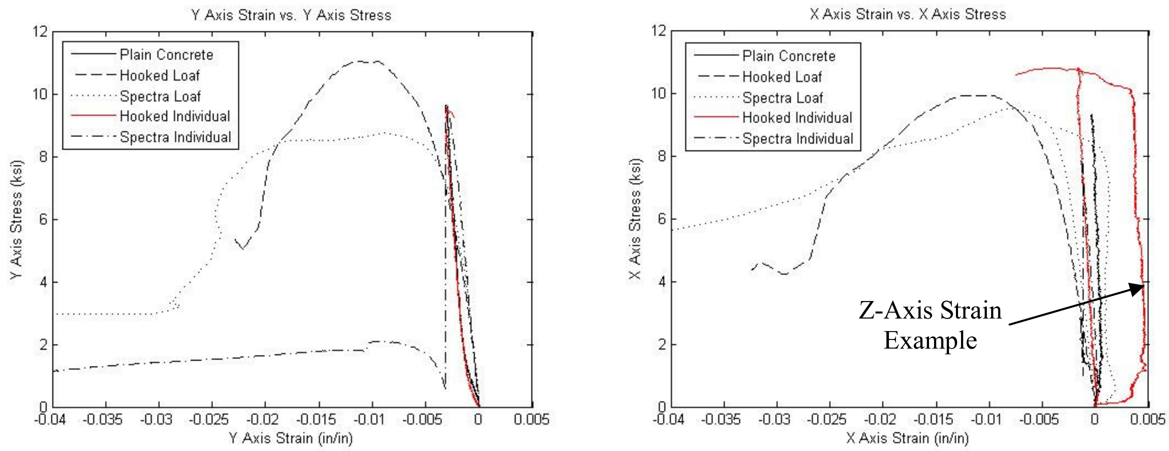

Figure 5. Y-Axis (left) and X-Axis (right) Stress-Strain Response of Plain Mortar and 2% Fiber Volume Fraction Concrete

4. TARGET APPLICATIONS FOR HPFRCC MATERIAL

The seismic behavior of reinforced concrete coupling beams (RCCB) and their structural role in shear wall systems has been the subject of investigation for several decades. The first studies attempted to characterize the elastic behavior of coupled wall structures through basic modeling (including laminar analysis), forming the underlying practice of strength design based on elastic structural response, even though such structures are typically expected to perform in the inelastic range. Vast subsequent experimental investigations (Paulay & Binney 1974, Barney et al. 1980, Tassios et al. 1996, Galano & Vignoli 2000, among others) explored a wide range of steel reinforcement arrangements, with the traditional conventionally reinforced concrete coupling beam (CRCCB) and the diagonally reinforced concrete coupling beam (DRCCB) being the most prevalent. Governing failure modes for CRCCBs are flexure, sliding shear, or diagonal tension, while governing failure modes for DRCCBs are buckling of compression bars (after diagonal ties have failed, subsequent to concrete spalling), often followed by fracture, or significant concrete spalling at support faces.

Although current codes of practice, such as ACI 318-05 (2005), consider both types of RCCBs and prescribe their implementation based on span-to-depth ratio and factored design shear stress on the gross section, it is widely known that DRCCBs have greater energy absorbing and deformation characteristics than CRCCBs. However, prescribed diagonal reinforcement detailing of DRCCBs has proven to create construction difficulties due to reinforcement congestion between the diagonal bars and transverse reinforcement. Several experiments thereafter employed the relatively new concept of using HPFRCC in coupling beams to increase shear strength and stiffness retention, in addition to reducing the amount of transverse reinforcement (thus reducing current reinforcement congestion issues of DRCCBs), while still maintaining the same ultimate failure mode of the buckling of diagonal compression bars and/or fracturing of diagonal bars (Canbolat et al. 2005). Other related investigations (Parra-Montesinos et al. 2006) have also shown a relaxation on confinement reinforcement requirements in structural walls through the use of fiber reinforced cement composites, and the possibility of using the damage tolerant HPFRCC material near the base of such walls in seismic design applications is also being considered. In addition to coupling beams and structural walls, this sort of HPFRCC is also being explored for use in infill panels for seismic retrofitting of steel moment frames. Single-panel and double-panel tests have been conducted, and a large-scale pseudo-dynamic test of an infilled frame is planned to occur in the near future.

Many practical applications exist in industry for the use of HPFRCC to improve structural seismic performance. In fact, buildings have already incorporated Engineered Cementitious Composites (ECC) to improve the performance of coupling beams, such as in the 27-story Glorio Roppongi High Rise in central Tokyo and the 41-story Nabeaure Tower in Yokohama (completed in 2007). Nevertheless, the full behavior characterization of HPFRCC structural elements still remains to be developed, which is where the results of this material-level study will most quickly be applied within the field of earthquake engineering.

5. CONCLUSIONS

Results from an experimental investigation on high-performance fiber-reinforced cementitious composites indicate that the material has many possibilities as an energy-dissipating material for structural elements susceptible to seismic events. The inclusion of both the Spectra (polyethylene) and hooked steel fibers greatly increases the biaxial compressive strength of the concrete, especially when initially cast into a fairly three-dimensional configuration, as well as having a dramatic effect on the ductility of the material. In the future, completion of tension tests will further the understanding of the behavior of this sort of HPFRCC and provide more comprehensive knowledge about the material and its fully biaxial behavior. Such thorough understanding of HPFRCC has many implications, including making computer modeling and the extension of the material's use to more large-scale structural applications possible. Additionally, a database of existing tests of structural concrete conventionally and diagonally reinforced coupling beams under reverse cyclic loading is under construction and can be used to assess behavioral trends and predominant failure modes. Combining the knowledge and behavioral trends gained through laboratory tests of the HPFRCC materials with the vast coupling beam experimental information already available in the literature, it should be possible to redefine the design and performance of coupled wall systems for seismic applications.

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