V-557

Modeling Fiber Distribution Nonuniformity in Cement Composites Using Discrete Element Methods

John Bolander Jr., Member, University of California, Davis
Shigehiko Saito, Student Member, Kyushu University

Introduction

Together with experimentation, analytical and numerical methods are playing an important role in developing new cement-based materials for structural application. Success in these efforts depends on research in several interrelated areas, namely material micro/mesostructure, composite properties, and methods of processing (Fig. 1). While advances are being made within each area, there is a recognized need for comprehensive approaches which provide quantitative links between these areas.

Reference 2 presents a new computational approach for modeling short-fiber reinforcement in cement composites. Each fiber is modeled as a discrete entity, both prior to and after cracking. There is a direct coupling between physical parameters defined local to the fibers and composite performance indicators, such as strength, energy consumption, crack width and crack distribution. Actual fiber distributions can be used as program input. This avoids the abstractions associated with statistical averaging of the fiber actions and, importantly, provides a natural means for investigating the effects of fiber distribution nonuniformity on FRCC performance.

Model Overview

The matrix material is modeled as an assemblage of rigid particles interconnected along their boundaries through flexible interfaces, as shown by the numerical specimen in Fig. 2. The original formulation of the system equations for this approach is provided by Kawai [3]. Randomness in the mesh geometry does not represent some local structure of the material, but rather is introduced to minimize mesh bias on crack direction.

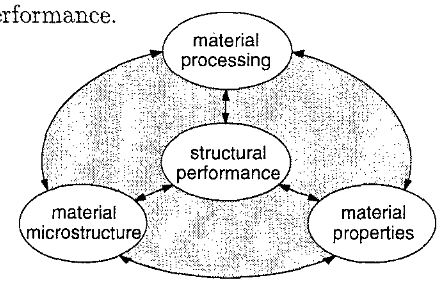

Figure 1 Structural performance through material development (adapted from Li [1])

Fibers are introduced into the specimen using a pseudo-random number generator; this provides a nearly uniform fiber distribution, except along the specimen boundaries which naturally show some directional bias (Fig. 2.) Prior to cracking, fiber actions are constrained to the displacements of the rigid particles; the number of system degrees of freedom is independent of the number of fibers. The precracking fiber model is general in that any linear relation between fiber axial stress and matrix strain can serve as a basis for stiffness calculations. During cracking, regular beam elements are inserted to model fibers bridging opposing crack faces. Beam nodal displacements are constrained to those at the rigid particle centroids. Fiber axial response follows a micromechanical model describing the nonlinear process of fiber debonding and pull-out [4]; fiber flexural response is assumed to be linear elastic. Interaction effects between fibers are neglected, as if each fiber is in isolation.

Numerical Analyses

Several series of numerical FRCC specimens have been tested under direct tension loading [2], as shown in Fig. 2. Smooth, straight, randomly oriented fibers which have high modulus and high strength are used. Provided there is a high degree of uniformity in the fiber distributions, there is excellent agreement with theoretical relations based on ordinary mixture rules for both composite elastic modulus and the critical volume fraction of fibers defining the transition from single to multiple cracking. Specimens with less than the critical volume fraction of fibers exhibit only single-cracking prior to pull-out, as shown by the deformed mesh and load-deflection plots given in Fig. 2, where ℓ is fiber length and σ_{mu} is the unreinforced matrix tensile strength.

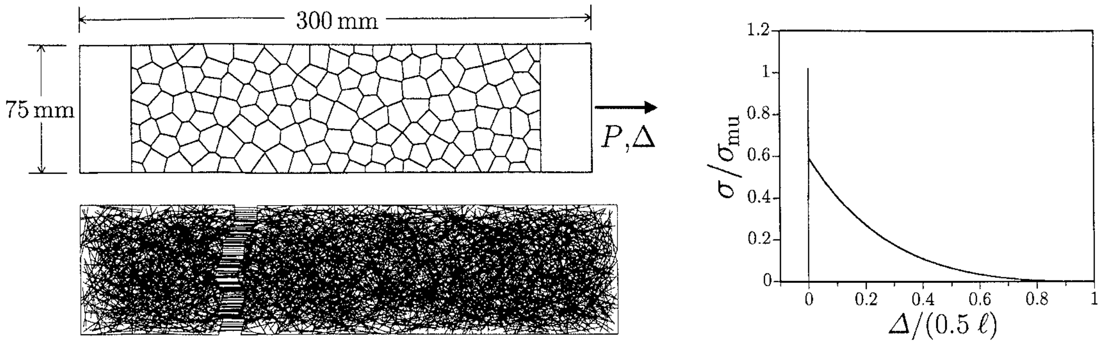

Figure 2 Numerical test specimen and response to tensile loading ($V_f = 1\%$)

Fiber Distribution Nonuniformity

The presence of aggregate inclusions, gravitational effects, proximity to specimen boundaries, and methods of dispersion and mixing during the production process affect the degree of fiber distribution uniformity within the specimen. The discrete modeling of fibers presented here is a natural, direct means for bringing these factors into the computational framework (provided, of course, there are experimental or numerical techniques for specifying the actual distribution of fibers.)

Nonuniform fiber distributions can be generated by conditioning the placement of additional fibers on the presence of fibers previously introduced into the specimen. Although this is quite artificial, the resulting distributions are useful in illustrating how such nonuniformity affects composite performance. Stress distributions over the cross-section may be strongly nonuniform and there is a tendency for one-sided crack growth to occur, sometimes leaving intact matrix material over the cross-section. For analysis results presented here, a simpler mesh of rectangular elements is used (Fig. 3). This same figure also shows a nonuniform fiber distribution for $V_f = 1\%$.

As shown in Fig. 4, the volume fraction of fibers local to first cracking is significantly less than the global volume fraction of fibers, especially for the nonuniform distributions. Although not presented here, these calculations also indicate that nonuniformity of the distribution can greatly reduce post-cracking strength and toughness, as well as the ability to achieve distributed fracture.

References

[1] Li, V.C. (1993) From micromechanics to structural engineering - The design of cementitious composites for civil engineering applications. *Proc. JSCE*, No. 471/I-24.

[2] Bolander, J.E., Saito, S. (1997) Discrete modeling of short-fiber reinforcing in cement composites. *J. Adv. Cement Based Mat.*, (under review).

[3] Kawai, T. (1978) New discrete models and their application to seismic response analysis of structures. *Nuclear Engng. Design*, **48**, pp. 207-229.

[4] Naaman, A.E., Namur, G., Alwan, J.M., & Najm, H. (1991) Fiber pullout and bond slip I: Analytical study. *ASCE J. Engng. Mech.*, **117**(9), pp. 2769-2790.

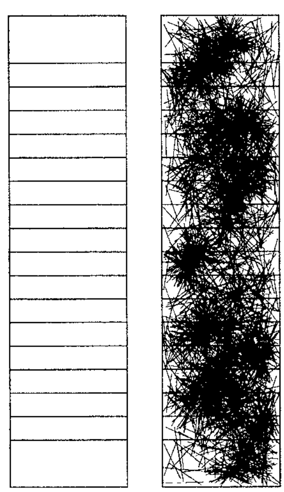

Figure 3

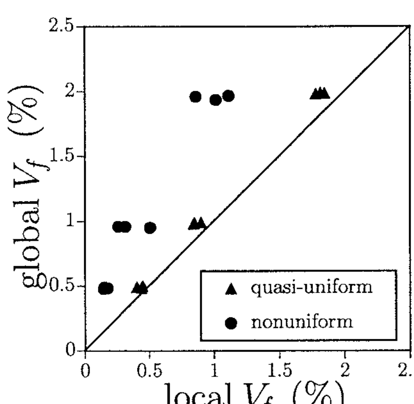

Figure 4