Effects of Strain Gradient on Process Zone Formation in Cement-Based Composites

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INTRODUCTION

Due to their heterogeneous nature, concrete and similar cement-based materials exhibit complex nonlinear behavior during loading, even under uniaxial tension. Conventional finite element models for concrete cracking in tension avoid the details of the fracture process, but rather use macroscopic notions of either crack stress vs. opening (discrete models) or stress vs. strain (continuum models) to describe fracture.

In recent years, there has been growing interest in modeling the details of the fracture process zone, including its size and the distribution of strain, damage, and energy consumption within its limits. Research in this direction is helping to create more efficient cement-based materials and also overcome certain deficiencies with the conventional analysis models.

Lattice models have come from the field of theoretical physics and have recently been applied to simulating fracture in a variety of materials. This research employs the lattice-type random particle model given by Schlangen and van Mier [1] for simulating fracture processes in concrete. The special aspect of our work is the computation and graphic portrayal of fracture energy distributions obtained with the model.

PROBLEM IDEALIZATION AND SOLUTION PROCEDURE

The idealization of the test specimen and boundary conditions [2] is shown in Fig. 1. The lattice model is used in the central region where fracture is likely to occur and bilinear four-node elements are used to model the surrounding elastic region. Compatability is insured at the lattice/elastic region interface by augmenting the standard equilibrium equations with an appropriate set of constraint equations.

Concrete within the lattice region is modeled by three components: 1) aggregate, 2) matrix, and 3) aggregate-matrix interface. As the distribution of these components strongly affects the fracture process, care was taken to generate a realistic distribution for analysis. The distributions shown in Table 1 were first generated in three dimensions, afterwhich a section was taken for 2-D analysis. One such section, excluding particles of diameter smaller than the lattice element length, is shown alongside the model in Fig. 1. Lattice elements are assigned material properties according to their location relative to the three material components.

Loading is applied incrementally and at each load stage the effective stress acting in each lattice element is computed. The lattice element with the highest effective stress is removed from the lattice if that stress level violates its specified fracture strength. The calculations proceed in this manner removing one lattice element at a time.

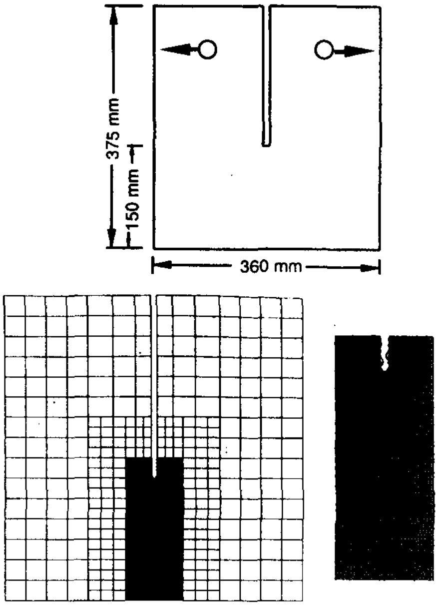

Figure 1 Specimen and analysis model

ANALYSIS RESULTS

Fig. 2 shows the extent of fracture in the model at intermediate and near-final stages in the loading history; more complete results are given in another paper in this proceedings [3]. Disorder in the material causes the fracture process to have a width extending over several lattice elements.

The energy released by each fractured lattice element has been computed and then transformed into a rectangular array for plotting purposes. This information is shown in Fig. 3. Energy profiles taken near the midsection of the ligament and just below the notch tip are shown in Fig. 4a and b, respectively. Energy is left in unspecified units since the fracture criterion used here has not yet been scaled to reflect global stress levels. Figs. 2 through 4 tend to show process zone width varies, beginning as a narrow region near the notch tip and then widening out to a near constant size over the mid-portion of the ligament.

The bold line in Fig. 5 indicates the average energy profile computed from four sections evenly spaced over the mid-portion of the ligament (the thin lines show the profiles at these four sections.) Since the fracture path meanders along the ligament length, these energy profiles have all been justified about the dominant crack centerline at their respective location. Non-symmetry of the profiles about the crack 'centerline' is due in part to insufficient width of our lattice region. It is clear that a large portion of energy is being consumed by the formation of the dominant crack, while peripheral microcracking consumes only a limited amount of energy. These findings are supported by the work of other researchers [4, 5]. Finally, 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 [6].

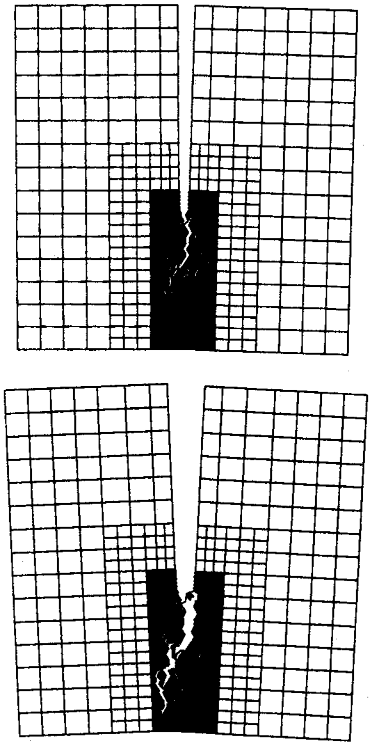

Figure 2 Fracture simulation

aggregate diameter (mm)	Unit weight (kgf/m^3)
0 - 3	608
3 - 8	635
8 - 16	676

Table 1 - Aggregate distribution [2]

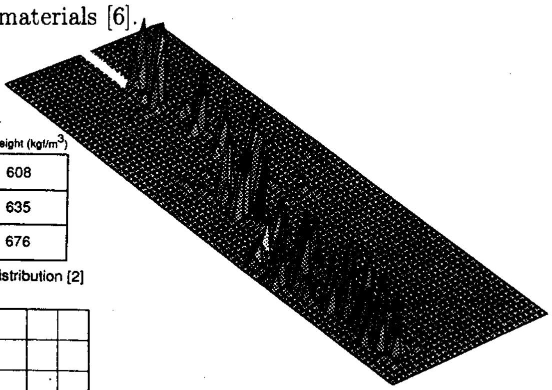

Figure 3 Energy distribution

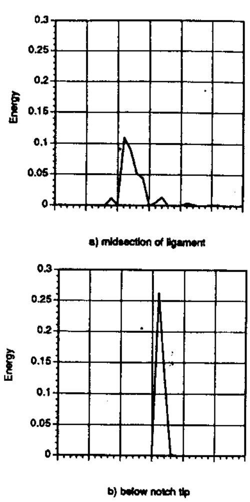

Figure 4 Energy profiles

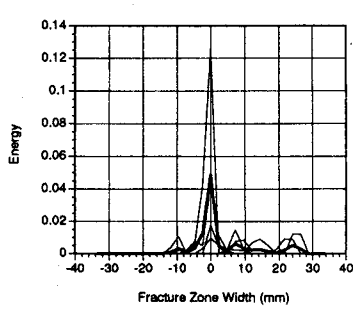

Figure 5 Average energy profile

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