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Derivation of crack bridging stresses in engineered cementitious composites under combined opening and shear displacements

Chang Wu[a,*], Christopher K.Y. Leung[a], Victor C. Li[b]

[a] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong, China
[b] Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, USA

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A B S T R A C T

The mechanical behavior of Engineered Cementitious Composites (ECC) is strongly dependent on the bridging of cracks by fibers. Due to the bridging action of fibers, tensile and shear stresses can be transferred through cracks in ECC members. In this study, a micromechanics based theoretical model is proposed to describe the shear transfer mechanism on the crack surface due to fiber bridging effect. The model focuses on flexible fibers and both the normal stress along the crack opening direction and the shear stress transferred across the crack surfaces are derived under the coupled effect of crack opening displacement (COD) and shear sliding. With the proposed model, the mechanism of fibers contributing to the shear transfer can be understood and the effect of various micromechanical parameters can be investigated. The simulation results can provide insight on the behavior of ECC under shear loading when cracks are propagating under mixed mode.

1. Introduction

To overcome the brittleness of concrete and the difficulty to control the formation and opening of cracks, various approaches to reinforcing cementitious composites with fibers have been made. Specifically, High Performance Fiber-Reinforced Cementitious Composites (HPFRCC), which is highly ductile material exhibiting multiple cracks and strain-hardening characteristics under uniaxial tensile stress, has been developed and gained ground in research and application [1–3]. As a class of HPFRCC, Engineered Cementitious Composites (ECC) is designed according to basic principles of micromechanics and fracture mechanics [4–6]. Prepared with cement, mineral admixture, fine aggregates (maximum grain size is usually 0.15 mm), water, superplasticizer and < 2% volume of short fibers, the ultimate tensile strength of ECC can reach over 3%, while the opening of each crack is usually controlled to be < 60 μm [7–9].

Due to its ultra-high tensile durability and energy dissipation capacity, ECC is being considered for replacing conventional concrete in structures in high-intensity earthquake regions [10]. The shear behavior of ECC members has therefore attracted the attentions of many researchers and designers. While obvious improvement in performance has been demonstrated by various experiments on shear critical specimens [11–21], most investigations on the behavior of shear-critical ECC structural members are experimental in nature and limited in modeling aspects. In a number of studies [22–24], models for predicting the shear behavior of ECC members have been proposed, but all of these models are modified from models for concrete according to empirical test data. Without considering the effects of fiber, matrix and interface on the fundamental crack bridging mechanisms, these models are limited in accuracy and applicability to general cases.

The highly improved tensile ductility of ECC compared with ordinary concrete is achieved by the crack bridging effect of fibers. Moreover, due to the fiber bridging effect, tensile and shear stresses can be transferred through multiple cracks in ECC members. As a fundamental mechanism governing the behavior of cracked ECC members under shear loading, the shear transfer mechanism of fibers on the crack surface must be properly understood. While crack fiber bridging behavior of ECC under direct tension has been widely studied [4,8,25], little attention has been paid to the effect of fibers on the shear transfer behavior of cracked ECC. Several experimental studies have been conducted on this issue [21,26], but theoretical models considering the fiber bridging action for quantitatively evaluating the shear transfer capacity of cracked ECC are rather rare. Kabele [27,28] built a multiscale framework for modeling structural performance of HPFRCC, in which analytical models for simulating the bridging stresses of a fiber-bridged crack under opening and sliding are outlined from microscale to mesoscale. However, the model did not consider two-way fiber pullout which is a commonly observed mechanism in ECC. Also, the modeling of matrix spalling is relatively basic as the occurrence of spalling is assumed to be governed by an arbitrary fiber inclination

* Corresponding author.
E-mail addresses: changwu@ust.hk (C. Wu), ckleung@ust.hk (C.K.Y. Leung), vcli@umich.edu (V.C. Li).

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angle.

This paper aims at establishing a micromechanics-based theoretical model to describe the shear transfer mechanism on the crack surface of ECC with respect to the fiber bridging action. Following the framework outlined by Kabele [27,28] and focusing on cementitious composites reinforced with flexible fibers, both the normal stress along the crack opening direction and the shear stress transferred parallel to the crack surfaces are derived under the coupled effect of crack opening displacement (COD) and shear sliding. The fiber snubbing effect and strength reduction of inclined fibers, fiber rupture, matrix spalling as well as two-way fiber pullout mechanism are considered. With the proposed model, the behavior of a single crack in ECC under mixed crack mode is analyzed and discussed. The effects of various micromechanical parameters on the shear transfer behavior on the crack surface of ECC are investigated. The simulation results can provide insight on the behavior of ECC under shear loading when cracks are propagating under mixed mode. It is expected that the proposed model will provide useful fundamental understanding for the further development of a rational model for predicting the shear behavior of ECC members.

2. Modeling of single fiber behavior under combined opening and sliding

2.1. Modeling of single fiber pullout behavior

Prior to establishing a model for simulating the crack bridging behavior, the single fiber pullout behavior against the surrounding matrix should be first investigated. Single fiber pullout tests [5,8] indicate that two stages can be observed when a fiber embedded in matrix is subjected to a pullout force, and they are: (1) debonding stage and (2) pullout stage. The debonding process can be simulated as the propagation of a tunneling crack along the interface between fiber and matrix. The pullout stage begins after complete debonding of the interface which is usually accompanied by a load drop. In the debonding stage, the behavior of the interface is controlled by both chemical bond and frictional bond; while in the pullout stage the behavior of the interface is fully governed by the frictional bond [8,25]. The pullout force (P) versus pullout displacement (u) relation of an aligned fiber with a certain embedded length (L_e) was theoretically derived by Lin et al. [25] as:

$$P(u) = \begin{cases} \pi\sqrt{\frac{1}{2}E_f d_f^3(\tau_0 u + G_d)(1+\eta)} & (0 \le u \le u_0) \quad (a) \\ \pi\tau_0(L_e - u + u_0)[d_f + \beta(u - u_0)] & (u_0 < u \le L_e) \quad (b) \end{cases} \tag{1}$$

in which, E_f and d_f are Young's modulus and diameter of the fiber, respectively, and η is a parameter representing the ratio of effective stiffness between fiber and matrix. Eq. 1 can fully describe the single fiber pullout behavior by assuming constant frictional bond (τ_0) and chemical bond (G_d) of the interface at the debonding stage (Eq. 1(a)), and by setting a coefficient β to consider the slip-hardening/softening effect during the pullout stage (Eq. 1(b)). The same P-δ relation is applied in the present study. The critical displacement (u_0) at which the fiber is completely debonded is given by:

$$u_0 = \frac{2\tau_0 L_e^2(1+\eta)}{E_f d_f} + \frac{L_e}{E_f}\sqrt{\frac{8G_d E_f(1+\eta)}{d_f}} \tag{2}$$

For randomly distributed short fiber reinforced cementitious composites, most of the fibers are not oriented normal to the crack plane. When a randomly oriented fiber is subjected to a pullout force due to pure opening of a crack as shown in Fig. 1(a), the fiber bridging force will increase due to the "snubbing effect" [29]. The pullout load for an inclined fiber ($P(\phi)$) is then related to the pullout force of an aligned fiber ($P(0)$) through the following equation, assuming the fiber to change direction over a frictional pulley [4,30,31].

$$P(\phi) = P(0)e^{f\phi} \tag{3}$$

In Eq. 3, the parameter f is defined as snubbing coefficient.

2.2. Consideration of shear sliding

When the two surfaces of the crack shown in Fig. 1(a) begin to undergo relative sliding, the fiber bridging the two crack surfaces will be pulled out further and the part of fiber between the crack surfaces will rotate by an angle as shown in Fig. 1(b). At a given crack opening displacement (COD), ω, and sliding, Δ, the rotating angle γ and the actual pullout length δ are related by the following equations:

$$\gamma = \arctan\left(\frac{\Delta}{\omega}\right) \tag{4}$$

$$\delta = \sqrt{\Delta^2 + \omega^2} \tag{5}$$

The bridging force (P) along the pulled-out part of the fiber can be resolved to a normal component (P_n) and a tangential component (P_t), as shown in Fig. 1(c). The force P_n and P_t can be considered as the bridging force for resisting crack opening and sliding, respectively, and are expressed as:

$$P_n = P\cos\gamma \tag{6}$$

$$P_t = P\sin\gamma \tag{7}$$

Due to the rotating of the fiber, the snubbing effect on the pullout behavior of single fiber is changed. In Eq. 3, the expression of snubbing effect is a function of ϕ, however, sliding has resulted in a change of the angle between the embedded and pulled out parts of fiber. To correctly describe the snubbing effect of single fiber behavior under combined opening and sliding, the expression should be modified as

$$P(\alpha) = P(0)g(\alpha) = P(0)e^{f\alpha} \tag{8}$$

The key to modeling the single fiber pullout behavior under combined opening and sliding is therefore to determine the intersection angle α. More generally, a 3D randomly oriented fiber bridging the crack is taken into account as shown in Fig. 2. Taking the intersection of the fiber and upper crack plane as the origin, a Cartesian coordinate η-μ-ξ is defined in Fig. 2, in which the plane μ-ξ represents the upper crack surface and η-axis is normal to the crack plane. The crack surfaces are assumed to slide along the direction of the μ-axis. To express the orientation of the embedded and pulled out components of the fiber bridging the crack, a spherical coordinate system is introduced, and the relation between the two coordinates is also depicted in Fig. 2. The orientation of the embedded part of the fiber is determined by arbitrary polar angle ϕ and azimuthal angle θ. After sliding, the relative geometric relationships among ϕ, θ, rotating angle γ and intersection angle α can be observed from Fig. 2. Based on the relative geometric relationships of the angles, the intersection angle α can be derived with trigonometric transform method and expressed as:

$$\alpha = \arccos(\cos\phi\cos\gamma + \sin\phi\sin\gamma\cos\theta) \tag{9}$$

In the case of 2D random distribution, the intersection angle α can be obtained by setting $\theta = 0$ in Eq. 9 to simplify the expression into:

$$\alpha = |\gamma - \phi| \tag{10}$$

2.3. Consideration of fiber strength reduction and rupture

For those fibers with strong slip-hardening behavior after fully debonded, Yang et al. [8] suggested that fibers with sufficiently long embedded length will rupture during the pullout process rather than being completely pulled out. In addition, some fibers are vulnerable to bending and shear, and consequently exhibit strength reduction effect when loaded at an inclined angle to the crack plane. This strength