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A method for modeling the damage behavior of concrete with a three-phase mesostructure

Yi Xu, Shenghong Chen *

State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, 8 Donghu South Road, Wuhan 430072, PR China

HIGHLIGHTS

- A method for modeling concrete with a three-phase mesostructure is presented.
- Material deterioration is described by the elasto-viscoplastic damage model.
- Good accordance between the numerical results and the experimental data is obtained.
- Damage behaviors of concrete under uniaxial compression and tension are studied.

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ABSTRACT

Study on the mechanical response and damage behavior of concrete, especially its mesostructural failure mechanism, still remains an important issue in civil engineering and material science. In this paper, a method for modeling the damage behavior of concrete with a three-phase mesostructure consisting of coarse aggregates, homogeneous mortar matrix and the Interfacial Transition Zone (ITZ), is presented. Mechanical responses and damage deterioration of these phases within concrete are modeled by the elasto-viscoplastic damage model. The proposed method is then validated against experimental data with respect to its effectiveness. Numerical simulation tests have been further carried out to model the uniaxial behaviors of concrete in compression and tension. The simulation results show that the multiphase distribution in the mesostructure remarkably affects the mechanical response and damage behavior of concrete.

1. Introduction

Concrete is the most prevalent construction material with a vast range of applications around the world, and study of its physical and mechanical properties still remains an important issue in civil engineering and material science [1–4]. As a man-made material, mechanical response of concrete is affected by a variety of factors, especially its multiphase composition and mesostructure. In general, aggregates (gravel, crushed stone and sand) in different shapes and sizes, bonding with cement paste, form the internal structure of concrete. Therefore, concrete is highly heterogeneous at the mesoscale and its composite behavior (e.g., damage, crack and failure) is extremely complicated.

Laboratory tests are one of the most important and traditional means to study the mechanical properties of concrete but very few of them can be employed to handle the issue raised from mesostructure. Recently, some new techniques, such as acoustic emission [5,6] and X-ray Computed Tomography (CT) [7–9] have been developed to detect the crack propagation within concrete. However, these new techniques are still immature and costly for quantitative analysis. With the advance in computer technology and development of numerical methods, mesoscale modeling based on Finite Element Method (FEM) has been more and more widely accepted to study the mechanical behavior of concrete, known as the concept of "numerical concrete" [10–12]. In general, a mesoscale model for concrete is assumed as a three-phase composite material consisting of coarse aggregates (greater than 4.75 mm in size), mortar matrix, and the Interfacial Transition Zone (ITZ) between them, which is usually recognized as the weak zone in concrete [13–15].

The random aggregate structure (RAS) [11,12,16] is a commonly used mesoscale model for numerical simulation to investigate the composite mechanical behavior of concrete, in which many significant progresses have been achieved over the last decades. For example, Wriggers et al. [16] generate a 3D RAS model with the

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* Corresponding author.
E-mail address: chensh@whu.edu.cn (S. Chen).

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aggregates of spherical shape for concrete, and provide a good prediction concerning the compressive damage behavior of concrete with the help of the scalar damage model by Mazars [17]. Qu and Chen [18] develop a 3D RAS model with spherical and polyhedral aggregates, and study the crack propagating behavior of concrete with the maximum tension strain fracture rule. Du et al. [19] propose a 2D model taking circular, elliptical and polygonal shape of aggregates into account, and explore the tensile failure behavior of concrete. Wang et al. [20,21] generate 2D RAS samples comprising aggregates and pores, and simulated the tensile damage behavior of concrete by a scalar damage evolution law. Since many of these models are still in 2D, and the few existing 3D models are assumed to be two-phase composite without the existence of the ITZ structure, therefore they might be insufficient for resembling the concrete in reality and consequently the simulated results may not be fully representative.

In this paper, a method for better modeling the damage behavior of concrete at mesoscale is presented. A more realistic 3D mesostructure is generated for concrete, in which aggregates with different particle shapes, high volume content, and actual size distribution are modeled. Several techniques are introduced to discrete the mesostructure containing ITZ. Based on the elasto-viscoplastic damage model, a numerical test method for concrete has been established with the help of FEM. The proposed method is contrasted against experimental data to demonstrate its applicability and effectiveness. The numerical tests have been further performed to study the damage behaviors of concrete in uniaxial compression and tension.

2. Construction of the mesostructure for concrete

For the purpose of numerical test, an exquisite mesoscale model of concrete must be generated at first. It is assumed that concrete is a three-phase composite material consisting of coarse aggregates, homogeneous mortar matrix and uniform ITZ layer (see Fig. 1). A 3D mesostructure with these three phases is generated, in which some actual features including the shape, volume content and size and spatial distribution of coarse aggregates are considered to closely model the real concrete.

2.1. Generating aggregate particles

2.1.1. Mathematical description of different particle shapes

Coarse aggregates generally occupy 40–50% volume of concrete and form the material skeleton playing an important role in its properties and mix proportions [16]. The shape of coarse aggregates depends on their types [20], i.e., gravels have a rounded shape while crushed stones have an angular or irregular shape. As the most prevailing exercise, spherical and ellipsoidal particles for gravel aggregates and convex polyhedral particles for crushed stones are stipulated in the hereinafter study.

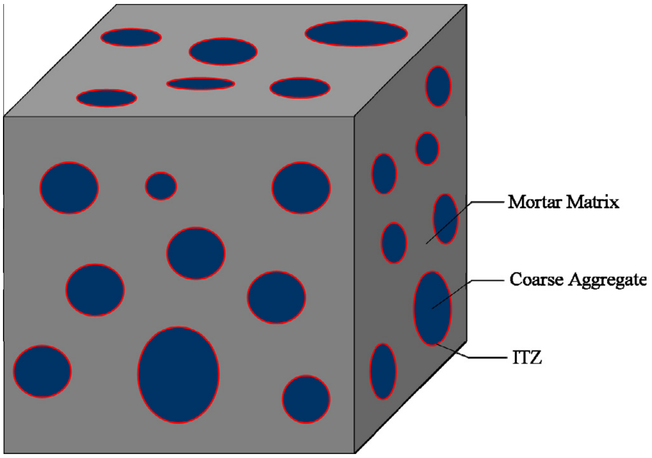

Fig. 1. The three-phase mesostructure for concrete.

Only four parameters are demanded to describe a sphere in mathematics, i.e., the center (x_c, y_c, z_c) and the radius r (Fig. 2(a)). While an ellipsoidal particle is more complicated, which requires nine parameters [22,23], i.e., the center of the ellipsoid (x_c, y_c, z_c), the semi-principal axes (a, b, c) and the three Euler angles, (α, β, γ), to describe its orientation in 3D space (see Fig. 2(b)). The geometrical model of an ellipsoid is expressed as,

$$X^T Q X = 0, \tag{1}$$

where $X^T = [x, y, z, 1]$, Q is the 4×4 coefficient matrix of the ellipsoid including its axes, position and orientation, which may be derived from the aforementioned nine parameters [22,23].

The faces of a convex polyhedron are assumed to be triangular (see Fig. 2(c)), so that it can be described as a set of triangles (f_i) and a set of points (p_j). A polyhedron is defined as convex where its surface does not intersect itself, which means that for each face on the particular surface, all the rest faces will be at the same side of it.

2.1.2. Particle size distribution

Aggregate size distribution is an important factor in concrete mix design and optimization. As of the well known size distribution, the Fuller curve [16] postulates that

$$P(d) = 100\sqrt{d/d_{\max}}, \tag{2}$$

where $P(d)$ is the cumulative percentage of aggregate particles with a size smaller than d and $d_{\max}$ is the maximum particle size of the aggregate.

Once the aggregate size distribution is determined by Eq. (2), the volume content of aggregates in different size ranges and their amount may be calculated for particles generation [16].

2.1.3. Particles generation

In particles generation, poorly shaped ones (e.g., needle or platy shaped) should be avoided. For this purpose, the shape characteristics of aggregate particles are identified. A widely used parameter termed as "sphericity" [24,25] is adopted here to characterize the shape of an aggregate particle, which is defined as

$$s = \sqrt[3]{v/v_s}, \tag{3}$$

where v is the volume of the particle and v_s is the volume of its minimum circumscribed sphere.

Fig. 3 shows a distribution graph of sphericity, in which p_i means the distribution proportion of particles in each interval (s_i, s_{i+1}).

The composite shape index of all aggregate particles, I, is then expressed as

$$I = \sum \frac{1}{2}(s_i + s_{i+1})p_i, \tag{4}$$

which normally represents the overall shape characteristics of aggregates.

2.2. Particles arrangement

The generated aggregate particles are arranged and placed in a cubic or cylindrical shaped region, which depends on the type of