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A multi-level micromechanical model for elastic properties of hybrid fiber reinforced concrete

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HIGHLIGHTS

- A micromechanical model is presented to predict effective properties of HFRC.
- Three levels are considered to estimate the effective property of HFRC.
- Results illustrate the feasibility of this model.
- Our model can be used to optimize the design of the HFRC.

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ABSTRACT

There is a demand for multi scale micromechanical models to disclose and analyze the effects of microstructure on macro mechanical properties of hybrid fiber reinforced concrete (HFRC). This study involved presenting a multi-level micromechanical model that involves cement paste level, concrete level, and hybrid fiber reinforced concrete level to quantitatively predict the effective isotropic and elastic properties of HFRC under ambient temperature. For the purposes of homogenization, the volume fractions of different phases at different levels are determined by means of a modified Power's model. In the multi-level micromechanical model, hydration products of clinker, sand, coarse aggregate, and hybrid fiber are comprehensively considered. A homogenization stepping framework is presented to realize upscaling from microstructural properties to the effective elastic properties of a macrostructure for HFRC. Additionally, several substepping homogenizations are also presented to estimate the effective elastic properties of an equivalent medium with respect to the cement paste and hybrid fiber reinforced concrete. Comparisons with experimental data from extant studies are implemented level by level. Subsequently, the influences of aggregate, sand, fiber type, and hydration degree on the properties of HFRC are discussed based on a proposed multi-level micromechanical model. Finally, the mixture ratio of steel fiber and *w/c* are investigated with respect to the HFRC design to obtain anticipated elastic properties.

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1. Introduction

Fibers with various mechanical properties are mixed with cement or concrete to overcome several disadvantages of plain concrete. The addition of various types of fibers results in the combination of the excellent tensile properties of fibers with the high compressive properties of concrete, and this leads to an improvement in ductility, strength and fire resistance of concrete [1–3]. Hybrid fiber reinforced concrete (HFRC) is widely applied in several practical projects, such as cable-stayed bridge, high-rise building structures, and underground structures, due to its well-established performance [4–17].

Elastic parameters of materials are basic needs for structural design. Extant studies conducted multi scale experiments to study the mechanical properties of concrete, FRC, and HFRC, and proposed several empirical formulations to predict their effective properties and further promote their applications [18]. Numerical methods were proposed because a large amount of funding and

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Nomenclature

CH	calcium hydrates: $Ca(OH)_2$	$\bar{\varepsilon}_i^{\prime p}$	disturbed strain of phase i by considering interaction between particles
CSH	calcium silicate hydrates	$\bar{\varepsilon}_i^{\prime m}$	average strain perturbation tensor in the matrix
HFRC	hybrid fiber reinforced concrete	$\bar{\sigma}$	overall averaged stress tensor
C	concrete	S_i	fourth-order Eshelby tensor of phase i
CAP	capillary pore	I	symmetric fourth-order unity tensor
IP	inner product	k_i	bulk modulus of phase i
OP	outer product	μ_i	shear modulus of phase i
CP	cement paste	k_*	effective bulk modulus of the composite
eqI	equivalent medium I	μ_*	effective shear modulus of the composite
$eqII$	equivalent medium II	v_i	Poisson's ratio of phase i
C_i	fourth-order elastic stiffness tensor of phase i	α	degree of hydration
C_*	effective fourth-order elastic stiffness of the composite	ρ_i	density of phase i
ϕ_i	volume fraction of phase i	V_i	volume of phase i
$\overline{\varepsilon^*}$	overall averaged equivalent eigenstrain	w/c	water-cement ratio
$\bar{\varepsilon}_i^*$	overall averaged equivalent eigenstrain of phase i		
$\bar{\varepsilon}$	overall averaged strain tensor		

natural resources are required for actual experiments. Several models were formulated to investigate the effects of interfaces between fiber and concrete, fiber orientation, type, length, and volume fraction on the macro mechanical characteristics of concrete [19–23]. Furthermore, numerical simulations provide an approach to study inhomogeneous mediums such as lattice models [24], random aggregate models, [25] and random mechanical characteristics models [26,27]. The analytical model is more direct and convenient in terms of estimating the elasticity of the material and optimizing material design to obtain anticipated properties when compared with those of numerical simulation [28–30]. The prediction and estimation of overall mechanical properties of random heterogeneous multiphase materials is widely developed in materials science and engineering [31]. In order to predict the elastic properties of concrete, various micromechanical models were extended through a homogeneous representative volume element (RVE) with macro equivalent physical properties of the inhomogeneous medium [32,38] and included dilute methods [33,37], M-T methods [34], self-consistent methods [35], and differential methods [36,37]. Therefore, several analytical results were obtained for FRC or HFRC over the last decade by assuming that composites are macro homogeneous. Examples of these include studies by Chen (2016) [39], Pyo, S. and Lee (2009) [40], Carolyn W. (1990) [41], and Halpin, J. C. (1969) [42]. The micromechanical models encompasses continuum mechanics related to the microstructure of inhomogeneous composites and demonstrated its serviceability to unravel the working mechanism and hybrid effects of FRC and HFRC.

Nevertheless, models based on a self-consistent method can significantly overestimate overall mechanical properties when the volume fraction of inclusion is high as noted by Tandon and Weng [43]. In accordance with a study conducted by Ju and Chen [44–46], results based on the M-T method coincide with the non-interacting solution for composite that contains undirectionally aligned and identically shaped inclusions, and this suggests that the M-T method can underestimate or even neglect interactions between inclusions. In order to address this issue, a novel higher-order ensemble-volume averaged micromechanical framework was presented by Ju [44] to predict effective elasticity of multiphase composite by considering explicit probabilistic pairwise interactions between phases with identical shape or identical properties. Subsequently, a micromechanical model was presented by considering identically shaped phases with different properties [47]. Currently, very few micromechanical models examine HFRC based on mortar or cement paste matrix levels [39], and there is a paucity of studies examining HFRC based on very fine scale (nanometer or micrometer level) levels. A topic of fundamental material design and practical importance with respect to the applications of HFRC involves estimating their effective elastic properties, such as mechanical properties, volume fraction, spatial distribution, and micro geometries, of each component at different scales from microstructural information under an ambient temperature. In keeping with the micromechanical framework proposed by Ju and Chen [44–46], the primary objective of the present study is involved in developing a multi-scale model to predict overall elastic properties of HFRC based on microstructural information ranging from nanometers to decimeters.

The present study is organized as follows. The basic theory of micromechanical models, involves a governing equation, single inclusion composite, and double inclusions with different properties as presented in Section 2. Subsequently, a multi-level homogeneous model is developed to estimate the elastic modulus of HFRC based on its microstructure, and this includes cement paste level, concrete level, and a hybrid fiber reinforced concrete level. A generalized self-consistent method is utilized to obtain the effective equivalent medium IC. Additionally, finer levels of inner products and outer products are discussed. Furthermore, a homogenization stepping scheme is adopted to realize the transition from a nanometer level to a decimeter level, and several substepping homogenizations are adopted to predict effective modulus at the cement level and HFRC level. The prediction and experimental data are compared with other existing models in Section 4. In Section 5, parametric sensitivity analysis is presented to study the influence of factors on effective HFRC modulus. Moreover, material design is discussed to determine fiber volume fraction when the anticipated elastic properties are desired. Finally, a few conclusions are presented.

2. Basic theory

In this section, basic theories are introduced, and this includes Ju's theory and the generalized self-consistent method, which are the basic theories to the formulation of the model in this paper.

2.1. Governing equation based on Ju's micromechanical framework

In order to obtain overall elastic properties of multiphase composites, it is necessary to perform an ensemble-volume averaged process within a reasonable representative volume element (RVE) [44,67,78]. A basic continuum mechanics framework based

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