FRACTURE ANALYSIS OF CONCRETE MICROSTRUCTURE USING INTERFACE ELEMENTS

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Abstract: A 14×14cm concrete specimen is represented in 2-D by 16 irregular aggregate pieces surrounded by mortar. The possibility of cracking is introduced by inserting interface elements along all aggregate-mortar and mortar-mortar element boundaries. The continuum elements remain elastic, while interface behavior is given by a fracture energy-based work-softening plastic model with a coupled normal-shear failure surface. Preliminary numerical results are presented of the specimen subjected to pure tension, showing quite reasonable crack patterns and overall average response.

Resumen: Una muestra de hormigón de 14×14cm se representa en 2-D mediante 16 áridos irregulares rodeados por mortero.La posibilidad de fisuración se introduce insertando elementos de interfase a lo largo de todos los contactos entre elementos triangulares, de tipo árido-mortero y mortero-mortero. Los elementos de medio continuo se suponen elásticos, mientras que para la interfase se supone un modelo plástico con superficie de rotura en función de la tensión normal y tangencial y reblandecimiento por trabajo de fractura. Se presentan algunos resultados numéricos preliminares de la muestra sometida a tracción pura, en los que se obtienen esquemas de fisuración y respuestas globales bastante razonables.

1 INTRODUCTION

Complex aspects of fracture of composite materials require explicit consideration of their components and microstructure. Some studies of this kind, using the FEM, can be found in the literature of concrete [1, 2, 3]. In this paper, on-going research at ETSECCPB-UPC along this line is summarized, and some preliminary results are presented. The microstructural discretization used is borrowed from [2], with a total of 16 pieces of irregular aggregate, arranged in approximately 4 × 4 and surrounded by the matrix (Fig. 1). Aggregates and mortar are discretized with triangular finite elements with linear elastic behavior. The FE mesh also includes zero-thickness interface elements with double nodes, along all mortar-mortar and mortar-aggregate inter-element boundaries. A similar mesh was already used in [4], for the study of sulphide-induced differential expansions in the concrete of two gravity dams. The use of interface elements for fracture analysis was proposed in [5] and developed later in [6, 7, 8, 9]. The model adopted for interface behavior is described in the following section. It incorporates the possibility of crack opening if certain levels of shear/normal stresses are reached. With interfaces inserted all over the mesh, cracks can open, close and develop specific paths depending on geometry, size, loading conditions, etc. with the only restriction that they must follow preestablished element boundaries. The mesh used contains 698 triangles, 630 interface elements and 1,400 nodes. Calculations have been run with the FE code DRAC and represented with the post-processor DRAC-VIU, both fully in-house developed at ETSECCPB-UPC [10].

2 INTERFACE CONSTITUTIVE MODEL

Interface behavior is formulated in terms of the normal and shear components of stresses (tractions) on the interface plane, $\boldsymbol{\sigma}=[\sigma_N, \sigma_T]^t$, and corresponding relative displacements $\mathbf{u}=[u_N, u_T]^t$ (^{t}=transposed). The model is analogous to that used for each potential crack plane in the multicrack model [11, 12, 13, 14, 15]. It conforms to work-softening elasto-plasticity, where plastic relative displacements can be identified with crack openings. The main features of the plastic model are represented in Fig. 2.

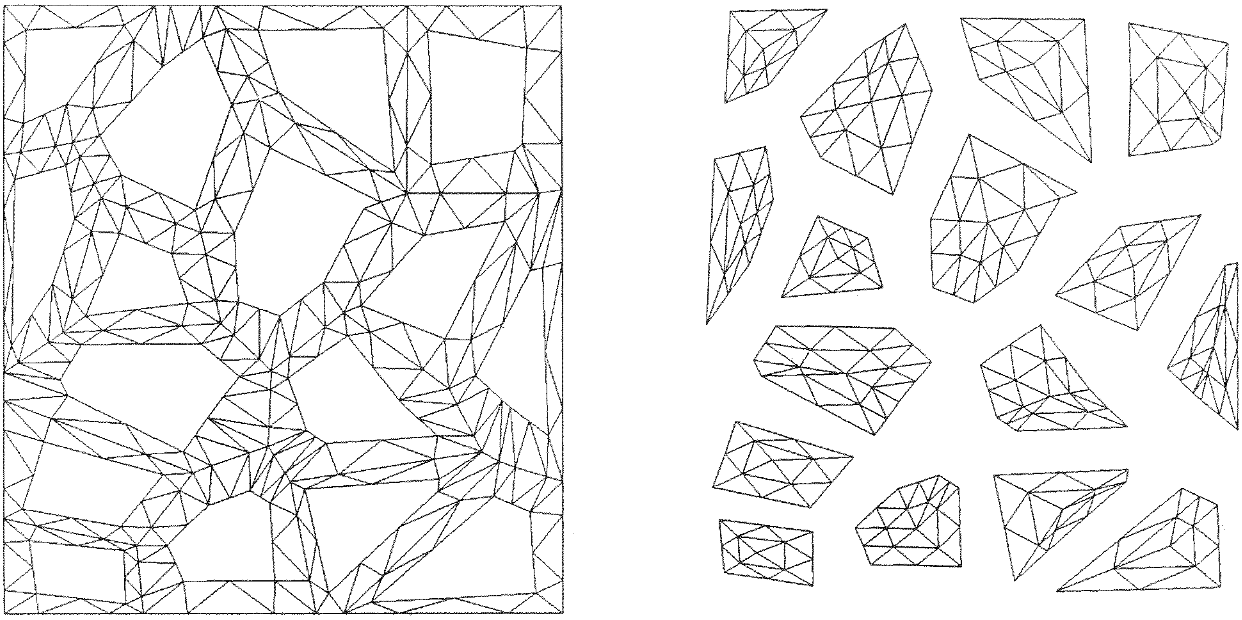

Fig. 1 — FE mesh for matrix (left) and aggregates (right)

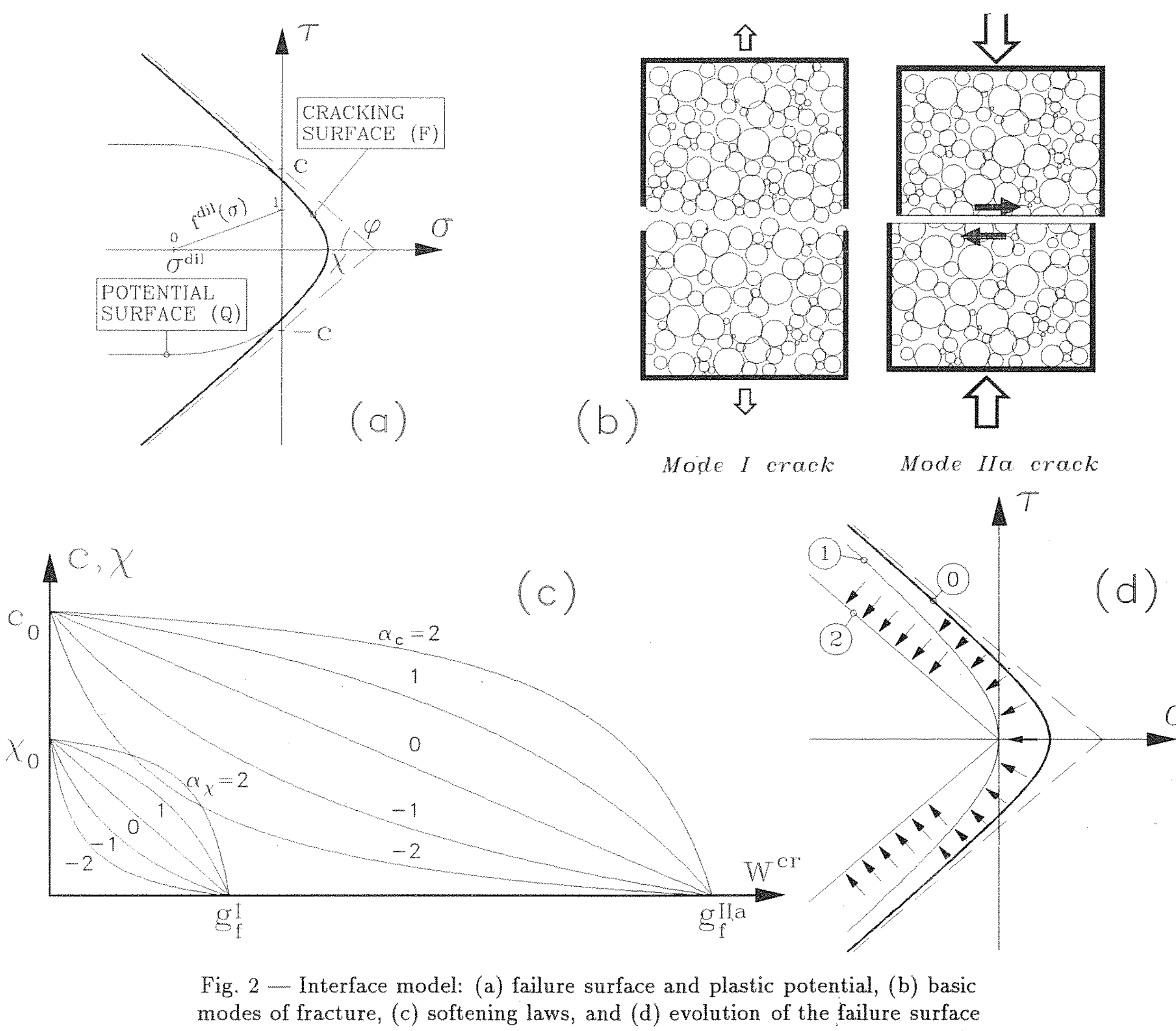

Fig. 2 — Interface model: (a) failure surface and plastic potential, (b) basic modes of fracture, (c) softening laws, and (d) evolution of the failure surface

The initial loading (failure) surface $F=0$ is given as a three-parameter hyperbola (tensile strength χ, c and $\tan\phi$; Fig. 2a). The model is associated in tension ($Q=F$), but not in compression, where dilatancy vanishes progressively for $\sigma_N \rightarrow \sigma^{\mathrm{dil}}$. Classic Mode I fracture occurs in pure tension. A second Mode IIa is defined under shear and high compression, with no dilatancy allowed (Fig. 2b). The fracture energies G_f^I and G_f^{IIa} are two model parameters. After initial cracking, c and χ decrease (Fig. 1c), and the loading surface shrinks, degenerating in the limit case into a pair of straight lines representing pure friction (Fig. 1d). The process is driven by the energy spent in fracture process, W^{cr}, the increments of which are taken equal to the increments of plastic work, less frictional work in compression. Total exhaustion of tensile strength ($\chi=0$) is reached for $W^{\mathrm{cr}}=G_f^I$, and residual friction ($c=0$) is reached for $W^{\mathrm{cr}}=G_f^{IIa}$. Additional parameters α_χ and α_c allow for different shapes of the softening laws (linear decay for $\alpha_\chi=\alpha_c=0$). The elastic stiffness matrix is diagonal with constant K_N and K_T, that can be regarded simply as penalty coefficients. A more detailed description can be found in [16].

3 NUMERICAL RESULTS

The example presented consists of the specimen of Fig. 1 subjected to two similar loading cases: uniaxial tension along x-axis and uniaxial tension along y-axis. In each case, uniform displacements are prescribed to all nodes of the corresponding edges while transverse displacements are free. Average stresses are obtained by summing nodal reactions and dividing by specimen size. Material parameters are, for continuum elements: $E=70,000$MPa (aggregate), $E=25,000$MPa (mortar), $\nu=0.18$ (both); for aggregate-mortar interface: $K_N=K_t=10^9$MPa/m, tensile strength $\chi_0=3$MPa, $c_0=4.5$MPa, $\tan\phi=0.8$, $G_f^I=0.00003$MPa$\times$m, $G_f^I=10G_f^{IIa}$ $\sigma^{\mathrm{dil}}=7$MPa; same for mortar-mortar interface except for $\chi_0=6$MPa, $c_0=9$MPa and $G_f^I=0.00006$MPa$\times$m (note that different elastic properties are assumed for aggregates and matrix, and that higher strength is taken for mortar-mortar than for aggregate-mortar interfaces). Elastic stiffnesses for interfaces are assigned high values compatible with not causing numerical difficulties. The iterative strategy used is an arc length-type procedure [8], which seems necessary to obtain convergence near and after the peak load. Resulting average stress-average strain curves are represented in Fig. 3, for both directions of loading. The cracking state for x-loading at about five times the peak strain is shown in Fig. 4.

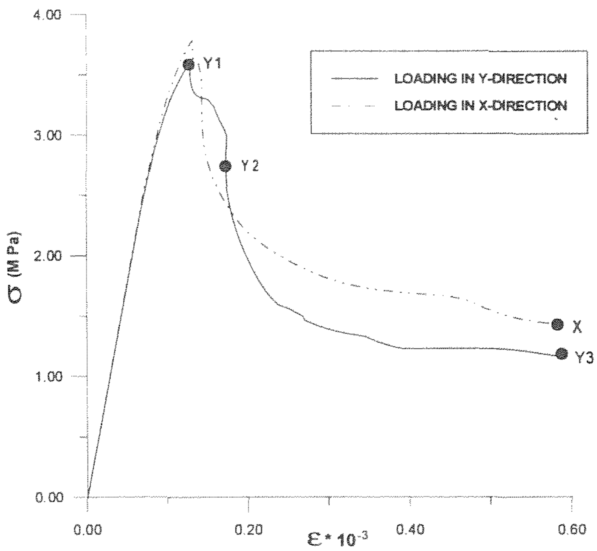

Fig. 3 — Average stress-average strain curves

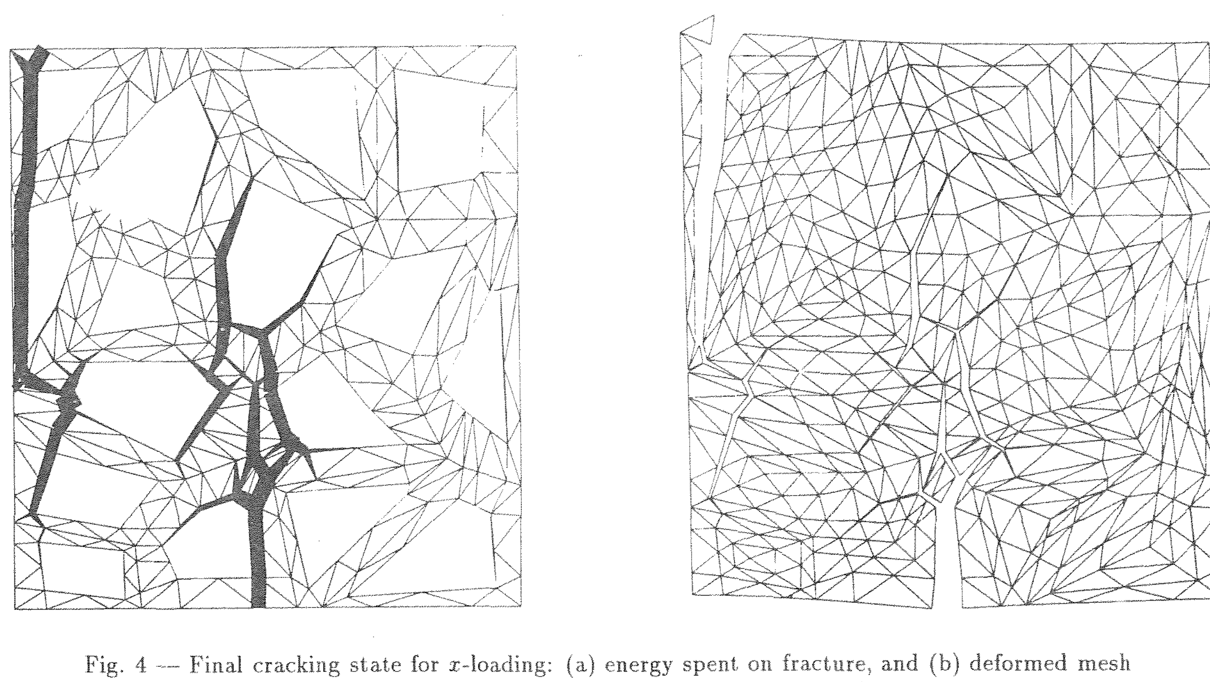

Fig. 4 — Final cracking state for x-loading: (a) energy spent on fracture, and (b) deformed mesh

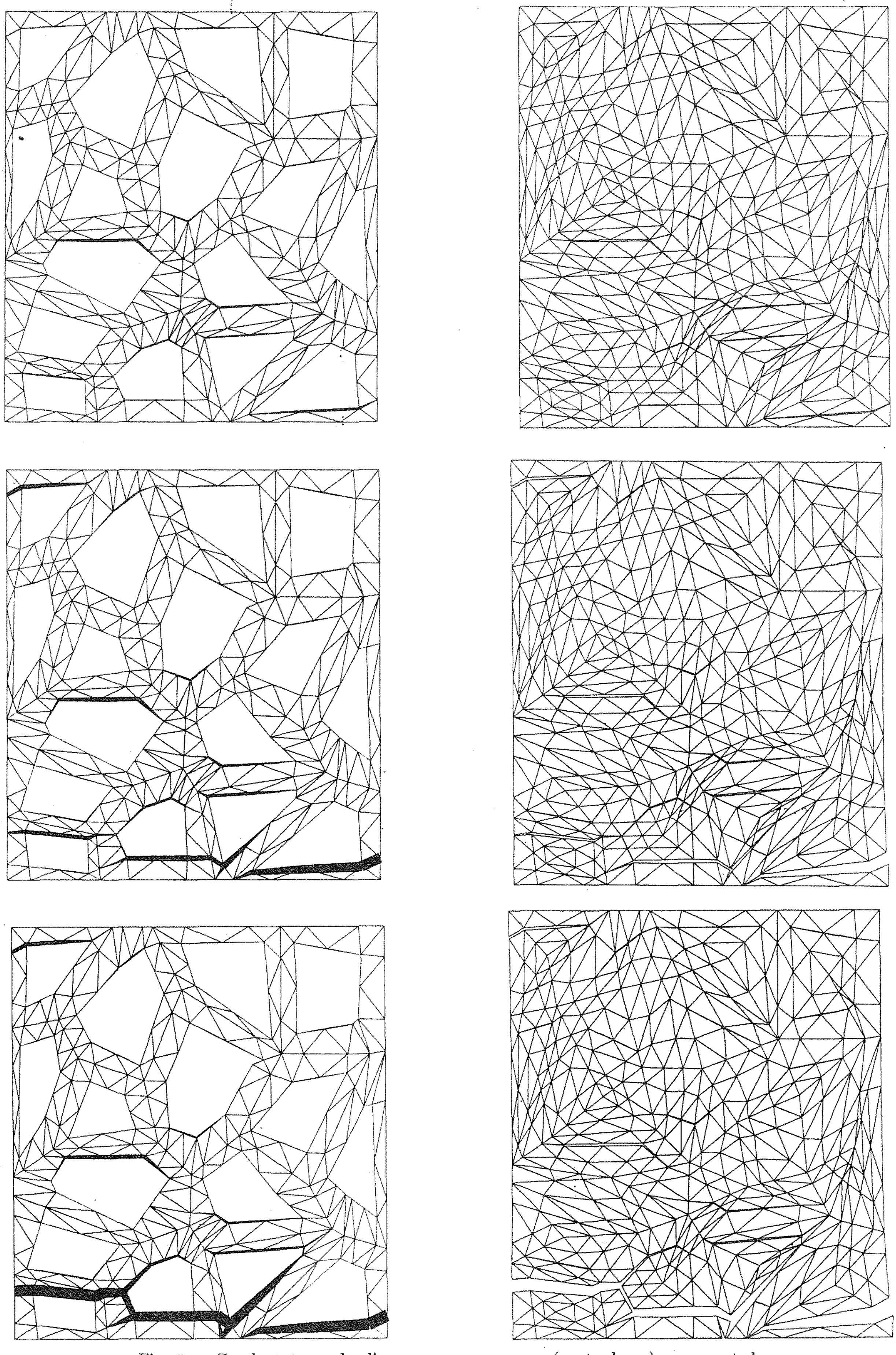

Fig. 5 — Crack states as loading process progresses (up to down), represented by amount of energy spent (left column) and deformed configuration (right column)

Cracking states at three loading stages indicated on Fig. 3 for the case of y-loading, are represented in Fig. 5. Surprising close agreement is obtained between both loading cases in terms of stress-strain curves, given the difference in crack patterns observed. In both cases, the macrocrack tends to develop along the interface nearest the edge of the specimen, which provides the shortest and least tortuous crack path perpendicular to the applied load. From Fig. 5, it is apparent that an initially distributed crack pattern turns, at some point near peak load, into a highly localized state, with a single crack developing through the specimen, and all other existing cracks unload.

4 CONCLUDING REMARKS

The research described continues at ETSECCPB-UPC to consolidate and improve the initial results obtained. In particular, further efforts are aimed at driving the tensile crack along a more tortuous path through the center of the specimen, instead of the nearly-straight path near the edge obtained so far. That may require alternative microstructural arrangements with more aggregate pieces (such as one with 3×6 currently in preparation), and improvement of strength characteristics of interfaces near the specimen edges. Additional interfaces in between continuum elements inside the aggregates themselves, are also being considered. These will be most likely needed to allow for aggregate tip cut-off in compression tests (preliminary results show no peak load due to too tortuous crack paths developing largely too much internal friction), and are surely required to extend the study to high-strength concretes, in which crack paths often cut through aggregate pieces instead of following aggregate-mortar interfaces.

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