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Micromechanical modeling of crack-bridging relations of hybrid-fiber Strain-Hardening Cementitious Composites considering interaction between different fibers

Jing Yu, Yixin Chen *, Christopher K.Y. Leung

Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Hong Kong SAR, PR China

HIGHLIGHTS

- Hybrid-fiber SHCCs with PVA/steel fibers at a fixed total fiber fraction are studied.
- Superposition method is used to model crack-bridging relations of hybrid-fiber SHCCs.
- Interaction between different types of fibers is considered by the matrix micro-spalling.
- Positive synergetic effect is observed between PVA and steel fibers in SHCCs.

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ABSTRACT

As tensile crack-bridging constitutive relations play an important role in the multiple cracking behaviors of Strain-Hardening Cementitious Composites (SHCCs), careful control of the crack-bridging relations is the key to a successful design of the materials. This study theoretically explores the crack-bridging relations of SHCCs with fixed total volume fraction (2.5%) of hybrid polyvinyl alcohol (PVA) and steel fibers. Since a large number of experiments at the single-fiber level are needed to determine the parameters for the micromechanical model, the snubbing coefficient, fiber strength reduction factor and Cook-Gordon parameter for mono-fiber composites were theoretically calibrated rather than experimentally obtained in this study. With these calibrated parameters, the crack-bridging relations of hybrid-fiber SHCCs were then modeled and compared to the test results. The superposition principle was used to address the contributions of different types of fibers, and the interaction between PVA and steel fibers was considered through the matrix micro-spalling in the modeling. The theoretically modeled crack-bridging relations of hybrid-fiber SHCCs were in good agreement with the test curves in terms of the tensile strength and the corresponding crack opening. The findings in this study provide a better understanding of fiber hybridizations in SHCCs.

1. Introduction

Strain-Hardening Cementitious Composites (SHCCs), also known as Engineered Cementitious Composites (ECCs), are high performance cementitious composites characterized by high tensile deformation capacity of several percent [1–19], which is several hundred times that of ordinary concrete. Rather than a localized crack in ordinary concrete under tension, SHCCs form multiple fine cracks with the crack width self-controlled to typically below 100 μm before final failure [1–19]. In addition, the compressive strength of SHCCs ranges from 20 MPa to 120 MPa depending on matrix proportions [1,20]. The excellent mechanical and durability properties make SHCCs attractive for civil infrastructures that are resilient, durable and sustainable, and a few full-scale construction applications have already appeared in the United States, Europe and Japan [20–23].

The crack-bridging (σ-δ) constitutive relation describes the relationship between crack-bridging stress σ transferred across a crack and the corresponding crack opening δ, which connects the micro-scale material parameters to the macro-scale multiple-cracking performance for SHCCs. Therefore, the control of the crack-bridging relations by tailoring material parameters of fiber,

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* Corresponding author.

E-mail addresses: jyuad@connect.ust.hk (J. Yu), ychenbu@connect.ust.hk (Y. Chen), ckleung@ust.hk (C.K.Y. Leung).

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Nomenclature

The following symbols are used in this paper

d_f	fiber diameter
δ	crack opening
E_c	elastic modulus of composite
E_f	elastic modulus of fiber
E_m	elastic modulus of matrix
f	snubbing coefficient
f'	fiber strength reduction factor
G_d	fiber/matrix interfacial chemical bond
J'_b	complementary energy
J_{tip}	crack tip toughness
k	matrix spalling parameter
K_m	fracture toughness of matrix
K_{tip}	fracture toughness of composites
l_e	fiber embedment length in the single fiber pull-out test
L_f	fiber length
P	force acting on the fiber
s	fiber slippage displacement in the single fiber pull-out test
S_p	matrix spalling size
V_f	volume fraction of fiber
V_m	volume fraction of matrix
α	Cook-Gordon parameter
β_1	the first slip-dependent coefficient for the fiber/matrix interface
β_2	the second slip-dependent coefficient for the fiber/matrix interface
δ_0	crack opening displacement at σ_0
θ	fiber inclination angle
λ	scale factor for flaw size distribution function
ν	Poisson's ratio of composite
σ	crack-bridging stress of composites
σ_c	cracking strength of matrix in composites
σ_m	crack-bridging stress contributed from matrix
σ_{pm}	cracking strength of plain matrix
σ_{PVA}	crack-bridging stress contributed from PVA fibers
σ_{Steel}	crack-bridging stress contributed from steel fibers
σ_0	peak crack-bridging stress of composite
τ	fiber/matrix interfacial frictional bond and
τ_0	fiber/matrix interfacial frictional bond strength

matrix and fiber/matrix interface is the key to a successful design of SHCCs that fulfills the requirements on tensile strength, ultimate tensile strain and steady-state crack width in particular [24].

Micromechanical modeling of crack-bridging relations in discontinuous random-fiber reinforced cementitious composites was first carried out by Li and Leung [25], which was based on a model with constant interfacial friction. However, obvious divergences had been observed when the model was used for a fiber/matrix system with strong slip-dependent interface, especially for the crack opening prediction at the maximum stress. Later, the slip-dependent interfacial property was accounted by Li et al. [26]. As for SHCCs, a crack-bridging model accounting for random fiber orientation, fiber snubbing effect and slip-hardening interfacial bond was derived by Lin and Li [27]. At the same time, Kanda and Li considered more factors including the apparent strength reduction of fiber with inclination angle [28], fiber rupture [29] and interfacial chemical bond of hydrophilic fibers [30] for the micromechanical model. Then, an updated crack-bridging model was obtained by Lin et al. [31], where the interfacial fracture toughness, frictional bond strength and post-debonding slip-hardening coefficient were explicitly accounted for, and the fiber rupture and fiber strength reduction were also considered. To account for the material variability, Kanda et al. [32] explored the probabilistic distribution of the initial flaw size, while Maalej [33] studied the fiber strength distribution based on the Weibull weakest-link statistics. Built on the model in Lin et al. [31], Yang et al. [24] presented a more mature crack-bridging model of SHCCs to improve the accuracy of crack opening prediction, where new mechanisms of fiber/matrix interactions including fiber two-way debonding and pull-out, matrix micro-spalling and Cook-Gordon effects were considered. Recently, based on the model in Yang et al. [24], a modified crack-bridging model was derived by Lee et al. [34,35] where fiber distribution characteristics was further considered, and a fatigue-dependent crack-bridging model was proposed by Qiu and Yang [36]. It should be pointed out that all the aforementioned micromechanical models are for mono-fiber systems.

High-modulus polyethylene and polyvinyl alcohol fibers are the most commonly-used fibers in SHCCs [1,2,4–9,11–13,15,17]. In recent years, the utilization of hybrid fibers in appropriate combinations for cementitious materials has attracted extensive attention due to their potential benefits comparing to mono fiber reinforcements [37]. To further improve the performance of materials, using hybrid polymeric/steel fibers in SHCCs has been explored by several researchers [38–47]. Specifically, the authors have experimentally explored the crack-bridging relations of SHCCs with fixed total volume fraction (2.5%) of hybrid polyvinyl alcohol (PVA) and steel fibers [48]. The mix proportions and fiber properties are respectively shown in Table 1 and Table 2, and the average test results are summarized in Fig. 1. More information on the material used and the novel test method, as well as all the individual test curves can be found in Yu et al. [48].

To provide a better understanding of the fiber hybridization in SHCCs, this study theoretically explores the mechanical properties at the single-crack level of SHCCs with fixed total volume fraction (2.5%) of hybrid polyvinyl alcohol (PVA) and steel fibers. The micromechanical modeling was based on the model for mono-fiber systems presented in Yang et al. [24]. As discussed in Yu et al. [48], a large number of experiments at the single-fiber level are needed to determine the parameters for the model. Therefore, in this study, some micromechanical parameters for mono-fiber composites (P25S00 and P00S25 in Table 1), including the snubbing coefficient, fiber strength reduction factor and Cook-Gordon

Table 1
Mix proportions.

Mixture ID	Fiber (vol.%)		Matrix mix proportion (by weight)					
			Binder			Water/Binder	Silica Sand/Binder	Super-plasticizers/Binder (%)
	V_{PVA}	V_{Steel}	Cement	Fly Ash (Class F)	Silica Fume			
P25S00	2.50	0.00	0.18	0.80	0.02	0.20	0.20	0.41
P20S05	2.00	0.50						0.40
P15S10	1.50	1.00						0.39
P00S25	0.00	2.50						0.31