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Behavior of meso-scale heterogeneous concrete under uniaxial tensile and compressive loadings

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HIGHLIGHTS

- Meso-scale concrete models are constructed with numerical concrete modeling approach.
- The geometrical shape and random distribution of aggregates are considered.
- Mesh sensitivity and the influence of the ITZ are investigated.
- The variation of micro-damage evolution and the macroscopic response is analyzed.
- The statistic characteristics of concrete under tension and compression are discussed.

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ABSTRACT

Meso-scale modeling approach is helpful for understanding the mechanism of both global nonlinear behavior and local failure pattern of concrete materials and structures. As a typical multiphase composite material, concrete is composed of randomly-distributed coarse and fine aggregates, mortar, interfacial transition zone (ITZ) together with initial pores or defects. The meso-scale mechanical behavior of concrete usually exhibits nonlinear and stochastic characteristics. In this paper, the influence of both distribution and geometrical shape of aggregates, the existence of ITZ, and meshing approach on macro stress-strain relationship, damage evolution and the final failure pattern of concrete are studied systematically. The results indicate that the effect of meso-scale structure of concrete on the nonlinear and stochastic characteristics of macro stress-strain curves and failure patterns is different when the concrete specimen is under tension and compression loadings. Comparatively, the geometrical parameters of coarse and fine aggregates have limited effect on the macroscopic tensile strength, but obvious effect on the post-tension segment and the compressive macro stress-strain curve. Moreover, the damage evolution and failure pattern of concrete under uniaxial tensile and compression are sensitive to the meshing approach. The existence of ITZ affects the tensile and compressive strength of concrete significantly. The statistic characteristics of macro stress-strain curves under both tension and compression loadings from the multi-scale simulation is compared with that from experimental studies and the rationality of the meso-scale simulation approach is validated.

1. Introduction

In most of the current structural design and numerical studies of large-scale concrete structures, concrete is usually modeled as a homogeneous material. However, concrete is a multiphase composite material composed of coarse and fine aggregates, mortar, interfacial transition zone (ITZ), pores and initial defects. Generally, numerical analysis on the structural performance of concrete structures can be performed at micro-level (10^{-7}–10^{-4} cm), meso-level (10^{-4}–10 cm) and macro-level (3–4 times the maximum aggregate volume) [1,2]. In order to figure out the physical mechanism of stochastic cracking phenomenon and the randomness in macro stress-strain curves of concrete under different loading conditions, meso-scale modeling approaches have been developed rapidly due to significant improvement in computing performance of computers in recent years.

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For the purpose of establishing the geometrical models with more realistic aggregates, the shape and position of aggregates can be determined by the microscopic X-ray computed tomography (CT) imaging technique [3]. It has been mentioned that the load-carrying capacities and crack pattern were affected by the random distribution of aggregates. Similarly, the in situ X-ray CT images were also adopted in the 2D/3D homogenization and fracture analysis of concrete [4]. Besides, the statistical analysis indicated that the macroscopic responses were significantly affected by the random spatial distribution of aggregates. In addition to the imaging method based on CT scanning approach and the random aggregate method (RAM), plenty of numerical concrete modeling technologies including the lattice model [5], meso-mechanical model [6,7], particle discrete element model [8], random particle model [9], beam-particle model [10], rigid-spring element [11] and Gurson model [12,13] have been successfully applied in the concrete study at meso-level. In contrast, the application of random aggregate method is more extensive due to its clear concept and programming convenience. The generation and packing techniques of random aggregate in numerical concrete have been enriched and continuously developed in recent years. From the initial circular or spherical aggregates [9], elliptical or polygonal aggregates to random convex-concave polygonal aggregates [1,14], a variety of aggregate growth and cast intrusion criteria have been proposed gradually, resulting in more realistic geometrical shape for aggregates and ITZ for 2D and 3D modeling.

For uncovering the damage evolution and failure mode, in addition to the concrete damage plasticity (CDP) model developed by Lee and Fenves [15], the cohesive zone model was also an effective and efficient approach, especially for uniaxial tension loading cases. Moreover, by means of meso-scale modeling methods with dynamically-inserted cohesive elements, the failure mode of concrete specimen was investigated [16]. The difference of peak strength and fracture energy between 2D and 3D models has been discussed. In order to investigate the physical mechanism of size effect in concrete, the meso-scale fracture of concrete specimen established with random aggregates and pores was numerically analyzed [17]. The research findings indicated that the macroscopic strength and toughness of concrete were both related to the specimen geometry and the randomly-distributed aggregates and pores, which matched well the empirical size-effect laws. Moreover, the energy release rate-based plastic-damage model for concrete proposed by Wu et al. has been introduced in the FE modeling to investigate the typical nonlinear performances of concrete structures under different loading conditions [18]. Currently, the stochastic damage model has also been developed to investigate the nonlinear and stochastic behaviors of concrete observed in experimental studies and to describe the transfer of random characteristic of concrete from material level to structural level [19].

The meso-scale numerical analysis based on RAM and the material definition with the CDP model has also been approved as an effective approach to investigate the mechanical behavior of concrete components. For uncovering the crack propagation process in the recycled aggregate concrete (RAC) [20], the old and new IZT layers and mortar were explicitly modeled in 2D planner model and the CDP model was employed as the constitutive law for mortar and the ITZ. It is worth mentioning that the material properties and thickness were defined according to the experimental measurement using advanced nanoindentation technique. The research findings showed that the damage pattern and cracking evolution obtained from digital image correlation (DIC) measurement matched well with numerical results. It was suggested that the mechanical properties of RAC would be apparently enhanced through optimizing the mix design and improving the material property of the ITZs. Moreover, since the concrete structures are usually exposed outside, complex environment factors such as thermal conduction and corrosion will be involved during the service life. Therefore, the multi-physics analysis based on meso-scale modeling and computational homogenization method has been proposed recently. The effective thermal conductivity and the temperature distribution in concrete specimens at different loading levels were discussed based on meso-scale numerical simulation [21]. The failure modes induced by corrosion of steel bars were numerically investigated and agreed well with the macroscale simulation based on homogeneous assumption and the experimental observations [22]. In addition, the meso-scale modeling has also been introduced to the numerical study on large-scale concrete structures. In order to consider the size effect of concrete, stocky RC columns were numerically investigated at full scale with a 2D model[23]. Compared with the experimental data, the meso-scale models were proved efficient and reliable to perform parametric analysis on the failure behavior of full-sized concrete components at meso-level. Moreover, the 3D full-scale analysis on the failure mode of simply supported RC beams under impact loading was performed on the basis of the random aggregate method while considering the dynamic increase factor in the material definition of mortar and ITZ at the same time. The results showed that the impact responses, including acceleration, the velocity and impact stress distribution, were consistent with the measured results [24]. However, the structural behavior is commonly analyzed with numerical models constructed by single aggregate sample without considering the variation in meso-scale structure of concrete, which weakens the persuasiveness of the numerical findings to some extent.

It can be seen that the internal physical mechanism of the stochastic cracking and structural behavior of concrete at macro level has not been systematically studied in most of the current meso-scale studies. Here, meso-scale numerical models composed of randomly-distributed aggregates with different geometry shapes, mortar and the ITZ are established with two kinds of meshing approaches. The failure pattern, cracking evolution and the macro stress-strain relationship of concrete under uniaxial tension and compression are comparatively investigated in this study.

2. Meso-scale modeling of concrete with random aggregates generation and packing approach

2.1. Random aggregate generation and packing method and numerical concrete models

The Monte Carlo simulations of meso-scale dynamic compressive behavior of concrete based on X-ray computed tomography (CT) images carried out by Huang et al. indicated that the difference in the initial slopes of the macro stress-strain curves is small due to the change in the meso scale structure of concrete [25]. However, obvious variation in peak stresses and post-peak descending segments is observed. Meanwhile, according to numerical study on failure processes of modeled recycled aggregate concrete (RAC) under uniaxial compression, the macro stress-strain curves of modeled specimens with different material strengths but identical aggregate geometry sample presents significant variation in structural behavior at macro level [26]. The initial stiffness, the peak stress and the macro stress-strain curves derived from FE models of modeled natural aggregate concrete (MNAC), modeled recycled aggregate concrete (MRAC), modeled cored aggregate concrete (MCAC) and modeled cement mortar (CM) are significantly affected by material properties of aggregates, mortar and the ITZ.

In order to model the meso-scale structure of concrete, a random aggregate generation and packing program is developed while