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Modeling of phase interfaces during precritical crack growth in concrete

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ABSTRACT: This project involves the combined use of lattice-type models, x-ray tomography, and imaging techniques to investigate fundamental aspects of fracture of micro-concrete specimens. Tomographic images of the unloaded specimens provide the initial configuration of three-dimensional lattice-type models, which are based on a three-phase representation of the material meso-structure: hardened cement paste matrix, aggregate inclusions, and matrix-inclusion interface. In this paper, the lattice model is used to study debonding of a spherical inclusion under far-field uniform tension. It is found that the matrix-inclusion interface is toughened by local heterogeneity in the form of random variations of interface strength. This finding is relevant to our ongoing modeling of specimens with spherical inclusions, where a near one-to-one correspondence has been achieved between the meso-structures of the physical and numerical specimens.

1 INTRODUCTION

Fracture processes in concrete typically involve the nucleation and/or growth of multiple defects, in contrast to conventional engineering fracture mechanics in which crack growth extends from a single, dominant crack. The debonding of aggregate inclusions at sub-critical load levels can be viewed as a source of defects, typically distributed throughout the material. The interaction and potential coalescence of these multiple cracks, as well as the interactions of this crack system with the various phase fractions, affect the morphology of the fracture surface and composite toughness. To better understand aggregate debonding and its potential effects on fracture development, the authors are combining 3D lattice models of fracture with high-resolution tomographic imaging of micro-concrete specimens under loading (Landis & Bolander 2009). This paper describes recent developments of the lattice modeling approach and its application to investigating precritical cracking in concrete materials.

2 METHODOLOGY

The development of lattice models has been motivated, at least in part, by the need to model inherently discontinuous phenomena that affect behavior at one or more length scales of a material. Along with the classical approaches described in Herrmann & Roux (1990), a variety of lattice-type models have been developed to study fracture of disordered materials, including concrete (Schlangen & van Mier 1992, Vervuurt 1997, Cusatis et al. 2003). The approach considered here is based on the rigid-body-spring concept of Kawai (Bolander & Saito 1998).

As is common for lattice models, the material domain is discretized as a collection of two-node elements (Fig. 1). The use of semi-irregular node positioning is preferred for several compelling reasons, some of which become apparent later in this paper. The dual Delaunay-Voronoi tessellations define element connectivity and are prominent in the assignment of element properties. Each lattice element consists of a zero-size spring set that is connected to nodes i and j via rigid-arm constraints (Fig. 1c); the spring set is located at the centroid of the Voronoi facet common to nodes *i* and *j*. The spring stiffnesses are set according to: $k_n = k_s = k_t = A_{ij}E/h_{ij}$, where A_{ij} is the area of the Voronoi facet, E is the elastic modulus of the material, and h_{ij} is the element length.

From the meso-scale model of concrete in Figure 2, two types of elements are noticeable, i.e., elements that represent: 1) one of the principle phases (matrix and aggregate), which are assumed to be homogeneous; and 2) the interfaces between principle phases. Whereas the size, geometry and orientation of elements representing the principle phases are randomly set, and have no relation to material structure, elements representing phase interfaces are oriented normal to the interface. Element length is adjustable and can approximate the small interface thicknesses of cement composites (Scrivener 1989). The matching of element orientation and size to phase interfaces reduces mesh bias and facilitates the realistic modeling of those material features.

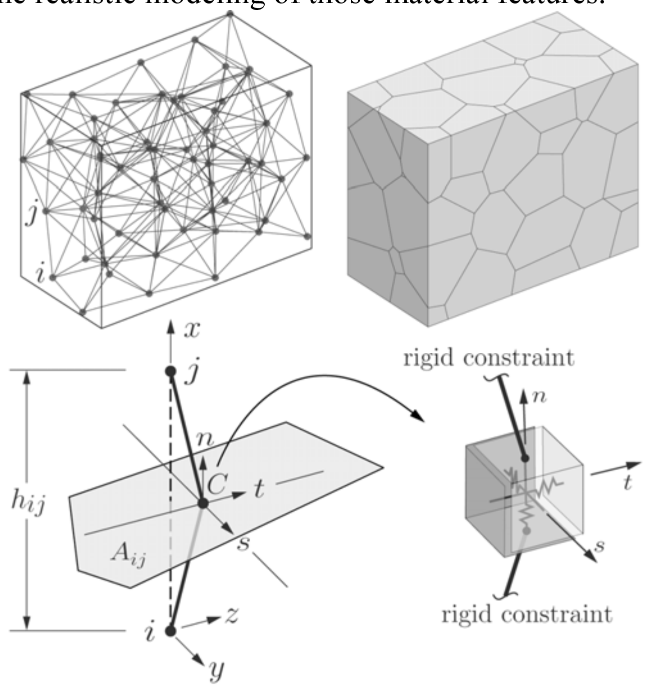

Figure 1. Domain discretization: (a) Delaunay tessellation of nodal point set; (b) dual Voronoi tessellation and (c) typical lattice element ij extracted from the network.

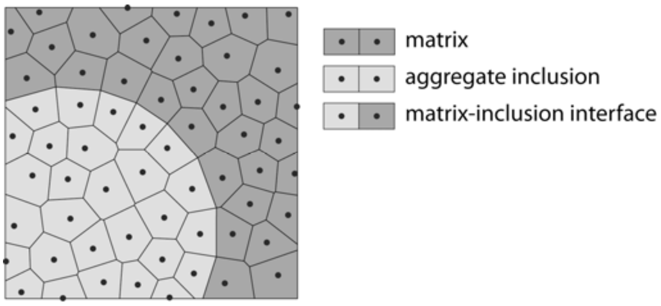

Figure 2. Assignment of lattice element properties according to phase composition of the concrete mesoscale.

Loading produces deformations within the spring set of each affected element. The corresponding spring forces are converted to measures of stress in one of two ways, depending on the element type:

- For elements representing one of the principle phases, the resultant of the spring set forces is divided by the projected area (in the direction of tension) of the associated Voronoi facet. This stress forms the basis on an energy conserving, grid insensitive modeling of fracture within the randomly discretized homogenous phases (Berton & Bolander 2006).
- For elements representing phase interfaces, axial spring forces corresponding to the *n-s-t* directions (Fig. 1c) are divided by the area of the associated Voronoi facet, A_{ij}. The resulting values can be represented as a point *P* in stress space as shown in Figure 3, in which *c* and ψ are parameters defining the assumed Mohr-Coulomb fracture surface; f_t is tensile strength for loading normal to the interface. Criticality of an interface element is calculated as the ratio $\rho = OP/OP_O$ where OP_O is the point at which OP intersects the failure surface. For each computational cycle, the most critical element with $\rho > 1$ undergoes fracture (Yip et al. 2006).

Additional details of the element formulations, fracture modeling, and solution procedure are presented elsewhere (Bolander & Saito 1998, Yip et al. 2006).

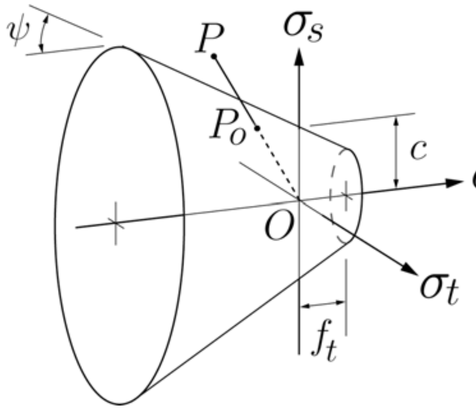

Figure 3. Mohr-Coulomb criterion with tension cutoff.

3 INTERFACE FRACTURE SIMULATION

Consider the basic case in which a spherical aggregate is under uniform (far-field) tension. The uniform tension condition is implemented by making the aggregate diameter *d* small relative to the domain size of 100*d*, as shown in Figure 4. The large size difference is not essential, but it illustrates the versatility of the meshing procedure. The aggregate inclusion is assumed to be stiff relative to the matrix at a modular ratio of $E_a/E_m = 10$, where subscripts *a* and *m* denote the aggregate and matrix, respectively. Interface thickness has been set to $t_i = d/50$ for these simulations. Element breaking is brittle and governed by a Mohr-Coulomb surface with a tension cut-off (Fig. 3). Two types of (weak) interface were considered: one of uniform strength and the other of varying strength. For the latter case, the strength of interface elements was normally distributed about a mean value μ, which is equal to the strength assumed for the uniform case. A large coefficient of variation (of 50%) was used for the assignment of element strengths for the non-uniform case (Fig. 5a). Spatial dependency of these strength variations, which has not been introduced in these calculations, is necessary for increasing the physical basis and reducing mesh size bias on the results.

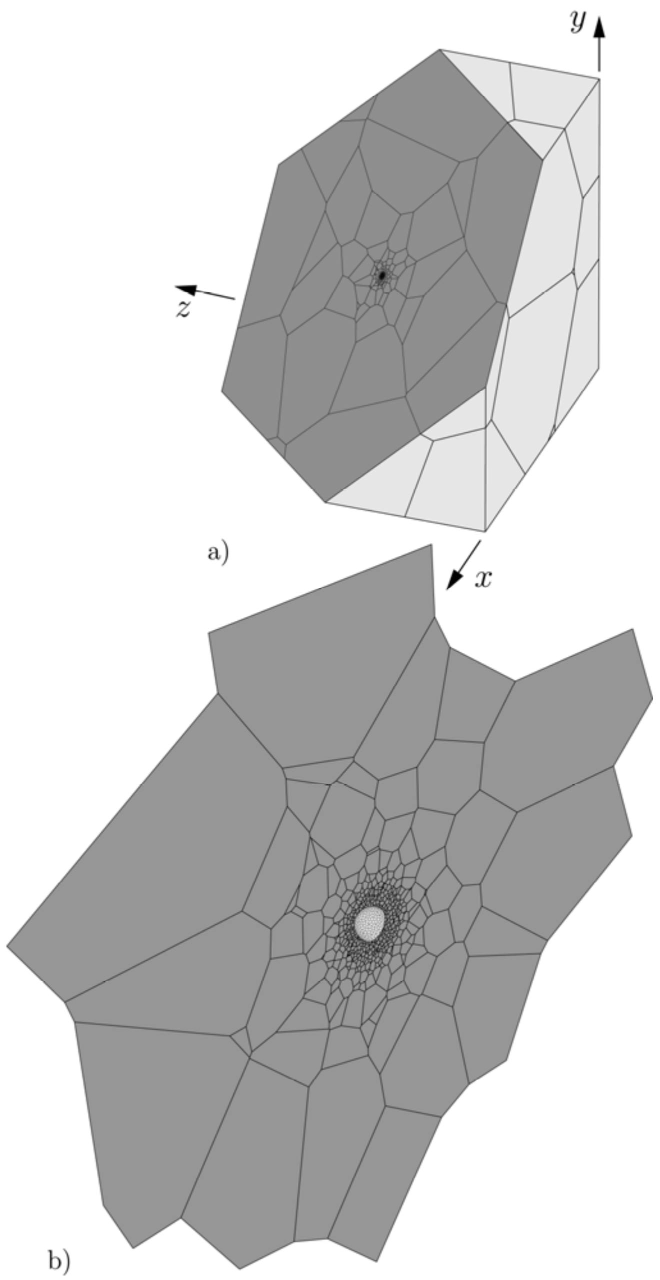

Figure 4. (a) Sectional view of spherical inclusion of diameter a embedded within a cube of size 100a and (b) enlarged view of the sphere discretization (Landis & Bolander 2009).

With increasing loading, interface elements most directly aligned with the loading direction are the first to break (Fig. 5b). Positioning of the corresponding fracture events in Mohr-Coulomb stress space signifies element breaking under nearly pure tension. Due to the sudden removal (brittle fracture) of the first of these elements, neighboring elements undergo fracture even without increasing the load point displacement. This unstable crack propagation, characterized by fracture events drifting from the fracture surface, is assisted by the lack of artificial heterogeneity in the interface modeling. By appropriately advancing/retracting load-point displacements, snap-back is avoided and the fracture events can be held to the fracture surface. However, sequencing of events is not altered and the depiction of events (in Fig. 5c) is arguably more descriptive of model behavior. As aggregate debonding continues, it is increasingly a tension-shear phenomenon. The fracture process eventually stabilizes, in the sense that small increases in load point displacement do not produce bursts of element breakages.

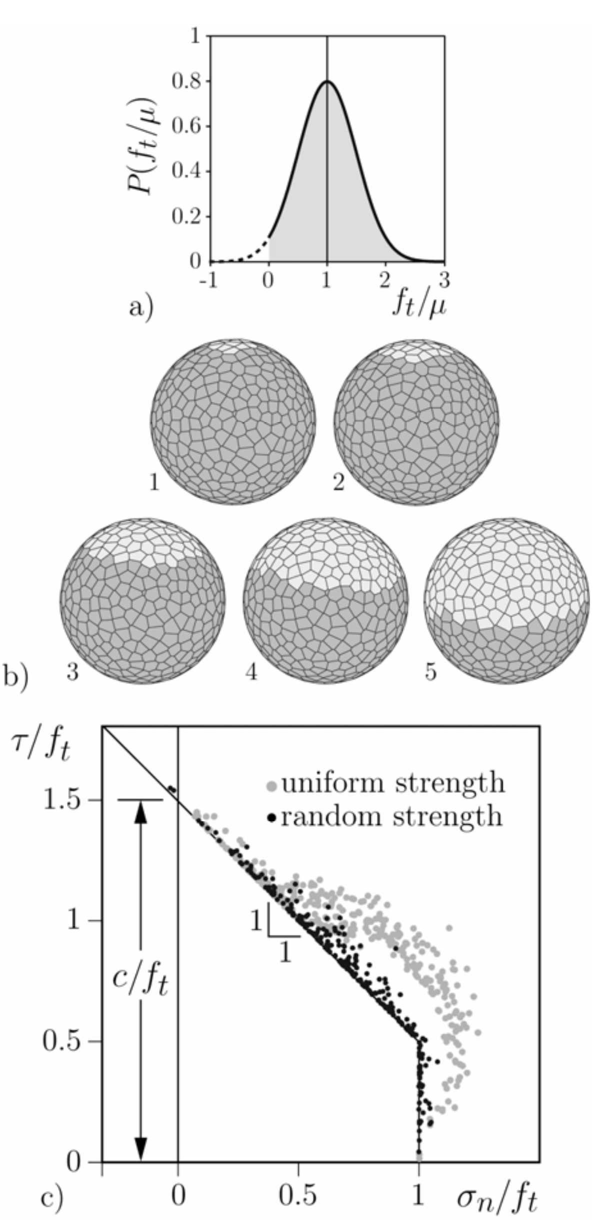

Figure 5. (a) Probabilistic assignment of interface element strength; (b) debonding of a spherical inclusion within a vertical tension field; and (c) distribution of fracture events about the fracture surface.

The same tensile loading simulation is repeated for the second case, in which interface strength is randomly distributed. This statistical form of heterogeneity results in more stable fracture of the interface, as evidenced by movement of the bulk of the fracture events toward the fracture surface (Fig. 5c). From another perspective, load-point displacements can be gradually increased without the dramatic snap-back behavior seen from the uniform interface model. Similar forms of toughening have been produced in tensile fracture simulations of cement composites (Schlangen & van Mier 1992).

4 SIMULATION OF MICRO-CONCRETE FRACTURE: CURRENT EFFORTS

Current efforts include the combined analysis and experimental study of micro-concrete tested in a split-cylinder configuration. Initial geometries of the 3D lattice models are based on tomographic images of the unloaded micro-concrete specimens (Fig. 6). As previously described, the material discretization is based on a three-phase representation of its meso-structure: hardened cement paste matrix, aggregate inclusions, and matrix-inclusion interface. Spherical glass beads are used as the inclusion phase. The Voronoi polygons appearing inside the cylindrical domain (Fig. 6b) correspond to the interface between the matrix and glass bead inclusions. Efforts are currently being made toward reducing computational expense associated with these simulations to enable parametric study.

5 CONCLUSION

Lattice models were used to simulate fracture of the matrix-inclusion interface, which is one form of pre-critical cracking in concrete materials. For a spherical inclusion embedded within a matrix under uniform (far-field) tension, interface fracture transitions from a mode I to mixed-mode process. Interface fracture is markedly brittle when considering brittle interface elements of uniform strength. A cascading effect is observed, in which fracture events gradually drift from the fracture surface (even when holding the load-point displacements constant). The fracture process is significantly toughened through statistical variation of interface strength. Although the breaking of individual elements is brittle, the breaking process is quasi-stable in that load-point displacements can be progressively increased without significant snap-back behavior. Our ongoing work involves the study of such interface toughening and its effects on fracture of micro-concrete specimens.

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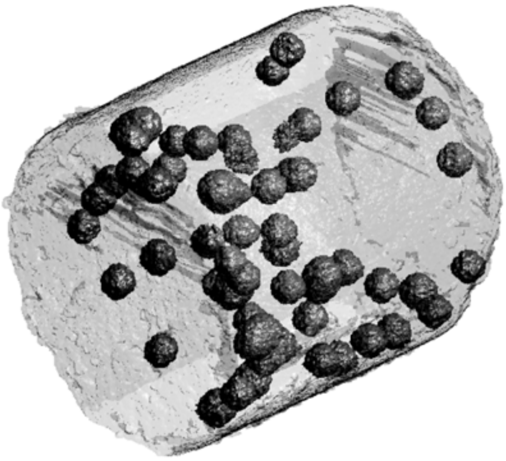
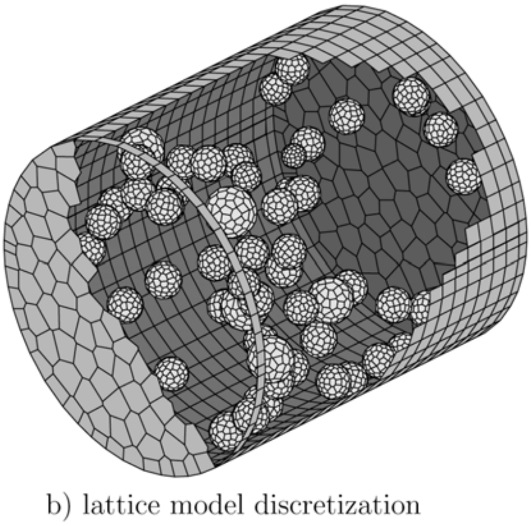


a) segmented tomographic image



b) lattice model discretization

Figure 6. Split-cylinder testing of glass bead-mortar composites: Mesh correspondence to material structure.