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Zero-thickness interface model formulation for failure behavior of fiber-reinforced cementitious composites

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ABSTRACT

This paper deals with simulating the mechanical response of fiber-reinforced cementitious composites (FRCCs) by means of a zero-thickness interface model formulated within the framework of discrete-crack approaches. Following a similar model already available in literature for plain concrete, the formulation of the interface element is further developed and extended to capture the key mechanical phenomena controlling the FRCC behavior. An original approach is introduced for reproducing the complex influence of fibers on the cracking phenomena of the concrete/mortar matrix. Numerical analyses demonstrate the capabilities of the proposed model and show a very good agreement with experimental results on FRCC tests.

1. Introduction

Cement-based materials like concrete and most of the cohesive-frictional media are characterized by low strength and brittle response in low confinement and tensile stress states. These deficiencies can be mitigated by randomly adding short steel fibers into the cement mortar. Fibers play a relevant role in the post-cracking regime providing resistance to crack opening processes. In this sense, fiber-reinforced cementitious composites (FRCCs) may result in a less brittle and possible quasi-ductile behavior even in case of tensile loading, exhibiting strain-hardening processes with multiple cracks and relatively large energy absorption prior to failure. Composites with these relevant features take the name of high performance fiber-reinforced cementitious composites (HPFRCCs) [1].

Moreover, fibers spread up within the concrete matrix also influence its durability, as they control the crack opening and reduce the diffusion phenomena which lead to corrosion.

In the recent past, several test methods and theoretical models have been proposed for investigating the mechanical behavior of FRCCs. Most of the performed experimental analyses and proposed constitutive theories, however, focused on one or few aspects of the composite mechanical behavior. Fanella and Naaman [2] proposed a possible characterization of the stress–strain properties of fiber-reinforced mortars in compression. They proposed an analytical expression in terms of the key composite parameters (e.g. fiber types, volume fraction, etc.) that influence the stress–strain response and the toughness index of the composite.

Experimental tests aimed at investigating the FRCC failure behavior in compression and tension were performed, among others, by Ezeldin and Balaguru [3] and Barros and Figueiras [4], respectively. Abrishami and Mitchell [5] proposed an equation for predicting the tension-stiffening effect induced by fibers on steel-fiber-reinforced concrete (SFRC). They reported the importance and the fundamental influence of the fiber bond strength in the post-crack response behavior. While the benefits of fibers on strength and ductility were demonstrated in [6,7] based on direct shear test results on FRCC specimens characterized by different strength levels. Regarding the strength capacity of FRCC, Mirsayah and Banthia [8] proposed an empirical expression for the ultimate shear strength. FRCC capacity to resist fracture processes under static, dynamic or impact loads is given in [9]. The strength at first-crack of FRCC on beams under three-point bending is defined in [10]. An alternative proposal to evaluate the capacity of three-point beams is also given in [11].

The constitutive models currently available in the scientific literature for simulating the mechanical response of FRCC can be classified, as follow, on the basis of their observation scale:

- *Meso-scale models:* thereby the interaction among the different phases of the composite (i.e. fibers, matrix and coarse aggregates and their interfaces) is explicitly considered. Key contributions in this filed are due to Cusatis et al. [14] who considered the effect of fibers dispersed into a proposed lattice discrete particle model (LDPM), as well as in [15–20], among the others.

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- *Macro-scale models:* in this case FRCC are ideally considered as continuum media and modeled within the theoretical framework of the smeared crack approach. Among the others, the contributions by Hu et al. [21], who proposed a single smooth biaxial failure surface for FRCC, the one by Seow and Swaddiwudhipong [22], who introduce a five parameter failure criterion for FRCC with both straight and hooked steel fibers, and the paper by Minelli and Vecchio [23], who proposed a model based on a modification of the compression field theory, are worthy of mention. Other relevant contributions can be found in [24,25].
- *Structural-scale models:* these models, based also on the general continuum approach, capture the essence of structural members made of FRCC. Typical examples of structural-scale formulations are those related to either cross-sectional moment versus curvature or panel shear force versus lateral displacements. For instance, structural-scale formulations for FRCC structures are proposed by Stang and Olesen [26] and Lee and Barr [27] who characterized the complete load–deflection curve for FRCC three-point beams, as well as Billington [28] that proposed a formulation for retrofit analysis of structures made of ductile FRCC. Regarding bending behavior of FRCC beams a comprehensive summary can be found in [29] where different semi-analytical models based on the stress equilibrium in critical cracked sections are presented.
- *Multi-scale models:* in these models coupling effects of the different scales of observation are taken into account: i.e. micro-, meso-, macro- and structural scales of observation. The objective of these formulations is to develop an efficient approach to simulate the intrinsic multi-scale and multi-physics nature of the problem under consideration [30,31].

Thus, the progress made in the modeling fiber effects on both concrete composites is mainly based on the classical continuum smeared crack approach. This includes most of the proposals related to macro-scale models where the fiber-reinforced matrix was considered as a continuum. As it is well known, classical or continuum models for simulating quasi-brittle materials like concrete, see [32,33], are characterized by strong FE-size dependence of the localization band width and, consequently, to a loss of objectivity of their results. On the contrary, in the discrete crack approach (DCA) the discontinuity of the displacement field due to cracking is directly incorporated into the finite element formulation. The most effective procedure to use the DCA is the one based on interface elements. Interface formulations may only include traction-separation laws [34–36] or, eventually, constitutive relations based also on the more complex mixed-mode type of fracture [37–40].

This paper refers to a novel and promising approach to account for the fiber effect in concrete composites and mortar. It is based on the discrete or fixed crack approach and incorporates relevant aspects of the fiber–mortar interaction. In this sense, the proposal takes into account both the bond-slip and the dowel effects.

The proposed interface model for FRCC is based on flow theory of plasticity and fracture energy concepts to control the energy release during cracking processes in mode I and II. This model is an extension of the previous interface formulation for plain concrete by Carol et al. [37] and in [12,13] to take into account the interaction between cement/mortar and steel fibers. These fibers are considered to be embedded in the interfaces. The fiber–mortar interaction that includes the fiber bond strength and the dowel effect of fibers crossing the interface, is implicitly incorporated by means of the mixture theory by Trusdell and Toupin [41], following the approach used in [42].

For the sake of simplicity, the present model is formulated in 2D, as Lopez et al. [12,13] did in a similar proposal for simulating the fracture behavior of plain concrete. In particular, they demonstrated that the results obtained in 2D successfully reproduced experimental behavior under several basic stress states. Moreover, the numerical validation in this paper demonstrates the predictive capabilities of the proposed interface model of failure processes in FRCCs. The results in terms of peak strength, post-peak response and ductility as well as of their dependency on the fiber direction and content are realistic, and accurately reproduce the most relevant features of FRCC failure behavior.

The interface model proposed in this paper can be employed in mesoscopic analyses aimed at simulating failure processes possibly developing at the mortar-mortar and mortar-aggregate interfaces (Fig. 1). It should be noted that, as extensively discussed by many authors, see a.o. Lopez [43] and Kaczmarczyk and Pearce [44], mesoscopic analysis of concrete mixtures based on non-adapting meshes, as shown in Fig. 1, require sufficiently fine discretizations to avoid mesh dependence. As a matter of principle, the proposed interface formulation could be also employed in more general finite element models, oriented at simulating other possible failure modes of concern for FRCC and similar quasi-brittle materials. However, this aspect is beyond the scopes of the present paper and will be possibly addressed in future developments of the research.

Finally, it should be noted that the strategy proposed in this paper for modeling failure behavior of FRCCs based on the discrete crack approach and on interface elements can straightforwardly be extended to other well-known numerical techniques. In this regards, FEs with additional degrees of freedom [45,46] (FEs with embedded discontinuities known as E-FEM), or with additional nodal degrees of freedom [47,48] (X-FEM) could be considered as alternative numerical frameworks for FRCCs modeling. Other interesting procedures that could be also combined with the strategy in this paper for FRCCs are the so-called lattice models [49,50], the particle-based formulations [51,52], the element-free Galerkin [53,54], and the hybrid-Trefftz stress-based formulation in [44].

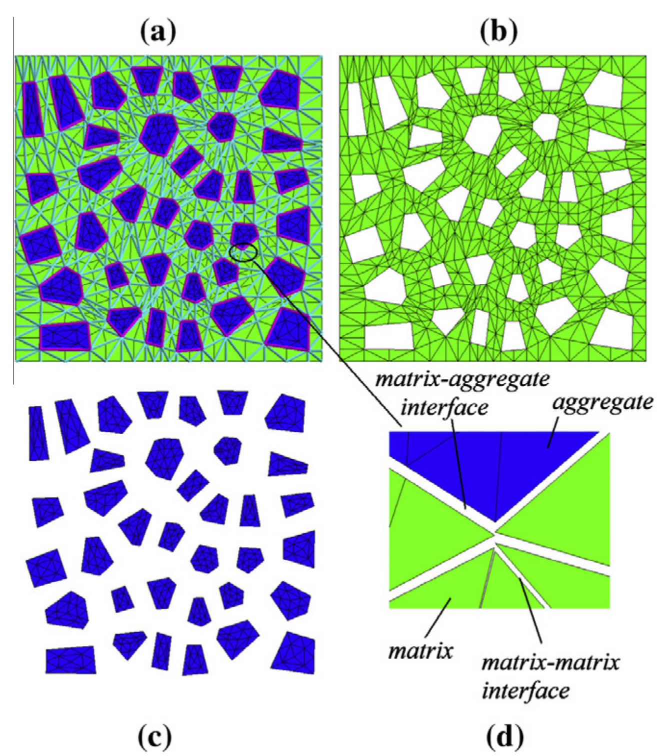

Fig. 1. FE discretization [12,13] (a) of 6 × 6 aggregate-arrangement, (b) matrix, (c) coarse aggregates and (d) interfaces.