Characterization of damage-healing-plasticity-breakage in multi-scale DEM-FEM modeling of granular material

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Abstract

The present paper aims to quantitatively characterize material failure at each of integration points of the FEM mesh generated for macroscopic continuum, to which a meso-structural RVE (representative volume element) is attributed, in terms of meso-structural quantities and meso-mechanical variables obtained by the numerical simulation of the RVE using crushable discrete element method (CDEM).

Granular material modeled as porous continuum at the macro-scale is highly heterogeneous and discontinuous medium with complex meso-structure at the grain scale. Multi-scale methods have been proposed to bridge its two distinct scales ranging from particle scale to continuum scale. As the macroscopic failure phenomena in granular structures are concerned significant meso-structural evolution in the granular material develops. The irreversible energy dissipation of effective continuum, such as damage-plasticity energy dissipation, is to be taken into account in the simulation and is required to characterize.

To achieve this target a second-order computational homogenization method for granular material with corresponding global-local mixed FEM - CDEM nested analysis scheme has been presented [1-5]. In the method the gradient Cosserat continuum model and the classical Cosserat continuum model are adopted at both the macro-scale (the overall structural scale) and the RVE scale (the local meso-structural material scale) respectively. A RVE attributed to a sample point of the mixed FE mesh is re-modeled as a discrete particle assembly representing discrete meso-structure of the RVE evolving with the load history, and is resolved by using the proposed crushable discrete element method (CDEM) [5,6]. With the DEM simulation and the proposed Voronoi cell model mesoscopic mechanisms of the macroscopic damage and plasticity of granular materials are detected [7,8].

The incremental form of the stress-strain relationship for the effective Cosserat continuum at the sampling point, to which the RVE is attributed, is formulated. The anisotropic elastic moduli tensors and incremental plastic state variables associated with evolving meso-structures for the effective Cosserat continuum of the RVE can be obtained. The meso-mechanically informed macroscopic damage factor tensor for anisotropic damaged Cosserat continuum of the RVE is fully determined in terms of the elastic moduli tensors associated with given undamaged (initial) and damaged (current) meso-structures of the RVE, with no need specifying the macroscopic phenomenological damage model.

Granular material is intrinsically a discrete and discontinuous medium, consisting of particles and voids. The particle breakage, significant development of relative dissipative sliding and rolling frictions among particles in contacts followed by loss of contacts, resulting in the reduction of macroscopic elastic stiffness and strength, are described by the material damage and plasticity in macroscopic continuum. By contraries, the evolution of the particle collocation may also result in the recovery of the elastic stiffness of the effective continuum of the RVE, i.e. the material healing. A thermodynamic framework is presented to distinguish incremental anisotropic damage and healing and to define the damage, healing and net damage variables of the effective anisotropic Cosserat continuum of RVE for granular materials. The coupled damage-healing and plastic process in anisotropic Cosserat continuum for granular materials is characterized in terms of densities of thermodynamic dissipations

that make effects of the damage-healing and the plastic component processes on the material failure quantitatively comparable.

The particle breakage, as a material failure phenomenon occurring in the discrete system, does not explicitly appear in the strain-stress constitutive relationship of the effective continuum. Instead, its effects on the material failure in the effective continuum of granular material is embodied via that (1) the further degradation of elastic stiffness in addition to the reduction of elastic stiffness due to loss of contacts, re-orientation of contacts among particles in contact and concomitant volumetirc dilatation of the RVE, and (2) the further dissipative sliding and rolling movements among particles in contact as compared with the dissipative movements among particles in contact without consideration of particle breakage. Namely, the effects of particle breakage on the failure of macroscopic continuum are merged into the thermodynamic dissipations attributed to both the net elastic damage combining the damage and the healing and the plasticity, in addition to those dissipations with no particle breakage taken into account in the simulation.

Keywords: granular materials, computational homogenization method, FEM-DEM, RVE, characterization, damage-healing-plasticity, particle breakage,

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