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Fracture analysis of fiber reinforced concrete structures in the micropolar peridynamic analysis framework

Amin Yaghoobi, Mi G. Chorzepa *

College of Engineering, University of Georgia, Athens, GA 30602, USA

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ABSTRACT

In this study, an effective meshless model is proposed for fracture analysis of cracks in fiber reinforced concrete structures. The cementitious material is modeled using the micropolar peridynamic approach which is a generalized form of the bond-based peridynamics. A semi-discrete approach is incorporated in the micropolar peridynamic framework to study the effect of fiber reinforcement on the fracture analysis of cracks in cementitious materials. Therefore in the proposed fiber reinforced concrete modeling approach, the macro-scale fibers are randomly distributed in the cementitious material, and the forces developed in the fibers are indirectly applied to the cementitious material particles. This fracture analysis method used for fiber-cementitious material composites improves the computational efficiency. Furthermore in contrast to the finite element method, there is no need for mesh refinement and monitoring crack initiations/propagations in the proposed peridynamic framework. The crack development is an inherent feature of the proposed analysis framework. The accuracy of the proposed fracture analysis model is demonstrated through a comparison of available experimental results and simulation outcomes of fiber reinforced concrete beams with a notch at varying locations along the span.

1. Introduction

Fibers enhance the mechanical properties of the cementitious composite structures by providing bridges across cracks. Many experimental studies have been demonstrated that fibers significantly improve tensile strength, ductility, and load carrying capacity [1–3]; however, the performance of fiber reinforced cementitious composites is highly dependent on the fiber volume fraction, orientation, and spatial distribution [4,5]. Therefore, it is important to develop a novel, yet practical, analytical method to investigate multiple parameters that affect the strength of fiber reinforced concrete (FRC) structures and provide an alternative to laboratory tests.

A comprehensive review of the literature illustrates that previous numerical studies on the behavior of the FRC structures can be classified in two main categories: homogenization and discrete methods. A homogenization method generally represents FRC composites as a homogenized isotropic material, and thus the effect of fibers is considered in the material properties and fracture models [6]. In this approach, experimental results or analytical approaches are used to determine the model parameters [6,7]. On the other hand, a discrete modeling method has gained popularity in the recent years [8–10], discretely modeling individual fibers in composites. For FRC composites, two forms of discrete models have been developed: (1) fully-discrete and (2) semi-discrete models.

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* Corresponding author.
E-mail address: chorze@uga.edu (M.G. Chorzepa).

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Nomenclature

β	fiber-matrix interface slip-hardening parameter
$\boldsymbol{\theta}, \boldsymbol{\theta}'$	rotation of material point $\mathbf{x}, \mathbf{x}'$, respectively
Δ	fiber pull-out distance
δ	horizon radius
Δ_0	pull-out distance at which debonding is completed
δ_c	central deflection
Δ_f	scaled pull-out distance
$\mathcal{H}_{\mathbf{x}}$	horizon of material point, $\mathbf{x}$
λ	damage coefficient
λ_f	fiber activation parameter
λ_{max}	maximum damage coefficient
$\mathbf{b}$	body force vector
$\mathbf{F}$	micro-beam force vector
$\mathbf{f}$	pairwise force vector
$\mathbf{K}$	micro-beam stiffness matrix
$\mathbf{m_b}$	external moment vector
$\mathbf{m}$	pairwise moment vector
$\mathbf{R}$	spatial region
$\mathbf{U}$	micro-beam displacement vector
$\mathbf{u}, \mathbf{u}'$	displacement vector of material point $\mathbf{x}, \mathbf{x}'$, respectively
$\mathbf{x}, \mathbf{x}'$	reference position vector of a material point
ν	Poisson's ratio
τ_0	frictional stress on the debonded surface
a	notch location
A_f	fiber cross section
c, d	micro-elastic constants
d_f	fiber diameter
$dV_{\mathbf{x}}$	infinitesimal volume of material point $\mathbf{x}$
E	elastic modulus
E_f	fiber elastic modulus
f	magnitude of pairwise force vector, $\mathbf{f}$
f_c	uniaxial compressive strength
f_t	uniaxial tensile strength
G_d	fiber-matrix chemical bond
G_f	fracture energy
l	bond length
l_e	fiber embedded length
l_f	fiber length
P	fiber pull-out force
P_c	central applied load
P_r	residual load
P_u	ultimate load
s	stretch
s_{0c}	compressive stretch limit
s_{0t}	tensile stretch limit
s_{ft}	parameter affecting the slope of the softening
s_{uc}	ultimate compressive stretch limit
s_{ut}	ultimate tensile stretch limit
v_f	fiber volume fraction
v_m	matrix volume fraction

In a fully-discrete model, fibers are populated as truss or beam elements and coupled to solid concrete elements [11]. Therefore, the fully-discrete method may appear to be a better representation of FRC composites as it perceptibly reflects the spatial distribution and orientation of fibers. However, in presence of thousands and potentially millions of fibers, increasing degrees of freedom (DoF) by explicitly modeling macro or micro-scale fibers is not the most efficient numerical method. In order to address this deficiency, a semi-discrete concept was developed in which fibers are not explicitly mod-