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A modified rigid-body-spring concrete model for prediction of initial defects and aggregates distribution effect on behavior of concrete

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A R T I C L E I N F O

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A B S T R A C T

A modified rigid-body-spring concrete model was developed by considering the contact between elements after the failure of the springs. The discretization and definition of elements and springs were based on the three phases of concrete, including the coarse aggregates, the mortar and their interface. Based on the modified rigid-body-spring model, stress–strain curves and failure modes of concrete specimens with preset holes under uniaxial loads were simulated firstly, the simulated results were validated by those obtained from tests; and then, the effect of initial defects and distribution of coarse aggregates on mechanical behavior of concrete were investigated. It was found that with the increase of initial defects amount, the strength, elastic modulus and Poisson's ratio of concrete decreased nonlinearly; and, the statistical analysis revealed that variability of the mechanical properties of concrete was mainly affected by the random distribution of coarse aggregates.

1. Introduction

Concrete, as a highly heterogeneous material, has complicated fracture mechanisms, which is strongly affected by its meso-structure, such as aggregates, mortar, interface between aggregates and mortar and micro-cracks. However, study of these influences has been restricted mostly to experiments. Numerical tools are good options to gain some insight into the problems. Many attempts [1–5] have been made to investigate the fracture process of concrete by mechanical model at meso-level.

Rigid-body-springs model (RBSM), which is attractive due to its simplicity, freedom in mesh layout and generation, and providing a discrete representation of material disorder and failure [6] is being used to analyze concrete fracture at meso-level [3–5]. Nagai et al. [3,4] have discretized concrete as aggregates, mortar and interfaces between aggregates and mortar with different mechanical properties, and used the static relaxation method to analyze the failure of concrete. Even though neighbor connectivity was defined, there was no special emphasis on contact modeling, which considered the re-contact of an element with neighbor elements. Therefore, some complicated issues, such as nonlinearity in compression and crack closing or reopening in the model could not be considered, which influenced the simulated results to some extent [6].

Remarkably, concrete was always assumed as a three composites material without any initial defect in previous studies [1–5]. However, initial defects are thus inherent to concrete, which have great influence on the properties of concrete, notably its strength [7].

Besides, as we all know that aggregates (including fine and coarse) are the major constituent of concrete and they generally occupy 75–80% of the volume of concrete. Previous studies [8–10] have been carried out to investigate the effect of aggregate characteristics, such as mineralogy, shape, surface texture, size and proportions of aggregates, on the behavior of concrete. Yin et al. [11] found that coarse aggregates distribution has obvious influence on the crack path inside asphalt concrete. Ai et al. [12] investigated the influences of the distribution of crushed aggregates on the failure behavior and strength of heterogeneous polymer concrete. However, researches, especially statistical analysis, focusing on the effect of the random distribution of coarse aggregates on concrete behavior are still limited and its effect is not yet well established.

In this paper, a modified RBSM for concrete is presented, which allows the element relationship conversion from connection to contact to describe the re-contact of an element with neighbor elements; and, the dynamic relaxation procedure of discrete element method is adopted in the simulation to avoid the complex calculation of stiffness matrix in the RBSM. Then, by using the proposed mechanical model, the influence of initial defects (voids and cracks) and random distribution of coarse aggregates on mechanical properties of concrete is investigated in detail. The paper is organized as follows. In Section 2, the proposed model is presented. In Section 3, material properties and calculation parameters are discussed. Section 4 is devoted to the model validation,

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and Section 5 presents the predictions of the initial defects and aggregates random distribution effects on concrete mechanical characteristics. Finally, the major conclusions are summarized in Section 6.

2. Modified rigid-body-spring concrete model

To consider its meso-structure, concrete was assumed to be a three-phase composite material, with the coarse aggregates as the dispersed phase, the mortar as the continuous phase, and the zero-sized interfaces as the interfacial phase.

2.1. Mesh generation

The mortar in concrete was assumed to be a kind of idealistic material that is homogeneous and isotropic and discretized into an assemblage of rigid polygon elements using Voronoi diagram [13], which has been found to be beneficial at reducing the influence of the mesh arrangement on the cracking direction [6,14].

Let $P = \{P_1, P_2, \ldots, P_n\}$ be a set of points, which are called sites, on the two-dimensional Euclidean plane. The domain is partitioned by assigning every point in the domain to its nearest site. All those points assigned to form the Voronoi polygon $V(P_i)$:

$$V(P_i) = \{x : |P_i - x| \leqslant |P_j - x| \quad \forall j \neq i\} \tag{1}$$

Voronoi diagram and the Delaunay triangulation are both dual structures. The Delaunay triangulation is easier to be achieved mathematically, so it was executed first in this paper and then converted to the Voronoi diagram [13].

The diameter and number of coarse aggregates in concrete were calculated using Walraven's formula [15], from which the distribution probability of an aggregate with a certain diameter can be obtained according to Fuller's gradation [16]. The coarse aggregates were treated as regular polygons and distributed randomly into the section of a numerical specimen based on the "taking" and "placing" method, i.e., take the biggest aggregate from all the residual aggregates each time, and then place it in the section, meanwhile, avoid overlapping with the preexisting aggregates. After all the coarse aggregates were placed (Fig. 1a), the domain of mortar was discretized using the Voronoi diagram (Fig. 1b–d).

2.2. Connection of elements

After meshing, the aggregate and mortar elements were defined according to the phases of concrete. Each element had one rotational and two transitional degrees of freedom and was connected with its neighboring elements by zero-sized springs along their common boundary. The springs included normal spring in the normal direction and shear spring in the tangential direction, as shown in Fig. 2, in which x_i, y_i, θ_i and x_j, y_j, θ_j are the horizontal, vertical and rotational displacements of elements i and j, respectively;

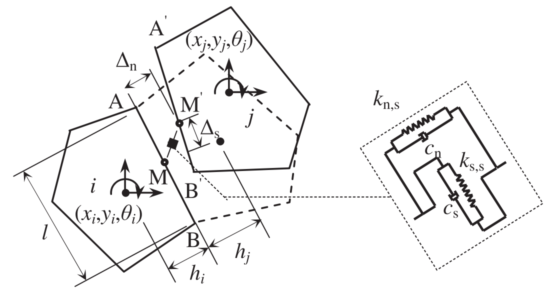

Fig. 2. Connection of elements.

$k_{n,s}$, $k_{s,s}$ and Δ_n, Δ_s are the stiffness and deformation of the normal and shear springs, respectively; l is the length of the common boundary of the two elements; and, h_i and h_j are the lengths of the perpendicular line from the center of gravity of elements i and j to the common boundary, respectively. Since the rotational displacement was very small in the static problems that are discussed in this paper, the rotational spring was not considered. There were also dampers with damping coefficients c_n and c_s respectively along the boundary, which were used to dissipate energy when solving static problems using the dynamic relaxation method.

Two kinds of spring groups were defined to take into account the mechanical properties of interface and mortar. The interfacial springs connected an aggregate and mortar elements, and the mortar springs connected two mortar elements (Fig. 3a). All mortar elements were assumed to be "rigid", and the deformations of mortar elements were represented by those of the mortar springs. The representative length of the mortar spring was $h_i + h_j$ (Fig. 3b). The aggregate elements were assumed to be rigid, not deformable, and would not fail. Therefore, if element i (or element j) was an aggregate element, h_i (or h_j) was set to be 0 to describe the totally rigid property of the aggregate element, and the representative length of the interfacial spring was then h_j (or h_i) (Fig. 3c). This measure is also adopted in the following sections, where the value of h_i or h_j needs to be used.

2.3. Constitutive model of springs

The stiffness of the mortar springs can be calculated based on the continuous material theory and the plane stress condition:

$$\begin{cases} k_{n,s} = \frac{E_e}{1-\nu_e^2} \cdot \frac{l}{h_i + h_j} \\ k_{s,s} = \frac{E_e}{2(1+\nu_e)} \cdot \frac{l}{h_i + h_j} \end{cases} \tag{2}$$

where $k_{n,s}$ and $k_{s,s}$ are the stiffness of the normal and shear springs, respectively, and E_e and ν_e are the elastic modulus and Poisson's ratio of the mortar at the mesoscopic level, respectively.

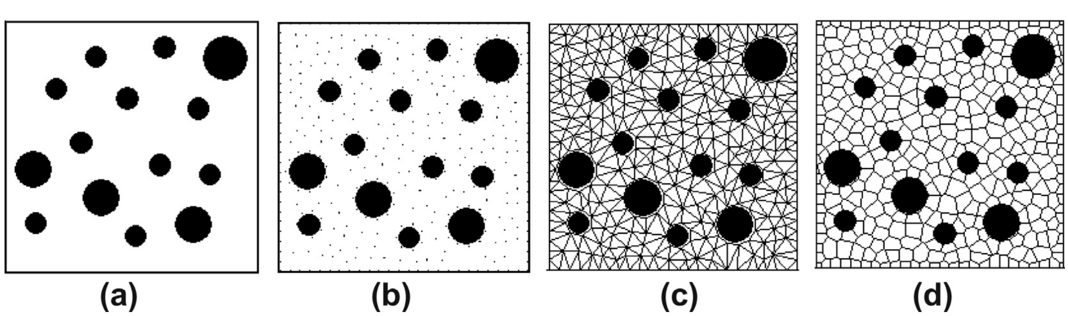

Fig. 1. Discretization of concrete material: (a) random distribution of coarse aggregates; (b) random distribution of Voronoi sites; (c) delaunay triangulation; and (d) voronoi diagram.