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Numerical model on the stress field and multiple cracking behavior of Engineered Cementitious Composites (ECC)

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HIGHLIGHTS

- The model numerically simulates the multiple-cracking process of ECC for the first time.
- The stress transferred to the matrix at various distances from the crack is derived.
- All key influential factors have been considered including chemical bond, slip-hardening, fiber rupture, and many others.
- Stress-strain curve of this material under tension was simulated which agrees well with experimental observations.
- This model provides insights into cause of the unsaturated-cracking phenomenon, which is most concerned for ECC application.

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ABSTRACT

Engineered cementitious composites (ECC) are materials exhibiting strain-hardening behavior with the formation of multiple cracks. The conditions for achieving multiple cracking have been investigated in the literature, but the sequential formation of cracks and the crack number/openings at a particular stress/strain level, are seldom studied. In this paper, a numerical model to simulate the overall stress-strain relation for an ECC member is developed. For a bridging fiber, the stress transferred to the matrix at various distances from the crack will be derived with consideration of chemical bond, slip hardening, fiber rupture and other factors. At any applied loading, the matrix stress field near the crack can be computed by summing up the stress transfer from all active fibers. With a new approach to describe the continuous variation of matrix strength along the member, the stress field in the matrix will be compared to the distributed matrix strength to determine the positions of new cracks. The strain at a given stress and the corresponding crack number and openings can then be obtained and the simulated stress-strain curve agrees well with experimental results. Insights from this model can facilitate the design of ECC with good mechanical performance as well as high durability.

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1. Introduction

Engineered cementitious composites (ECC), also known as the bendable concrete, is a class of high performance cementitious composites characterized by high tensile ductility of several percent [1–4]. ECC exhibits strain hardening behavior accompanied by the formation of multiple fine cracks rather than a localized large crack as in normal concrete [1,3]. With the crack width in ECC materials controlled to very small values (usually below 50-60 μm) [5], improved resistance to water/chemical transport and hence better structural durability can be achieved [6–8].

In the design of ECC, physical behaviors at three different length scales need to be considered. These include the slip-displacement of a fiber due to the opening of a crack, the propagation of a matrix crack bridged by many fibers with different orientation and embedment lengths, and the behavior of a tensile member containing inherent crack-like defects [9–11]. Micromechanics theories for modeling single fiber behavior have been developed since the 1970s [12–15]. Based on the single fiber behavior, the crack bridging behavior with randomly distributed fibers can then be computed by averaging methods proposed in [4,16–19]. At the tensile component level, the conditions to achieve multiple cracks have been investigated in the literature [1,2,12,20].

Despite the increasing interest in understanding the behavior of ECC, few researchers have studied the development of multiple cracks in an ECC member, such as the number of cracks (which

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governs composite ductility) and openings of cracks (which governs structural durability) at a particular stress level. In [21], the minimum crack spacing was derived without the consideration of strength variation along the member. As a result, the model predicts the simultaneous formation of cracks with uniform spacing, which is inconsistent with reality. In [22], a stochastic model with non-uniform matrix strength and fiber content was proposed to capture the influences of flaw-size determined matrix strength and fiber content on cracking behavior. With finite element method, another stochastic model [23] studied the influence of sample size which affects the inhomogeneity of material properties. Both models [22,23] emphasized the influence of material randomness, but the stress transfer (from fiber to matrix) in the vicinity of a crack, which physically determines the degree of multiple cracking, was overlooked. Recently in [24], an analytic model based on the stress transfer distance in matrix was developed to simulate the multiple cracking process. Besides non-uniform cracking strength, the effects of increasing crack opening and fiber rupture on the stress transfer have been taken into consideration. However, the strength variation in [24] was assumed to follow the Weibull distribution which varies randomly along the member, implying two neighboring sections can exhibit very different strength. This is inconsistent with test results showing the formation of cracks in one region followed by cracking in other regions, which can be explained by the fact that lower strength is resulted from local increase in porosity. This is often due to poorer compaction which happens not just along one section but within a certain region of the specimen. There is hence a correlation between the strength of neighboring sections that cannot be described by the Weibull distribution adopted in [24]. In addition, in the analytic model proposed in [24], the fiber/matrix interface is assumed to be governed by friction alone while various researchers [16,17,25] have reported the presence of chemical bond at the fiber/matrix interface. Also, slip hardening behavior [26] (i.e., the increasing in interfacial during fiber pull-out), which is significant for PVA-ECC materials, has been neglected. Adding the consideration of chemical bond and slip hardening to the analytic model inevitably leads to a more complex formulation which makes it impossible to obtain analytical solutions for integrals representing the average bridging stress from fibers under different situations (debonded, pull-out from one side, pull-out from both sides, rupture, etc.). In such a case, a numerical method needs to be introduced.

In this study, a new numerical model is developed to simulate the overall stress-strain relation for an ECC member. In this model, for a bridging fiber at a certain inclination angle, the fiber stress and the stress in matrix (resulted from interfacial stress transfer) will be derived as a function of the distance from the crack [16], where chemical bond, slip hardening behavior, effect of increasing crack opening and fiber rupture will all be considered. The stress field in the matrix near a crack can then be calculated by summing up the transfer from all the bridging fibers. In addition, a stochastic method that can account for the strength variation along the member, with correlation among neighboring sections, is proposed. By comparing the calculated stress field with the distributed matrix strength, the positions of new cracks are determined. At any given applied load, the number of cracks, the crack openings as well as the strain can all be obtained. The simulated stress-strain relation is then compared with experimental results and further analysis on the multiple cracking development and stress field evolution is conducted.

2. Stress field near a crack

When a crack forms in a brittle matrix composite, the stress released by the matrix is taken up by the bridging fibers. On the cracked plane, the fibers are stretched to a high strain level while the cracked matrix relaxes to zero strain. The strain difference between fibers and matrix results in interfacial shear stress through which the additional stress in fibers is transferred back to the matrix until the strain difference is eliminated. When the interfacial shear stress is high enough, debonding and sliding will occur at the interface. For a fiber perpendicular to the crack, stress transfer occurs through (1) interfacial friction along the debonded part of the fiber, and (2) a chemical bond at the end of the debonding zone. For an inclined fiber, there is an additional stress transfer due to the frictional pulley force at the exit point of the fiber [21].

In this section, the stress transfer via interface force and pulley force is studied for a single fiber first. After dividing bridging fibers into several categories under different statuses, the stress field near a crack will then be obtained by summing up the contributions from all fibers.

2.1. Stress transfer for a single fiber

2.1.1. Debonding stage

The derivation of load-displacement relation for a single embedded fiber has been described in [13,26]. Fig. 1 shows a fiber perpendicular to a crack with an embedment length of l_e and debonded over a length l_d along which fiber slippage occurs. The frictional bond strength is denoted as τ_0 and chemical bond strength as G_d. During the debonding stage (short-range relative sliding), the single fiber bridging load (P_d) is related to the fiber displacement relative to the matrix (δ) by [16]:

$$P_d = \pi\sqrt{(\tau_0\delta + G_d)E_f d_f^3(1+\eta)/2}, \quad \text{when } \delta < \delta_0 \tag{1}$$

where $\delta_0 = 2\tau_0\ l2\ e(1+\eta)/E_f\ d_f$ represents the fiber displacement when the fiber is completely debonded, and the debonding length l_d is given by [13]:

$$l_d = \frac{P_d - \sqrt{\pi^2 G_d d_f^3 E_f(1+\eta)/2}}{\pi d_f \tau_0(1+\eta)} \tag{2}$$

2.1.2. Pullout stage

After the fiber is completely debonded from the matrix (as shown in Fig. 2), the pullout stage commences. Assuming the elastic deformation of fiber to be relatively small compared to the embedded length of fiber, the fiber length remaining in the tunnel (l_p) can be expressed as [4]:

$$l_p = l_e - \delta + \delta_0 \tag{3}$$

For some types of fibers, particularly PVA fibers, slip-hardening behavior can be observed [26]. In this study, the frictional bond strength in pullout stage is assumed to vary linearly with the slip

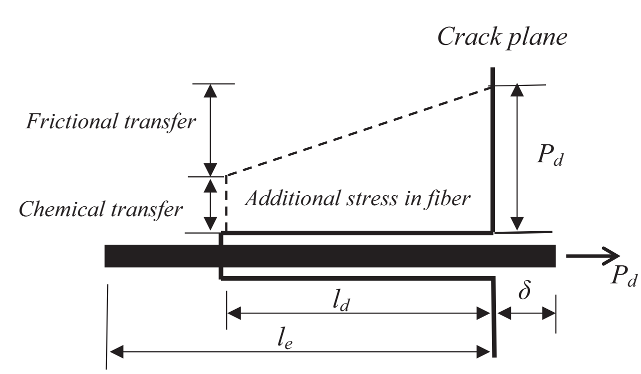

Fig. 1. Fiber in debonding stage.

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