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Case study

Meso-scale finite element modeling of non-homogeneous three-phase concrete

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ABSTRACT

Assumptionof material homogeneity is not realistic in study of the mechanical behavior of concrete. When a concrete specimen under loading condition starts to crack, it changes from a continuous state into a discrete one. Under such circumstances, application of classical finite element methods is no longer valid.

In this study, the authors used the meso-scale modeling in which concrete is assumed as a non-homogeneous three-phase material consisting of three phases; aggregate, cement paste, and internal transition zone (ITZ). Many mechanical properties of concrete depend on the size, geometry, and arrangement of its aggregates. In this paper, aggregates of different sizes are generated with circular, elliptical, and irregular shapes, and then randomly distributed within the specimen.

The lattice beam finite element method was used in which a regular or irregular meshing compromised of beam elements is constructed. This method is used to trace crack paths when concrete specimen is under loading condition. Three loading tests including three-point flexural, compression, and tensional tests were done. In order to validate the model, we expect the crack development of this concrete specimen model to be similar to previously established models.

1. Introduction

In the past three decades, mechanical behavior of concrete has been frequently reviewed. If concrete is considered as a homogeneous material, its behavior under loading cannot be understood properly. In fact, assumption of material homogeneity in the analysis of concrete cracking leads to unrealistic results. Nonlinear behavior in continuous solid bodies originates from two fundamental factors; material type and geometry. The former is considered when the stress-strain relation is linear and the latter when a change in the geometry leaves a significant effect on the load-displacement behavior of the material. Three modeling approach can be defined to investigate this issue; macro-scale models, meso-scale models, and micro-scale models.

In recent decades, researchers have presented various mechanical models based on geometry. These models can be generally divided into two categories: continuous element models and discrete element models.

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1.1. Continuous element models

Yamaguchi and Chen used the finite element method to study two-phase concrete in two dimensions (using six-node triangular elements for modeling the aggregates and eight-node tetrahedrons for modeling the mortar matrix) [1]. Mohamed and Hansen presented a 2-D finite model based on the finite element analysis [2]. Roelfstra and Wittmann proposed a model called "numerical concrete model" in which the mortar, aggregates, and the spaces between them were modeled as a number of elements with smaller size than aggregates one [3]. Lopez et al. first proposed a 2D model and subsequently a 3D model to analyze two-phase concrete specimens [4,5]. Proposing a three-phase 2D model, Zhou and Hao studied the behavior of concrete under dynamic tensile loading [6].

1.2. Discrete element models

These methods were first investigated by Cundall and Strack to analyze the stone [7]. Based on this method, the rigid body-spring model (RBSM) was later developed by Kawai [8] The lattice beam method which first introduced by Hrennikoff is another discrete element method [9]. After some modifications, Liu and Liang and used the lattice beam model to study the process of crack development in concrete specimens under pseudo-static and dynamic analyses [10]. It was shown in 1975 that cracking behavior improves if concrete were reinforced with steel fibers. Özcan et al. used ANSYS to study the behavior of steel fiber reinforced concrete (SFRC) under pseudo-static loading [11].

Analysis of cracking in concrete is not possible through implementing classical methods because the environment is changed from a continuous state into a discrete state. Since structures tolerate these loads through absorbing energy, the strain energy absorption as well as ductility play important roles in the structure stability. Due to its brittle behavior, unreinforced concrete is not considered a suitable material. Using fibers causes a ductile response and prevent a sudden rupture in concrete. Macroscopic phenomena such as ductility are in fact the result of a microstructural process occurring within the concrete internal structure. To study the microstructure of concrete, this material should be examined at a smaller scale. Due to the high computational power of computers today as well as the importance of high accuracy in research, the meso-scale modeling is the best modeling method. In this model, concrete is considered as a three-phase compound material consisting of aggregate, cement mixture matrix, and internal transition zone (ITZ). Aggregates have a significant effect on the mechanical behavior of concrete, and – in most studies – their shape is assumed to be circular for simplicity. However, in this study, the aggregates are randomly simulated in different shapes including circular, elliptical, polygonal, and irregular shapes to obtain more realistic results. In addition, fibers with different lengths and thicknesses are added to the specimen.

The main purpose of this study is to build a more realistic model in which aggregates have different shapes. Then the concrete specimen can be analyzed under different loading conditions. In order to build the concrete specimen, the modeling code is first written in MATLAB, turned into PYTHON file format, and then imported to ABAQUS. In next step, ABAQUS is utilized to study and analyze the forces and stresses developed in the specimen. In addition, the lattice beam finite element method is used in order to trace the crack paths.

2. Theory

Concrete is a compound material where aggregates are randomly placed within the cement paste. The internal structure of concrete is then far non-homogeneous due to the existence of two different phases therein and complex due to the randomness of aggregate arrangement. In addition, during concrete batching, water tends to accumulate around the boundaries of coarser aggregates [12], thus making the cement paste structure around those aggregates weaker than other regions within the concrete. These vulnerable regions are called internal transition zones (ITZ) and in spite of their negligible thickness (approximately 50 micrometers), they influence the mechanical behavior of concrete significantly [13]. Therefore, in this paper concrete is considered as a three-phase material consisting of aggregates, the cement paste, and ITZ.

3. Creating the meso-scale structure

To evaluate the behavior of concrete in the meso-scale state, it is necessary to build a random geometry for the concrete specimen. This geometry which comprises aggregates shape, size, and distribution should be as similar to real specimen's one as possible. The basis of building this geometry is the random distribution of the aggregates and filling the voids between them with cement paste. Since formation of the cement layer can be determined just based on distribution of the aggregates, a separate study of this layer is not necessary [13,14].

3.1. Building the aggregate part of the concrete specimen

Aggregates comprise 60–80% of a given concrete volume, and their size and shape influence the properties and mix design of concrete significantly. Aggregates can be generally classified into two groups: fine-grained aggregates and coarse-grained aggregates. The grain size in coarse grained aggregates is larger than 4.75 mm. For simplicity, most researchers use circular coarse-grained aggregates. To present a more realistic simulation in this study, both types of fine and coarse grained