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Tension stiffening in reinforced high performance fiber reinforced cement-based composites

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ABSTRACT

High Performance Fiber-Reinforced Cement-based Composite (HPFRCC) materials carry tension to strains greater than the yield strain of reinforcing steel and exhibit distributed compression damage with minimal spalling. Characterization of the interaction between the composite and steel reinforcement to large strains (i.e., >0.005) remains largely unknown. Three HPFRCC materials as well as concrete with a single reinforcing bar are tested in a prismatic specimen in uniaxial tension up to fracture of the reinforcement. Multiple cracking of the composite led to uniform bar yielding throughout the specimen and early hardening of the reinforcement at the location of dominant cracks. The reinforcement fractured within the HPFRCC at lower strain levels relative to the reinforced concrete. A modified approach based on planar analysis to estimate flexural strength of reinforced HPFRCC components using tension-stiffening data is proposed.

1. Introduction

The use of High Performance Fiber-Reinforced Cement-based Composite (HPFRCC) materials in structural design is intended to improve the performance of reinforced concrete structures. Structural-scale experiments have revealed several beneficial properties of these materials such as stable inelastic load-deformation behavior and enhanced ductility [1], and enhanced energy dissipation capacity [2,3] and shear capacity [4] relative to traditional reinforced concrete. The tension and compression properties of HPFRCC materials can result in reduced damage through crack control, increased strength and ductility, and potential reduction in reinforcement required for both shear and flexural resistance relative to traditional structural concrete.

A tension-stiffening effect provided to mild steel reinforcement by HPFRCC materials in tension and flexure has been observed by several researchers [5–9], wherein the HPFRCC materials have been identified as carrying tension beyond the yield strain of the mild steel reinforcement. However, the interaction between the steel and the HPFRCC materials is not yet known beyond strains in the order of 0.5%. An early strain hardening effect has been hypothesized [10], however, this effect is uncharacterized and poorly understood to date. Understanding the interaction between the steel and the ductile HPFRCC matrix up to large strains (i.e., fracture of the reinforcement) is of interest both for structural design and the development of modeling approaches for structural applications of reinforced HPFRCC materials.

The objective of this research is to characterize the elastic and plastic response up to fracture of three mild steel reinforced HPFRCC materials in uniaxial tension; a Hybrid Fiber-Reinforced Concrete (HyFRC), a Self-Consolidating Hybrid Fiber-Reinforced Concrete (SC-HyFRC) and an Engineered Cementitious Composite (ECC). The three HPFRCC materials differ in regards to their matrix composition (concrete vs. mortar) and their tensile strain capacities. ECC commonly exhibits tensile strains up to 3–5% whereas HyFRCs have a tensile strain capacity of 0.6–1%. All of the three HPFRCC mixes are compared to a normal weight concrete mix. A prismatic test specimen was designed to characterize the response in tension of the four different reinforced cementitious materials up to fracture of the reinforcing steel bar. The results from the tension stiffening tests are used to develop a design approach based on planar section analysis to predict high early strength in reinforced HPFRCC flexural members.

2. Experimental program

A normal weight concrete and three HPFRCC materials were evaluated in prismatic test specimens reinforced with a single mild steel bar. The experiments were designed to facilitate measuring

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the load vs. axial displacement of the composite specimens up to fracture of the steel reinforcing bar. In addition, the reinforcement in one specimen of each type of material was instrumented with strain gauges to characterize yielding, strain hardening and the distribution of strain along the bar. The tension stiffening data from this study is then used to propose and validate a method of estimating the flexural capacity of beam specimens from the first author as well as previous studies [1,6,11].

2.1. Materials

Four cementitious materials were studied: (1) a normal weight concrete, (2) an Engineered Cementitious Composite (ECC), (3) a Hybrid Fiber Reinforced Concrete (HyFRC) and (4) a Self-Consolidating Hybrid Fiber Reinforced Concrete (SC-HyFRC). The mixture proportions for 1 m^3 of each material are given in Table 1 and a summary of the fiber properties used in the different fiber-reinforced composites is given in Table 2.

2.1.1. Normal weight concrete

A normal weight concrete was used for the control specimens. The mixture consists of a water-to-binder ratio of 0.54 using Type I/II Portland cement, water, fine aggregate with a fineness modulus of 3.2, and coarse aggregate with a 9.5 mm maximum size aggregate.

2.1.2. Engineered Cementitious Composites (ECCs)

The ECC mixture used in this research had a water-to-binder ratio of 0.26, using Type II/V Portland cement, class F fly ash, silica sand (0.13 mm particle size), water, super-plasticizer (SP), a viscosity modifying admixture (VMA), and 2% by volume polyvinyl alcohol (PVA) fibers. The mixture contained no coarse aggregate.

A characteristic uniaxial tensile response of the ECC used in this research is shown in Fig. 1 with testing details reported in [10]. Multiple cracking in unreinforced ECC specimens with an average of 5–6 cracks was observed in a gauged length of approximately 180 mm. The properties of ECC in tension have been broadly studied including characterization of its pseudo-strain hardening and ductile behavior [12]. The pseudo-strain hardening behavior shown by the ECC is based on the load bearing and energy absorption capacity of the fiber bridging mechanism, i.e. the mechanism used by the fibers when transferring the load across open cracks. Two criterions were considered in the mix design, a strength criterion related to the matrix cracking strength and an energy criterion related to the fiber–matrix interface and the complimentary energy obtained from a fiber pullout test [12]. These properties allow the composite to exhibit multiple cracking at large values of tensile strain (typically between 1% and 5% depending on specimen size and geometry).

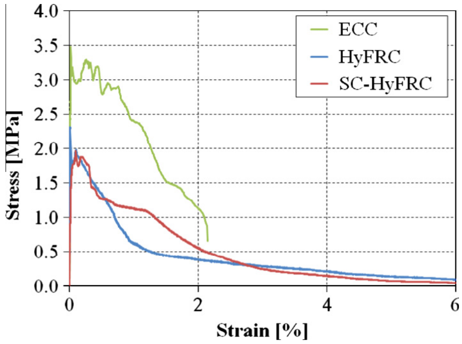

Fig. 1. Uniaxial tensile response of 83 mm × 159 mm by 864 mm dogbone-shaped specimens of ECC [10], HyFRC [10] and SC-HyFRC [10].

2.1.3. Hybrid Fiber Reinforced Concrete (HyFRC & SC-HyFRC)

The HyFRC mixture had a water-to-binder ratio of 0.54 and contained the same materials as the concrete mixture as well as superplasticizer, and both PVA fibers and steel fibers with different lengths and aspect ratios (Table 2). The self-consolidating HyFRC (SC-HyFRC) was a modified version of the HyFRC mixture to be utilized in highly congested reinforced concrete structures in seismic prone regions. The SC-HyFRC had a water-to-binder ratio of 0.45 and used only one type of steel fiber (30 mm long) with the PVA fibers, contained class F fly ash as well as different proportions of aggregates, and used a VMA to control segregation of the constituents. The same coarse (9.5 mm) and fine aggregates used in the concrete mix are included in these mixes to minimize shrinkage and creep.

A characteristic uniaxial tensile response of the HyFRC and the SC-HyFRC used in this research is shown in Fig. 1 with testing details reported in [10]. Multiple cracking was also observed in the unreinforced HyFRC and SC-HyFRC tests with an average of 3–4 cracks along the gauged length of approximately 180 mm. HyFRC composites are designed to carry tension up to and beyond the yield strain of conventional steel reinforcing bars using a performance-based approach [13], combining a concrete-based matrix

Table 1
Mixture proportions for 1 m^3.

Mix	Binder (kg)		Aggregate (kg)		Water (kg)	Chemical admixtures (wt.% binder)		Fibers[c] (vol.%)			
	C[a]	F.A.[b]	Fine	Coarse		SP	VMA	SF-1	SF-2	PVA-1	PVA-2
Concrete	423	–	872	742	228	–	–	–	–	–	–
ECC	547	656	438	–	312	0.5	0.11	–	–	–	2
HyFRC	423	–	825	749	228	0.2	–	0.8	0.5	0.2	–
SC-HyFRC	398	131	1013	406	238	0.93	2.22	–	1.3	0.2	–

[a] Cement described in Table 2.
[b] Fly ash described in Table 2.
[c] Fibers described in Table 2.

Table 2
Fiber properties.

Fiber	Mix	Material	Length (mm)	Diameter (mm)	Strength (MPa)	Stiffness (GPa)
SF-1	HyFRC	Steel, hooked end	60	0.75	1050	200
SF-2	HyFRC SC-HyFRC	Steel, hooked end	30	0.55	1100	200
PVA-1	HyFRC SC-HyFRC	Polyvinyl alcohol	8	0.04	1600	43
PVA-2	ECC	Polyvinyl alcohol	12.7	0.04	1600	43