Construction and Building Materials 114 (2016) 839–850

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

A multiphase micromechanical model for hybrid fiber reinforced concrete considering the aggregate and ITZ effects

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HIGHLIGHTS

- The presented framework can predict the properties of HFRC with the aggregate and ITZ effects.
- The properties of concrete and FRC can be calculated by the proposed micromechanical models.
- Different fibers can be considered by the multi-level homogenization scheme step by step.
- The homogenization sequence for different fibers has little influence on the predicting results.

ARTICLE INFO

Article history:
Received 7 July 2015
Received in revised form 31 March 2016
Accepted 2 April 2016
Available online 9 April 2016

Keywords:
Hybrid fiber reinforced concrete
Multi-level homogenization
Aggregate
Interfacial transition zone
Effective properties
Multi-phase micromechanical model

ABSTRACT

Very few micromechanical models are available for hybrid fiber reinforced concrete (HFRC), although it has been widely applied in many structures. To quantitatively predict the effective properties of HFRC with the aggregate and interfacial transition zone (ITZ) effects, a multi-phase micromechanical framework is proposed based on the material's microstructures. In the proposed model, the multi-types of fibers, aggregate, cement paste and ITZ are comprehensively considered. The volume fraction of the ITZ is analytically calculated based on the aggregate grading. Multi-level homogenization schemes are presented to predict the effective properties of HFRC. By utilizing the generalized self-consistent approach, the equivalent matrix composed by the aggregate, cement and the ITZ between them are obtained with the first and second level homogenization procedures. Through adding different types of fibers step by step into the equivalent matrix, the properties of HFRC are reached with the modifications to the Halpin-Tsai model. To demonstrate the feasibility of the proposed micromechanical framework, the predictions herein are compared with the experimental data, the Voigt upper bound and the Reuss lower bound. Finally, the influences of aggregate, ITZ, multi-types of fibers on the properties of HFRC are discussed based on the proposed micromechanical model.

1. Introduction

Fiber reinforced concrete (FRC) has been widely applied in many structures, such as frames, slabs, and tunnels, because the fiber addition in concrete can reduce the emergence and propagation of cracks, improve the mechanical behaviors, enhance the material's ductility, the impact resistance and the durability from the literatures [1–23].

Owing to the well-established performance of FRC, major efforts have been dedicated during the last decade to the modeling of its behavior. Empirical formulations to evaluate the elastic properties of concrete have been suggested by [24–28]. These formulations are obtained by means of laboratory tests, which is the phenomenological way to formulate the behavior of FRC. An attractive alternative to handle this kind of problem is provided by the framework of micromechanics, which reduces the laboratory expenses, meanwhile discloses the enhancing mechanism of fibers from the micro-scale level [29–33]. Teng et al. proposed a dedicated empirical formula for calculating the elastic moduli of steel fiber reinforced concrete(SFRC) through adopting the

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http://dx.doi.org/10.1016/j.conbuildmat.2016.04.008
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equivalent inclusion method [30]. Dutra et al. [29] proposed a micromechanical model for FRC and the linear elastic behavior is examined by implementation of a Mori–Tanaka homogenization scheme. Gal and Kryvoruk [31] employed the finite element method to analyze the properties of FRC using a two-step homogenization approach, where the *interfacial transition zone* (ITZ) between the aggregate and mortar is considered by a micromechanical homogenization process. Guan et al. [32] presented a stochastic micromechanical model to characterize the elastic modulus and Poisson's ratio of FRC.

Recently two or more types of fibers are usually added into the concrete to improve the material's performance, which is named by Hybrid fiber reinforced concrete (HFRC) [33–40]. Unfortunately, the current micromechanical models for FRC only consider one kind of fiber [29–32], very few micromechanical models for HFRC can be reached according to the author's studies. Furthermore, presently little attention is paid to the quantitative influence of the aggregate and ITZ on the properties of FRC [31], not to mention on those of HFRC. To address these issues in this extension, a multiphase micromechanical framework based on the material's microstructure is proposed to analytically investigate the mechanical performance of HFRC considering the aggregate and ITZ effects. A new multi-level homogenization scheme is presented to consider the effects of multi-types of fibers. Meanwhile, quantitative influences of aggregate and ITZ on the properties of HFRC are taken into consideration with the proposed homogenization framework and analytical calculations for the ITZ volume fraction.

The rest of this paper is organized as follows. In Section 2, a multiphase micromechanical model for the HFRC is presented based on the material's microstructures. Section 3 introduces the micromechanical representations for the ITZ, including its properties and the analytical calculations for its volume fractions. In Section 4, multilevel homogenization procedures are proposed to estimate the effective properties of HFRC. Numerical examples including experimental validations and comparisons with existing models are presented in Section 5, which also discusses the influences of the aggregate, ITZ and fibers on the macroscopic properties of HFRC based on the proposed micromechanical framework in this study. And some conclusions are reached in the final section.

2. Multiphase micromechanical model for HFRC

2.1. Microstructure of HFRC

Concretes are heterogeneous in nature and generally consist of different constituents or phases, such as aggregate, cement paste and C-S-H [41–45]. Further, the constituents of materials can be treated as homogeneous at a certain length scale, but when observed at a smaller length scale, the constituents themselves may become heterogeneous, i.e. a multi-scale phenomenon for heterogeneous concrete. For examples, the concrete can be treated as the homogenous material at the macroscopic material. At the lower level, the coarse aggregates are embedded in the mortar matrix, which can be treated as two-phase composite composed of the cement pastes and the sand particles. Moreover, the cement pastes are formed by homogeneous C-S-H with large CH crystals, aluminates, cement clinker and water [41,42]. Due to these heterogeneous and multi-scale natures, it is usually impractical and often impossible to describe all the precise characters of the microstructure of concrete. To investigate the ITZ effects on the concrete properties, the concrete are usually described by three phase material consisting of the bulk cement phase, the aggregates (sand and rock) and the ITZ between them [43–45], which implies that the lower length scale structures, like C-S-H, CH crystals and aluminates, etc., are not taken into considerations.

To predict the properties of HFRC with the ITZ effects, the microstructures of the HFRC are characterized by embedding the hybrid fibers into the three phrase material proposed by [43–45], which means HFRC is described by a multiphase composite formed by the bulk cement paste, aggregates, different types of fibers and ITZs in the present study.

2.2. Micromechanical model for hybrid fiber reinforced concrete

According to the previous studies [42–45], to simply the analysis, the shape of the aggregate is presumed to be spherical, although the geometry of the aggregates is quite complex in reality. The fibers are randomly distributed within concrete. They can be represented by a set of flat prolate spheroids which differ in orientations [29]. The interfaces between fibers and the cement paste are presumed to be well bonded [29–31]. Actually, there are ITZs between the fibers and concrete, which may deteriorate the effective properties of HFRC [46,47]. In this paper, we follow the assumption that the interface between the fibers and concrete is perfect according to many previous researches [29–31]. The quantitative effects of these ITZs between the fibers and concrete will be carefully investigated in our coming works.

Using the aforementioned assumptions, a multiphase micromechanical model for HFRC is proposed, as displayed in Fig. 1. The inner sphere is the aggregate phase, surrounded by a concentric ITZ shell. The aggregate and the ITZ shells are embedded in bulk paste matrix, where the shell elements are homogeneous and isotropic in composition and mechanical property. The hybrid fibers are randomly distributed in the ITZ and bulk paste matrix. By predicting the effective properties of the proposed model, the HFRC's macroscopic mechanical performance is revealed theoretically and quantitatively from its microstructures. It is noted that the effects of the different fiber lengths are not taken into considerations for simplification purposes in this study since they very slightly affects the moduli of fiber reinforced concrete according to the previous studies [11,13,25,29,30].

3. Micromechanical representations for the ITZ

3.1. The properties of the ITZ

The restrained placement of cement around aggregates results in a gradient of porosity, and therefore a gradient of properties, around each aggregate [48]. It seems reasonable that the ITZ can be divided into multi-layered spherical shells whose composition and properties are allowed to vary with distance from the aggregate surface and with the progress of hydration [43–45,48]. However, it is hard to get the exact gradient of ITZ properties, and different assumptions for the ITZ properties distribution are utilized in the previous work [43–45]. For simplifications, the ITZ

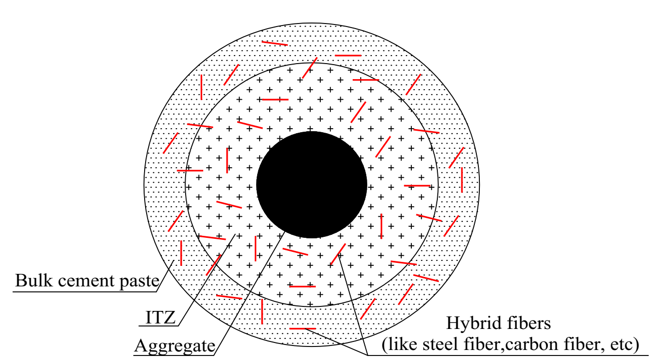

Fig. 1. Multi-phase micromechanical model for hybrid fiber reinforced concrete (HFRC).