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Biaxial behavior of high-performance fiber-reinforced cementitious composite plates

Raymond R. Foltz [a], Deuck Hang Lee [b,*], James M. LaFave [a]

[a] Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 N. Mathews Ave., Urbana, IL 61801, United States
[b] Department of Architectural Engineering, University of Seoul, 163 Seoulsiripdae-ro, Dongdaemun-gu, Seoul 02504, Republic of Korea

HIGHLIGHTS

- Structural behavior of HPFRCC materials under multi-axial loading was investigated.
- Various mixture proportions, fiber types, and casting methods were considered.
- Biaxial failure curves were constructed based on 127 plate specimen test results.
- HPFRCCs can exhibit enhanced biaxial compression performance vs. plain concrete.
- Modeling parameters were derived for nonlinear finite element analysis with HPFRCC.

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ABSTRACT

A total of 127 plate specimens were fabricated and tested, of various mixture proportions, fiber types, and casting methods, in order to investigate the behavior of both plain concrete and high-performance fiber-reinforced cementitious composite (HPFRCC) specimens under multi-axial loading. The majority of the test specimens were initially fabricated as larger loaf specimens, to achieve proper fiber directionality in the out-of-plane direction, and then cut and trimmed, with steel brush platens used for loading to minimize friction between the testing machine and the plate specimens. The test results indicate that HPFRCC materials can exhibit enhanced biaxial compression performance, compared to plain concrete specimens, due to passive confinement provided by fibers in the out-of-plane direction. The multi-axial behavior of HPFRCC materials obtained from the tests was further used to construct biaxial failure curves, and several modeling parameters have then been derived for nonlinear finite element analysis of HPFRCC planar members subjected to biaxial stresses.

1. Introduction

Typical concrete materials are characterized by quasi-brittle failure modes and low tensile strength, with limited ductility. In practice, reinforcing steel is added to provide a concrete structural member with the requisite tensile and confined compression capacities in order to achieve the desired strength and ductility levels. However, many structural concrete applications can require a large amount of reinforcing steel, resulting in construction of a design that is congested, costly, or even impractical [18,25,3,40,44,30].

According to Parra-Montesinos et al. [54], high-performance fiber-reinforced cementitious composites (HPFRCCs) can be defined as advanced composite materials that exhibit a strain-hardening tensile stress-strain behavior, with multiple cracking characteristics. Therefore, HPFRCCs could potentially alleviate the problems of low ductility and/or reinforcement congestion, through their inherent ability for bond and confinement (even with a reduced amount of transverse reinforcement), while still ensuring a ductile failure mechanism. This is because HPFRCCs have relatively large shear and tensile capacities with ductile hardening behavioral characteristics, and fibers at a stable crack interface can provide passive confinement, crack control capacity, and an additional energy dissipation mechanism [27,24,30,45]).

There have been a number of research efforts directed toward practical applications of HPFRCC materials in structural concrete members, such as coupling beams and beam-column connections, as well as in plastic hinge regions of beams, columns, and structural walls [25,15,16,1,26,6,39,40,43,53,41]. For proper and accurate analysis of such structural elements utilizing HPFRCC

* Corresponding author.
E-mail addresses: ray.foltz@gmail.com (R.R. Foltz), dklee@uos.ac.kr (D.H. Lee), jlafave@illinois.edu (J.M. LaFave).

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materials, constitutive models of HPFRCC in compression and tension must be developed, in full consideration of multiaxial stress effects.

According to the authors' literature review, many experiments have been conducted on fiber-reinforced concrete materials since the 1960s [1], and the multiaxial behavior of HPFRCC materials has also been investigated by various researchers [49,9,36,48,46,42,44,38]. However, most of these existing studies focused on the tensile and triaxial compression behavior of fiber-reinforced concrete, while there is limited experimental data on the biaxial behavior of HPFRCC [17,44].

In this study, an experimental program was carried out using a customized testing apparatus to investigate the biaxial behavior of both plain concrete and HPFRCC materials, with a total of 127 plate specimens fabricated and tested. Based on the test results, biaxial failure envelope curves were developed, and several modeling parameters were determined based on the concrete plasticity model provided in a commercial finite element analysis program.

2. Experimental program

The experimental program investigated the behavior of both plain and HPFRCC specimens under multi-axial loading. The specimens had various mixture proportions, fiber types, and casting methods. A total of 127 plate specimens were fabricated and tested; a summary of the test specimens used in this experimental program is provided in Table 1. The multi-axial response of the loaded specimens was used to construct biaxial failure curves and to inform modeling parameters for subsequent use in related nonlinear finite element models.

2.1. Materials and mixture proportions

In this testing program, two concrete mixes have been explored. The first is a mortar mix (MM), in which two different types of fiber – Spectra (polyethylene) or Dramix (hooked steel) – and three fiber volume fractions (1.0%, 1.5%, or 2.0%) were considered. Some test results for that mix have already been reported elsewhere [17,44].

The other mix was developed as part of a NEES research project entitled "Innovative Applications of Damage Tolerant Fiber-Reinforced Cementitious Materials for New Earthquake-Resistant Structural Systems and Retrofit of Existing Structures." Liao et al. [32] initially explored and established the basic mechanical properties of six different HPFRCC mixes as part of that project. The main objective in developing such mixes was to obtain a strain-hardening, self-consolidating concrete mix with 28-day compressive strength of between 5 and 9 ksi (34.5 and 62.1 MPa). Of the six mixes initially investigated in that previous study [32], a specific one is further explored as a focus of this current work, called NEES Mix #6 (NM6), in part because it was the most economical choice that met the other material design objectives.

Table 2 presents the proportions of each mix, by weight of cement. The MM was used in six different ways: at three different volume fractions (1.0%, 1.5%, and 2%) of two different fiber types (Spectra and Dramix). The Spectra® fibers were an ultra-high molecular weight polyethylene, a trademark of Honeywell [20], while the hooked steel fibers were Dramix® RC-80/30-BP by Inc [5], made of high-strength steel. NM6 only used the hooked steel fibers. Table 3 presents a summary of the fiber properties used in this study.

Table 2
Mixture proportions.

Matrix type		MM	NM6
Cement type III (Early ages)		1	1
Aggregate	Silica sand (Flint)	1	2.2
	Coarse aggregate	–	1.2
Fly ash class C		0.15	0.875
Chemical admixtures	Superplasticizer	*	0.005
	VMA	–	0.038
Water		0.4	0.8
Fiber	Type of fiber	Steel and Spectra	Steel
	Fiber volume content (%)	1.0, 1.5 & 2.0	1.5
28-day compressive strength, ksi (MPa)		80 (55.2)	5.5 (37.9)

* Superplasticizer added as needed when MM was too dry.

All test specimens were made using ASTM Type III Portland cement and class C fly ash. The coarse aggregate used in NM6 was a crushed limestone, with a maximum aggregate size of ½ in. (13 mm) and a specific gravity of about 2.7. The fine aggregate for all mixes was #16 flint silica sand, supplied by the U.S. Silica Company; the fine aggregate for MM had an ASTM C33 gradation of 30–70, while that for NM6 had an ASTM C33 gradation of 50–70. ADVA® Cast 530 was the polycarboxylate type superplasticizer used in each concrete mixture. For NM6, a fixed amount of superplasticizer was prescribed in advance, but for MM even more superplasticizer was added when the mix proved visually to be too dry. An additional viscosity modifying admixture (VMA – RHEOMAC® VMA 362) was used in NM6, to enhance viscosity and reduce fiber segregation in the presence of relatively high water-to-cementitious material ratios [32]. The water-to-cementitious-material ratios for MM and NM6 were 0.35 and 0.43, respectively.

2.2. Details of plate test specimens

For the multi-axial testing regime described herein, 60 and 67 test specimens were fabricated by an individually-cast method and a loaf-cast cut-and-trim method, respectively, all with dimensions of 5.5 × 5.5 × 1.5 in. (140 × 140 × 38 mm). This specimen size is similar to that used in historical concrete biaxial strength experiments [28,33,47,34,52,29,21,31].

In the testing program, two series (or generations) of multi-axial tests were conducted to investigate the influence of casting method on fiber orientation, and thus on biaxial behavior, of HPFRCC materials – i.e., individually-cast plate specimens and

Table 1
Test matrix and uniaxial compressive strengths.

Mix	Specimen type	Fiber type	Average uniaxial compressive strength, ksi (MPa)	Number of specimens
Mortar mix (MM)	Individual	Steel fiber	10.2 (70.1)	30
		Spectra fiber	8.7 (60.2)	21
		Plain	8.6 (59.4)	9
	Loaf	Steel fiber	6.6 (45.8)	17
		Spectra fiber	5.8 (39.9)	18
NEES Mix #6 (NM6)	Loaf	Steel fiber	4.9 (33.5)	20
		Plain	5.4 (37.3)	12