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Probabilistic crack bridge model reflecting random bond properties and elastic matrix deformation

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Abstract

A semi-analytical probabilistic model of an isolated composite crack bridge is presented in this paper. With the assumptions of heterogeneous fibrous reinforcement embedded in an elastic matrix the model is capable of evaluating the stress and strain fields in both fibers and matrix. In order to be applicable as a representative unit in models at higher scales, the micromechanical response of the composite crack bridge is homogenized by using a probabilistic approach. Specifically, the mean response of a crack bridge is obtained as the integral of the response of a single fiber over the domain of random variables weighted by their joint probability density function. This approach has been used by the authors in a recent publication describing a single crack bridge with rigid matrix. The main extension of the present crack bridge model is the incorporation of elastic matrix deformations and of boundary conditions restricting fiber debonding at the crack bridge boundaries. The latter extension is needed to reflect the effects of interactions with neighboring cracks within a tensile specimen with multiple cracks. The model is verified against three limiting cases with known analytical solutions (fiber bundle model, crack bridge with rigid matrix, mono-filament in elastic matrix) and is shown to be in exact conformity with all of these limiting cases.

Keywords: A. Microstructure, B. Bond strength, C. Micromechanics, D. Pull-Out Strength, E. Modeling

1. Introduction

The toughening effect of fibers used as reinforcement in ceramics is well known [17, 42, 2, 34, 16]. Provided that the interfacial layer allows for debonding and sliding of the fibers along the matrix, the notch sensitivity, thermal shock resistance and fracture toughness of fibrous composites can be significantly increased. If matrices with rather low tensile strength (e.g. cement-based matrices in textile reinforced concrete, ECC or SHCC) are reinforced with high-strength ceramic or polymer fibers, the aim is not only to increase the toughness but also to achieve a favorable quasi-ductile tensile behavior and increase the strength [55, 57, 33, 45]. The quasi-ductility is caused by multiple cracking of the matrix and fiber debonding. In general, these composites, which are the focus of the present article, can be called (quasi-)brittle-matrix composites (BMC).

If unidirectional BMCs loaded in tension are designed for structural applications, it is imperative that a large redistribution capacity is available before the ultimate failure due to localized fiber damage is achieved [29, 2, 3, 18, 50]. The whole process of the composite tensile response is accompanied by considerable stress redistributions both between and within the composite constituents [47, 64, 48, 21, 35]. The qualitative and quantitative characteristics of BMCs strongly depend not only on the material and geometric properties of the constituents and their interface [2, 70, 65, 39], but also on the statistical variability of these properties [55, 62, 37].

In order to avoid expensive numerical calculations, which are often highly redundant, considerable effort has been devoted to the development of multiscale models that employ homogenization techniques. Caggiano et al. [8] recently proposed the use of zero-thickness interface elements to reproduce the complex influence of fibers on the cracking phenomena of the concrete/mortar matrix.

The finite element method [66, 67, 65, 69], shear-lag analysis [51, 66, 48], Green’s function method [64, 67, 35] and the fiber bundle model with equal load sharing have been used (among others) in the past for the analysis of the microscale mechanics of RVEs (representative volume elements).
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