Cement and Concrete Composites 83 (2017) 188–201

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Bond behavior and interface modeling of reinforced high-performance fiber-reinforced cementitious composites

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A R T I C L E I N F O

Article history:
Received 8 March 2017
Received in revised form
14 July 2017
Accepted 18 July 2017
Available online 22 July 2017

Keywords:
High-performance fiber-reinforced cementitious composites
HPFRCC
Cyclic loads
Bond-slip
Finite element modeling

A B S T R A C T

High-performance fiber-reinforced cementitious-composites (HPFRCCs) reinforced with mild steel reinforcing bars have bond strengths that are higher than ordinary concrete under monotonic loading conditions. High bond strengths in HPFRCCs have been attributed to the material toughness of HPFRCCs, which effectively restrains splitting cracks under monotonic loads. Characterization of the interface between HPFRCCs and mild reinforcement under cyclic loads remains largely unknown. The bond-slip behavior of two HPFRCC mixtures are examined under monotonic and cyclic loads in beam-end flexural specimens. Bond strength is shown to deteriorate due to cyclic load reversals after the maximum bond stress is reached, resulting in lower bond-slip toughness. Three dimensional computational simulations are conducted to investigate observed crack patterns and internal deformations at the interface of the HPFRCC and steel reinforcement. Numerical simulation results predicted splitting crack patterns observed in physical experiments, and also suggest that interface crushing occurs at the intersection of the reinforcement lugs and HPFRCC material. Further, simulated performance shows that damage to the bond interface is altered by the deformation history applied to the interface.

1. Introduction and background

High-performance fiber-reinforced cement based composites (HPFRCCs) exhibit a psuedo strain-hardening behavior after initial cracking in tension [1], retain residual strength and generally do not spall in compression [2], and show multiple cracking and damage tolerance in structural components when subjected to large deformations [3,4]. Due to the high material toughness and damage tolerance of HPFRCCs, researchers have proposed their use in combination with steel reinforcement for numerous structural applications to resist seismic loads in flexure [3,4], shear [5,6], and retrofit applications [7,8]. These applications have shown that reinforced HPFRCC members can have component strength and ductility greater than ordinary reinforced concrete members. However, limited research has been conducted on developing a fundamental understanding of how HPFRCCs and reinforcement interact together, and how this interaction affects modeling and design approaches.

Moreno et al. [9] investigated the tension stiffening behavior of reinforced HPFRCC specimens and compared their behavior to reinforced concrete specimens. Tension stiffening results in concrete and HPFRCCs were consistent with prior research by Fischer and Li [10] and Bischoff [11] which showed that HPFRCCs and reinforcement deform compatibly at specimen strains below 0.50%. However, Moreno et al. [9] continued the experiments up to deformation levels that caused reinforcement fracture. Consistent with findings from tension stiffening studies on reinforced concrete (e.g. [12]), Moreno et al. [9] observed that after tensile cracks form in reinforced concrete tension stiffening specimens, splitting cracks develop, resulting in poor composite interaction. Splitting cracks in reinforced concrete specimens allowed deformation over the full specimen length, and fracture occurred at an average of specimen strain of 10.2% [9]. Splitting cracks were however effectively restrained in reinforced HPFRCC specimens. The minimal, or lack of, splitting cracks in reinforced HPFRCC specimens caused higher strengths for a given level of specimen deformation when compared to reinforced concrete specimens, but deformation

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http://dx.doi.org/10.1016/j.cemconcomp.2017.07.017
0958-9465/

localized in the reinforcement after a dominant crack formed in the reinforced HPFRCC members. The steel reinforcement in the reinforced HPFRCC specimens fractured at specimen strains of 3.5%, 6.8%, and 7.4%, on average, for three different HPFRCC materials [9].

The work by Moreno et al. [9] has emphasized the need for understanding reinforcement fracture in reinforced HPFRCCs, and how reinforcement and HPFRCCs interact together. Research on the monotonic bond behavior of reinforced HPFRCCs in flexural specimens has confirmed that bond strength and bond-slip toughness (i.e., the area under the bond-slip curve) is higher in reinforced HPFRCCs than in reinforced concrete [13]. Bond strengths of three different HPFRCC materials were shown to be 37% higher, on average, than in concrete for varying levels of confinement (i.e., cover-to-bar diameter ratio and volume of transverse steel reinforcement) [13]. The higher bond strength and bond-slip toughness of reinforced HPFRCCs has been attributed to the HPFRCC material toughness which restrains splitting cracks through fiber bridging [13]. The findings of higher monotonic bond strengths in reinforced HPFRCC flexural members are in line with previous work by Chao et al. [14] which showed higher bond strengths in reinforced HPFRCCs than concrete from direct pullout experiments.

Since reinforced HPFRCCs have been proposed for seismic applications, an understanding of bond behavior under cyclic loads is necessary to advance design and modeling approaches. Cyclic loads are expected to damage the bond between reinforcement and HPFRCCs through a combination of tensile splitting cracks and crushing of the interface. Experimental data on cyclic bond-slip behavior of reinforced HPFRCCs has shown cyclic deterioration of bond strength [14], but has been limited to pullout experiments which can have different results than specimens tested in flexure such as beam-end specimens, or lap-splice specimens [15].

A review of literature shows that reinforced HPFRCC members often fail due to reinforcement fracture rather than crushing of the HPFRCC material [16]. In cyclic experiments, reinforced HPFRCC members have lost strength due to reinforcement fracture before significant crushing in flexural [3,17] and shear-dominated members [5,7,18], as well as members with large axial loads such as bridge columns [19]. Reinforcement fracture has occurred in cyclic members varying in deformation from 2.5 to 15% drift [3,7], and the deformation level that causes fracture in reinforced HPFRCC components has been strongly affected by longitudinal reinforcement ratio [16]. Simulation tools that can predict how the HPFRCC and reinforcement interface deteriorates are needed to design, detail, and predict the behavior of reinforced HPFRCC components.

The focus of this paper is therefore to (1) understand how cyclic deformation histories affect bond performance in reinforced HPFRCCs in comparison to monotonic response, (2) characterize the observed experimental behavior through detailed three dimensional finite element modeling, and (3) understand how simulation of the interface between reinforcement and HPFRCCs is sensitive to selection of material properties and model paramters. A series of beam-end bond-slip experiments were conducted and results are presented under monotonic and cyclic loads for two different HPFRCC materials. Monotonic and cyclic beam-end bond-slip experiments were then modeled with numerical simulation and results are shown to compare simulated damage patterns with experimental observations.

2. Bond-slip experimental program

2.1. Materials

Two HPFRCC materials were investigated in this study: an Engineered Cementitious Composite (ECC) and a Self-Consolidating High-Performance Fiber-Reinforced Concrete (SCHPFRC) as shown in Table 1. These two HPFRCC materials were chosen as part of a larger study on the interaction of HPFRCCs and steel reinforcement [13,16]. These two materials have been investigated in several large-scale experimental studies, and represent ductile cement-based materials with a range of fiber types, binders, and aggregates [7,9,20,21].

The Engineered Cementitious Composite mixture used in this study was one developed using micromechanics principles for steady state cracking [22,23]. The ECC contained a mortar matrix with Type II/V Portland cement, Class F fly ash, water, silica sand with a 0.13 mm particle size, a viscosity modifying admixture, a high range water reducing admixture, and used Polyvinyl Alcohol Fibers (PVA) with a 2% fiber volume fraction. The PVA fibers were 12 mm in length, 0.04 mm in diameter, and had a tensile strength and stiffness of 1600 MPa and 43 GPa, respectively.

The SCHPFRC mixture was one designed to achieve a highly flowable self-consolidating concrete mixture that maintains strain-hardening and multiple cracking characteristics [24]. The SCHPFRC mixture was comprised of Type III Portland cement, Class C fly ash, water, coarse aggregate with a 9.5 mm maximum aggregate size, fine aggregate, a high range water reducing admixture, a viscosity modifying admixture, and hooked steel fibers with a 1.5% fiber volume fraction. The steel fibers were 30 mm in length, 0.38 mm in diameter, and had a tensile strength and stiffness of 2000 MPa and 200 GPa, respectively.

Representative mechanical properties of the ECC and SCHPFRC can be seen in Fig. 1. The ECC and SCHPFRC had average compressive strengths of 49 and 42 MPa, respectively, as measured by three 100 mm × 200 mm cylinders for each material. The flexural response of each mixture was measured by testing unreinforced beams loaded in four-point bending. The beams were loaded at the third points, had a 75 mm square cross section with a span length of 305 mm. The average peak bending stress was 9.5 MPa for the ECC and 9.0 MPa for the SCHPFRC.

2.2. Specimen design and test setup

Beam-end specimens, shown in Fig. 2, were used in this study since they produce a similar flexural tensile stress state to lap-splice specimens, such as those tested under monotonic loading by the authors [13]. Beam-end specimens are also considered to produce a more realistic stress state than traditional pullout experiments [15]. In beam-end specimens the reinforcement and surrounding cementitious material are in similar stress states (i.e., when the reinforcement is in tension, the surrounding cementitious material is in tension), whereas traditional pullout experiments result in confining compressive stresses on the cementitious material surrounding the reinforcement that is loaded in tension [15].

The beam-end specimens were 130 mm in width, 230 mm in height, and 380 mm in length. The reinforcement layout was selected based on beam-end experiments for ordinary reinforced concrete [25]. A 16 mm diameter reinforcing bar was bonded over a

Table 1
Mixture proportions for 1 m^3 of HPFRCC materials.

Mixture	Binder (kg)		Aggregate (kg)		Water (kg)	Chemical Admixtures (% wt. cement)		Fibers (% vol.)	
	Cement	Fly Ash	Coarse	Fine		VMA	HRWR	SF	PVA
ECC	547	656	–	438	312	0.11	0.50	–	2.0
SCHPFRC	377	253	415	793	253	1.30	1.30	1.5	–

VMA = viscosity modifying admixture.
HRWR = high range water reducing admixture.