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Application of combinational sphere element in meso-mechanical analysis of cemented particulate composite

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ABSTRACT

Combinational sphere element method is introduced to simulate the mechanical behavior of cemented particulate composite. A pair of particles and the cement matrix in middle are extracted from the composite, and they constitute a combinational sphere element (CSE). The stiffness of a CSE on axial direction, tangential direction and bending direction can be derived based on the mechanical model and assumptions. The stress distribution function in matrix can also be gained when the CSE supports load on each direction. The element stiffness matrix of CSE is obtained through the direct method. The CSE can be described by an equivalent rigid beam-spring model according to the element stiffness matrix, so the composite can be described by an equivalent rigid beam-spring lattice. Finally, an example is taken out to show the application of this new method. Stress distribution function, stiffness on three directions and macro effective elastic constants of composite can be obtained. The results agree well with the simulation results of the representative volume element. According to the damage criterion set reasonably, the damage evolution of the models with defects can be simulated.

1. Introduction

Particulate composite, such as rock, concrete, particle reinforced resin or metal matrix composites etc, is a kind of material which is widely existed in nature and widely used in engineering. According to the difference of the particle volume fraction, particulate composite can be divided into filling and cemented particulate composite. Filling particulate composite is a kind of closed-cell composite material which is composed of uniform particles discrete in the matrix and the matrix fill all the space between the particulates. The particle volume fraction of the composite is relatively low (generally below 50%). Cemented particulate composite is a kind of open hole composite material which is neck-connected between the particles by cement matrix as shown in Fig. 1. Fig. 1(a) is the mesoscopic structure of metal hollow balls composite material, and the cement matrix is epoxy [13]. Fig. 1(b) is the SEM micrograph and meso-scopic structure of Sandstone, which consists of quartz particles with siliceous and carbonate cement, and the quartz particle volume fraction is more than 52% [5,6,22]. There are many gaps between particles. The particle volume fraction is relatively high (generally more than 50%). The mechanical property of particulate composite depends on the meso-structure parameters such as modulus and strength of the particles and matrix, the volume content of particles and bonding strength of particles and matrix, etc. How to predict the macroscopic mechanical properties with the meso-structure parameters is concerned in the design and use of the particulate composite [19,16].

There are a lot of researches on filling particulate composite all over the world. The traditional inclusion theory, for instance Mori–Tanaka method, the generalized self-consistent method, differential method, the equivalent medium, multiphase model method etc [10,12,1], can be well applied on computing the mechanical performance of such kind of composite. The periodic unit cell model based on geometric modeling method in the study of particle reinforced composites mechanics performance has also been extensively researched and applied [3,4,11,8]. These methods mentioned upon obviously can not be applied to cemented particulate composite obviously. The discrete element method [2,7], put forward by Cundall in 1971, is a effective method dedicated to solve the non-continuum mechanics problems, and its initial research is the mechanical behavior of discontinuous medium material such as rock, etc. Wang and Xing [14], Xing and Yu [15] and Zhang et al. [17,18] have proposed another kind of calculation model on the study of particle composites by improving the discrete element

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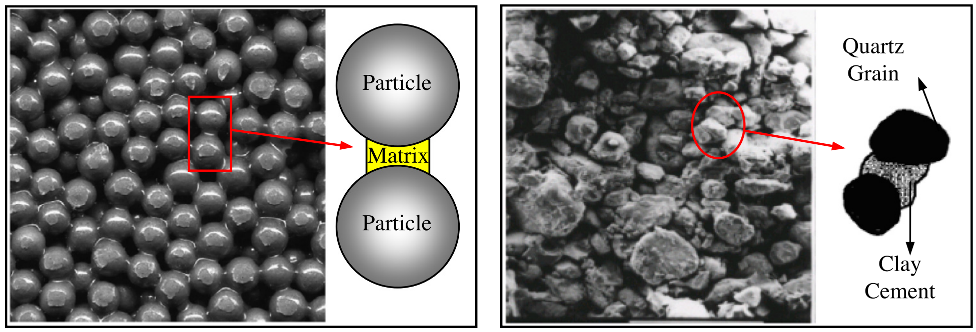


(a) The meso-structure of hollow-metal-balls composite (b) The meso-structure of sandstone

Fig. 1. Cement particle composites.

method, the beam-particle model. Through a large number of experiments, the macroscopic mechanical properties of particle composite can be gained. Based on the macroscopic mechanical properties, the strength, elastic and shear modulus of the beam and particle element was determined. Then the process from continuous deformation to failure of the composites under various loading condition can be simulated. Liu [9] developed a three-step element. According to the equilibrium conditions of the junction within paragraphs of unit element, the element stiffness matrix of the improved particle beam grid fault model of composite material is deduced. A mechanical model of a pair of spherical particles cemented by matrix, based on mesoscopic mechanics method, is established by Jack [5,6], Zhou and Wang [19] and Zhou [20,21]. The elastic, elastic–plastic and damage properties have been analyzed respectively. But the bending condition has not been considered on the pair of particles, and it can't simulate the macroscopic elastic–plastic and damage performance. In this paper, a combinational sphere element has been proposed by improving the spherical particles – cementing matrix model, based on mesoscopic mechanics model put forward by Jack and Zhou, with the whole spherical particle-cementing matrix model regarded as a composite element, and the element stiffness matrix of combinational sphere element has been set up. The method of analyzing the mechanical properties of the cement particle composites from micro to macro level has been proposed according to the method of beam lattice model. This theory combines the mesoscopic mechanics analysis method and the macro analysis method of beam lattice model from the model of Jack, and lays the foundation for the subsequent analysis of macroscopic fracture damage mechanics performance.

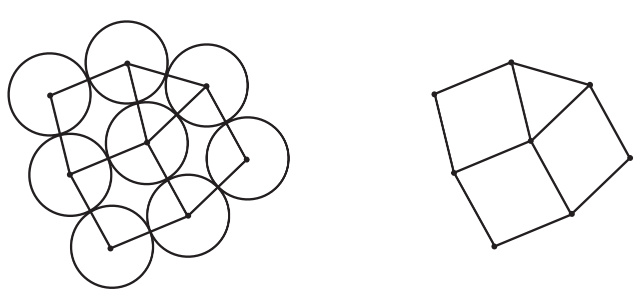
2. Model and assumptions

Cemented particulate composite is composed of particles connected with neck-like cementing matrix, shown in Fig. 2(a). If draw the centers of all the two adjacent cemented particles to the lines, the material is similar to a beam-lattice model as is shown in Fig. 2(b). According to the method of solving eam-lattice model, a pair of cemented particles is regarded as a combinational sphere element (CSE), similar to a beam element in the beam-lattice model. If the axial stiffness, tangential stiffness and bending stiffness of each CSE could be calculated, the stiffness matrix of CSE could be established. With the entire material model equivalent to the beam-lattice model, the mechanics performance of material could be analyzed from microstructure to macrostructure level.

In order to calculate the stiffness of one CSE from the perspective of mesoscopic, some assumptions should be put forward:

(1) Particles are regarded as elastic solid sphere which is homogeneous and have the same particle size.
(2) The neck-like cementing matrix is assumed as approximate cylinder with the same size, which its projection on x–z plane is circular. Two particles and the cements are coaxial.
(3) For particles, assuming that only the interface of particles and cement or its nearby area are deformable areas, while the other areas of particles are non deformable areas.
(4) Simplifying the deformable area of the particle as a elastic half space.

We set up a coordinate system on the symmetry plane of a CSE as shown in Fig. 3. Take x–z plane as the symmetry plane. y axis is collinear with the connection line of the two particle centers. The radius of the particle is R. The distance from a random point on the matrix to the axle line is represented by r. Draw a straight line through this point parallel to y axis, where intersected on the particles surface at point A. The thickness h of the matrix is a function of r. The thickness along y axis is h_0. The radius of matrix is r_c.



(a) Cemented particulate composite model (b) Equivalent beam-lattice model

Fig. 2. Equivalent beam-lattice model of cemented particulate composite.