Lattice discrete particle modeling of fiber reinforced concrete: Experiments and simulations

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ABSTRACT

Naturally accounting for material heterogeneity, the Lattice Discrete Particle Model (LDPM) is a meso-scale model developed recently to simulate the meso-structure of quasi-brittle materials by a three-dimensional (3D) assemblage of polyhedral particles. A meso-scale constitutive law governs the inter-action between adjacent particles and simulates various features of the meso-scale response, including cohesive fracturing, strain softening in tension, strain hardening in compression and material compaction due to pore collapse. LDPM has been extensively calibrated/validated, showing superior capabilities in predicting qualitative and quantitative behavior of concrete. As a natural extension for this discrete model to include the effect of dispersed fibers as discrete entities within the meso-structure, LDPM-F incorporates this effect by modeling individual fibers, randomly placed within the volume according to a given fiber volume fraction. In this investigation, the theoretical basis for LDPM-F is reviewed, and to calibrate/validate the numerical model, an extensive experimental study has been conducted to investigate the mechanical properties of various prismatic specimens containing different types (steel and synthetic) and dosages of fibers. Excellent predictive capability of LDPM-F is demonstrated through a rigorous calibration/validation procedure.

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1. Introduction

Concrete is by nature a brittle material that performs well in compression, but is considerably less effective when in tension, and thus reinforcement is often used to absorb these tensile forces so that cracking is either eliminated, e.g., in the case of prestressed members, or, at least, reduced. For many years, steel in the form of bars or mesh has been used as reinforcement for a large variety of structural elements. In recent years, new forms of reinforcement to improve concrete toughness have been developed, such as short randomly distributed fibers of small diameters, made out of steel, plastic, natural materials, recycled reinforcements, etc. (Li, 2003). Fiber reinforced concrete, characterized by a significant residual tensile strength in post-cracking regime and enhanced capacity to absorb strain energy due to fiber bridging mechanisms across the crack surfaces, shows a dramatic improvement in service proper-ties over plain concrete. ACI Committee 544 reported that the addition of fibers in a concrete matrix improves some mechanical properties of concrete, including impact strength and flexural toughness (ACI Committee 544, 1996). The most beneficial aspects of the use of fibers in concrete structures include durability im-provements through reduction in crack width and permeability (Belletti et al., 2008; Lepech and Li, 2009); potential cost savings where fibers are substituted for labor-intensive steel-reinforcing bars (di Prisco et al., 2009); and the mitigation of deterioration owing to shrinkage and the associated early age cracking. Fiber reinforced concrete has found many applications in tunnel linings, bridge decks, airport pavements, slabs on grounds, industrial floors, dams, pipes, fire protection coatings and marine structures. In addition, it can be also used for repair, rehabilitation, strengthening and retrofitting of existing concrete structures (ACI Committee 544, 1996).

Many numerical models have been developed to simulate the behavior of fiber reinforced concrete at different scales. Most ap-proaches simulate the mechanical response of these composites by means of phenomenological macroscopic models combined with fracture mechanics techniques, such as damage, crack and micro-plane models (Fanella and Krajcinovic, 1985; Li and Li, 2000; Peng and Meyer, 2000; Caner et al., 2013; Ferreira, 2007; Han et al., 2003). Fanella1 and Krajcinovic developed a nonlinear analytical

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model based on the principles of the continuum damage mechanics for the stress-strain behavior of fiber reinforced concrete subjected to monotonic compressive and tensile loading (Fanella and Krajcinovic, 1985). This model was later modified by Li and Li to characterize the tensile stress-strain response of the fiber reinforced concrete (Li and Li, 2000). Peng and Meyer proposed a simplified continuum damage mechanics model to describe the inelastic behavior of concrete reinforced with randomly distributed short fibers, including anisotropic damage, unilateral effect, coupled volumetric and deviatoric inelastic deformation and complicated failure mechanisms (Peng and Meyer, 2000). Caner et al. proposed a M7f model for fiber reinforced concretes under static and dynamic loads, which features many improvement over the earlier versions of microplane model, including a more realistic description of the fiber pullout and breakage (Caner et al., 2013). Ferreira addresses the use of R-curves to study the fracture behavior of high-strength concrete and steel-fiber-reinforced concrete subjected to cracking in a three-point bending configuration, where the R-curves are modeled through an effective approach based on the equations of linear-elastic fracture mechanics (Ferreira, 2007). Han et al. proposed a constitutive model based on total strain and applied it to simulate structural component tests, which captures fiber reinforced concrete's unique reversed cyclic loading behavior (Han et al., 2003).

However, experimental studies on fiber reinforced concrete have confirmed that the mechanisms responsible for the macroscopic mechanical responses mainly involve phenomena that occur at the meso-structural level. The cement fracture is the mechanism that triggers the failure of fiber reinforced concrete, but the subsequent mechanisms leading to complete failure is completely modified by the relative contents of fibers in the composite, and more importantly, by the bond characteristic at the fiber-matrix interface and all the phenomena associated with this effect (Guerrero and Naaman, 2000). Consequently, many discrete frameworks, such as rigid particle and lattice models, have been developed, taking explicitly into account the meso-scale phenomena (Bolander and Saito, 1997; Li et al., 2006; Schlangen and van Mier, 1992; Bolander and Sukumar, 2005; Bolander et al., 2008). A sequential multi-scale homogenization approach has been proposed by Kabele (2007), whose framework links analytical and computational models covering scales from micro-to macro-level. Recently, Oliver et al. (2012) proposed a two-scale approach in which the macroscopic model, at the structural level, takes into account the meso-structural phenomenon associated with the fiber-matrix interface bond/slip process.

In the present work, as first proposed by Cusatis et al. (2010), Schauffert and Cusatis (2012) and Schauffert et al. (2012), fiber reinforced concrete is analyzed by a multi-scale model, called LDPM-F, in which the fine-scale fiber-matrix interaction is solved independently and the overall response is analyzed in a 3D meso-scale framework based on the recently formulated lattice discrete particle model (LDPM). LDPM is a realistic 3D model of concrete meso-structure developed by Cusatis et al. (2011a), which has been extensively calibrated/validated under a wide range of quasi-static and dynamic loading conditions, showing superior capabilities in predicting qualitative and quantitative behavior of concrete (Cusatis et al., 2011b). LDPM is an improvement over the confinement-shear lattice model (Cusatis et al., 2003a, 2003b), which, along with LDPM, has constitutive laws analogous to those of the microplane model (Bažant et al., 2000; Di Luzio and Cusatis, 2013). As a natural extension for this discrete model to include the effect of dispersed fibers as discrete entities within the meso-structure, LDPM-F incorporates this effect by modeling individual fibers, randomly placed within the framework according to a given fiber volume fraction (Smith et al., 2014).

LDPM-F has many salient and unique features: (1) a realistic, three-dimensional modeling of concrete mesostructure, including a discrete representation of individual fibers randomly distributed therein; (2) a multiscale approach in which the effect of embedded fibers on the structural response is based directly on the micromechanics of the fiber-matrix interaction; (3) the ability to simulate not only tensile fracturing but also multiaxial compressive loading; and (4) true predictive capability demonstrated through a rigorous calibration/validation procedure. In this investigation, the theoretical basis for LDPM-F is reviewed, to calibrate/validate the numerical model, an extensive experimental study has been conducted to investigate the mechanical properties of various prismatic specimens containing different types (steel and synthetic) and dosages of fibers. The predictive capability of LDPM-F is demonstrated through a rigorous calibration/validation procedure.

2. Review of LDPM-F

In this section, the theoretical basis for LDPM-F provided by Schauffert and Cusatis (2012) is reviewed, and details of the previously established (Yang et al., 2008) micromechanical fiber pull-out model adopted for this study are presented.

2.1. Extension of LDPM to include fiber-reinforcing capability

LDPM simulates concrete mesostructure by considering only coarse aggregate. Particles with assumed spherical shape and in accordance with typical mix designs and granulometric distributions, are introduced randomly into the volume by a procedure which avoids particle overlapping and ensures that all particles are contained within the volume of interest. A Delaunay tetrahedralization of the particle centers, along with the nodes used to describe the external surface of the volume, is used to define the lattice system which represents the mesostructure topology. A 3D domain tessellation, anchored to the Delaunay tetrahedralization, creates a system of polyhedral cells. Each cell contains one aggregate particle (or a surface node), and adjacent cells interact through the triangular facets where they are in contact. Fig. 1 (a) shows two adjacent particles along with their polyhedral cells and the associated tetrahedron edge. In the LDPM formulation, the interface facets are interpreted as potential crack surfaces. A detailed description of the tessellation procedure and LDPM idealization of concrete meso-structure can be found in Cusatis et al. (2011a, 2011b).

The extension to LDPM-F to include fiber-reinforcing capability is performed by inserting individual fibers with randomly generated positions and orientations (Schauffert and Cusatis, 2012; Schauffert et al., 2012). The geometry of an individual fiber is characterized by diameter d_f, length L_f, and curvature. In this study, fibers are assumed to be straight, and non-circular cross-sections are simulated through an equivalent diameter calculated as $d_f = 2(A_f/\pi)^{1/2}$, where A_f is the fiber cross-sectional area. For a given fiber volume fraction V_f, the number of fibers N_f contained in a concrete volume V is determined by $N_f = \left\lceil 4V_f V/(\pi d_f^2 A_f) \right\rceil$, where $\lceil x \rceil$ indicates the ceiling function. The fiber system is then overlapped with the cell system and all the facets intersected by fibers are detected. For each intersection, the shorter and longer fiber lengths, denoted as L_s and L_l, respectively, on each side of the facet, along with the orientations of the fiber and the facet, characterized by unit vectors $\mathbf{n}_f$ and $\mathbf{n}$, respectively, are computed. In accordance with the current LDPM formulation, the facet depicted in Fig. 1(b) is the projection of the original tessellation facet onto a plane orthogonal to the associated tetrahedron edge. The projected facet is used in order to avoid non-symmetric behavior for the case of purely tangential movement between two particles and the consequent stress-locking effect which can occur (Cusatis et al., 2011a).