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Simulation of Concrete Fracture Using a Coupled Lattice-Boundary Element Model

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INTRODUCTION: This research employs a lattice-type random particle model [1] coupled to either finite or boundary elements for simulating fracture processes in concrete. Consider the compact tension test specimen and boundary conditions shown in Fig. 1. A lattice model is used in the central region where fracture is likely to occur and bilinear four-node elements (Fig. 1a) or quadratic boundary elements (Fig. 1b) are used to model the surrounding elastic region. For either case, compatability is insured at the lattice/elastic region interface by augmenting the standard equilibrium equations with an appropriate set of constraint equations.

The lattice used here is an assembly of beam elements whose properties are chosen to reflect the heterogeneity of the material. That is, concrete within the lattice region is modeled by three components: 1) aggregate, 2) matrix, and 3) aggregate-matrix interface. Loading is applied incrementally and at each load stage the effective stress acting in each lattice element is computed. In previous works, the lattice element with the highest effective stress is removed from the lattice if that stress level violates its specified fracture strength. Here, we allow elements to experience multiple *fracture events* in an effort to better model the 3-D nature of the problem. Computations proceed in this manner allowing one fracture event at a time.

PROCESS ZONE SIZE AND ENERGY DISTRIBUTION: Figs. 2 and 3 show a load displacement response and final crack pattern obtained from a similar, but slightly different, compact tension test specimen [2]. The thickness of the lines used to plot the lattice reflects the number of fracture events experienced by each beam element. Thus, regions appear lighter with increasing damage. Disorder in the material causes the fracture process to have a width extending over many lattice elements. The fracture process widens out from the notch tip, reaches a maximum width of roughly $4d_a$ over the central portion of the ligament, and then becomes quite narrow under the influences of higher strain gradient when approaching the compression face of the specimen. Highly damaged elements occur within a width of roughly $1d_a$ or less.

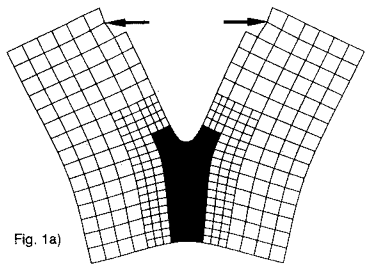

Fig. 1a)

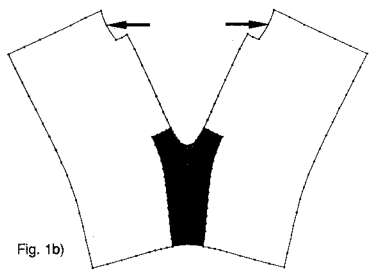

Fig. 1b)

The energy consumed by a fracturing element can be computed from the changes in load-point reactions at the imposed load-point displacements. By storing and later processing such information, the extent of the active fracture process zone (FPZ) between any two load-point displacements can be visualized. Figs. 4a-d show contour plots of the energy consumed for the displacement intervals indicated in Fig. 2. Fig. 4e shows the distribution of energy consumed during the entire loading history. These contours represent log($energy$) (i.e. consecutive contour energies differ by a factor of ten) with darker levels indicating higher energies. It is clear that most of the energy is being consumed by the formation of the dominant crack; peripheral microcracking consumes only a few percent of total energy. These findings are supported by the work of other researchers [3, 4]. Such estimates of energy consumption are not just of academic interest, but are an important characterization of material response and useful in the engineering of new high-performance cement-based materials [5].

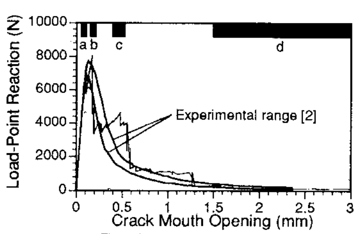

Fig. 2 Load-displacement response

REDUCING COMPUTATION TIME: A previous study [6] investigated the computational effectiveness of using boundary elements relative to using finite elements for the models shown in Fig. 1. Virtually identical linear and fracture responses are obtained. When using boundary elements the number of degrees of freedom was slightly reduced; however, because the boundary element stiffness matrices are fully populated, the mean half-band width of the global stiffness matrix roughly doubled and computational time increased accordingly.

This research points out that much computation can be saved by modeling only the active fracture region and its nearby vicinity with the lattice mesh. That is, as the FPZ proceeds along the ligament length, we update the lattice region accordingly and remesh the boundary element region (Fig. 5). There are some difficulties in determining: 1) a proper size (possibly variable) for the lattice region and 2) when to update the lattice/remesh the boundary element region. The lattice must cover the region where high energy events are occuring; the effects of neglecting some of the extremely low energy events occuring along the outer fringes of the process zone are being investigated. Also, the lattice region should not be advanced beyond any existing element 'bridges' across the main crack (i.e. there must be a percolation cluster between the pre-notch tip and a point a certain distance into the lattice region.) Some bridges remain intact well behind the fracture front and store up considerable energy in flexure before ultimately fracturing (as evident in Figs. 4b and 4c).

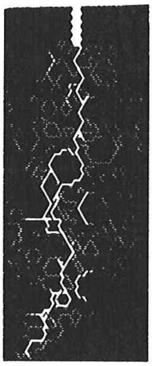

Fig. 3 Cracking pattern

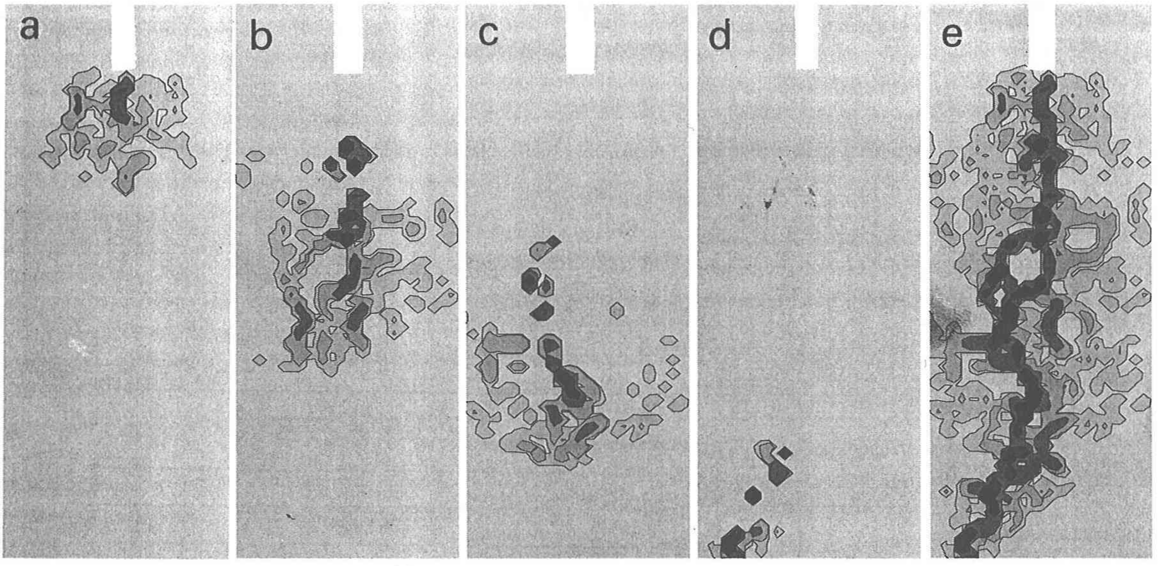

Fig. 4 Incremental energy consumptions

CONCLUDING REMARKS: Lattice models have been applied to simulating fracture in a variety of materials and give useful information concerning FPZ size and the distribution of energy with its limits. However, one of the greatest drawbacks of using lattice models is the tremendous amount of compution required to repeatedly solve the large system equations. The technique of coupling the lattice region with boundary elements appears to be effective in reducing the computational expense. This will permit tracing single, or perhaps multiple, dominant cracks through larger structures. Using coupled lattice-boundary element models becomes even more attractive when extending the lattice model to truly three-dimensional simulations.

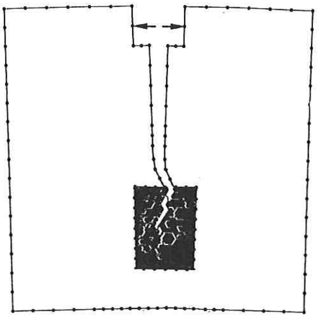

Fig. 5 Coupled lattice-boundary element model with adaptive remeshing capability

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