CONTINUOUS/DISCRETE COMPUTATIONAL MODELING FOR THE MULTISCALE SIMULATION OF CONCRETE FAILURE

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ABSTRACT

The scope of present work is to investigate and develop accurate and computationally efficient techniques to simulate failure behavior of quasi-brittle materials like concrete. More specifically, a new enhanced continuum model for concrete failure modeling has been developed and integrated into a multiscale simulation framework, which can be used to save computation time by coupling models targeting different length scales, e.g. the discrete model LDPM for the meso-scale simulation and the new continuous model for the macro-scale simulation.

First, a review of discrete and continuous models for simulating concrete failure is given. Three categories of discrete models are commonly found in the literature: lattice models, rigid body spring models and discrete particle models. Discrete models incorporate details on a microscopic level in order to explicitly account for material internal structures, e.g. heterogeneity, multiple length scales. In this sense, they are considered to be based on physical interpretation of the phenomenon at the scale of interest. However, due to their small discretization size and more detailed microscopic description, discrete models usually come with a huge number of degrees of freedom and are computationally demanding.

On the other hand, it is widely acknowledged that the classical continuum theory is not suitable for modeling material failures like strain softening, localization or fracture. The reason is well understood: when strain softening happens, the boundary value problem becomes ill-posed and the so-called mesh-dependency is observed; as the element size becomes smaller with mesh refinement, the energy dissipation tends to be zero, which is physically untrue and contradicts the experimental observations.

However, people are still working hard to develop enhanced models following the path of continuous approach, because continuous models are more computer friendly in terms of mesh generation, implementation and most importantly computational cost. Four continuous approaches including the non-local model, the strain gradient theory, the Cosserat theory and the rate-dependent model (only for dy-

namic loading conditions), have been proposed and attempted to solve the strain softening issue. Unfortunately, such models currently available are generally not accurate enough to predict concrete failure behaviors, plus some are quite cumbersome to implement, e.g. in non-local models stress update at a single point involves an integral convolution of strains over its surrounding region.

With the ambition to develop the state-of-the-art continuum model, the theoretical work proceeds with help from the newly developed model called Lattice Discrete Particle Model (LDPM), which, to the author's knowledge, is believed to be the most successful model to capture concrete failure mechanisms. Development of the new continuous approach includes three parts: 1) the continuum theory - High Order Micropolar Theory; 2) a constitutive model based on microplane concept - High Order Micropolar Microplane Theory; 3) finite element formulation for high order micropolar theory - High Order Micropolar Tetrahedral Element. Numerical examples have shown the capacity of present model to capture tensile fracturing behavior; other failure mechanisms will be explored in the future.

In current continuum theory, compared to the classical one, several enrichments are introduced: asymmetric strain/stress, high order strain/stress, rotation DOF, curvature/couple stress (moment per area). These enrichments, according to other theoretical work and experimental observations, have their physical basis. Because of such enrichments, the continuum model provides a new perspective to investigate behaviors of microstructured materials, not limited to concrete. Also, the new theory introduces a variable called material characteristic length, which not only represents the microstructure, but also provides a capacity to model the strengthening effect in micro-scales.

In the new constitutive model, weak locations inside the material is represented by the concept of microplane, which, by analogy, is the counterpart to the interacting facet between adjacent cells (e.g. element, particle) in discrete models. This new microplane model, compared to the classical versions, has accounted for material internal structure and heterogeneity by the characteristic length variable and orientations of microplanes, and thus is more suitable for modeling granular material like concrete.

Due to the enrichments introduced in the continuum theory, the new finite element has a versatile ability to model various continuum theories, including classical elasticity, Cosserat (micropolar) elasticity and strain gradient elasticity, which gives it a wide application potential. This element also shows excellent accuracy and convergence rate in the beam bending simulation.

Parallel to aforementioned work, a concurrent multiscale method called Bridging Scale Method (BSM) is introduced and implemented into the current framework to couple the meso-scale discrete model (LDPM) and the new macro-scale continuum model. In such simulation, the physical domain of interest (place where damage and failure most likely happen) which is usually a small portion of the problem domain, is modeled by the fine model while the rest is modeled by the coarse model, thus computational cost can be saved.

BSM includes a non-reflecting boundary condition which can eliminate the wave reflection issue at the fine-coarse scale interface that is commonly observed in direct multiscale simulations. However, the formulation of this boundary condition requires a periodic mesh structure in the fine scale, which is not the case for LDPM for obvious reasons. To solve this issue, a so-called periodic transition zone (PTZ) around the fine scale (LDPM) is proposed and the non-reflecting boundary condition based on such periodic transition zone is presented.

The multiscale computational framework developed in current work successfully combines the advantages of discrete and continuous models to maximize the balance between accuracy and computational cost. This framework has a promising application scope of modeling failures of concrete structures from small specimens or structural members to large ones like dams.