NEW RESULTS IN FRACTURE ANALYSIS OF CONCRETE MICROSTRUCTURE USING INTERFACE ELEMENTS

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Abstract: Following the work by Stankowski [1], a 14×14cm concrete specimen is represented in 2-D by two alternative arrangements of 16 or 36 irregular aggregate pieces embedded in a mortar matrix. In the FE analysis, the continuum elements remain elastic and the possibility of cracking is introduced by inserting interface elements along all aggregate-mortar and mortar-mortar element boundaries. Interface behavior is given by a fracture energy-based work-softening plastic model with a coupled normal-shear failure surface. Two FE discretizations are considered for the matrix of each aggregate arrangement: the one given originally, and a second one with element boundaries allowing less tortuous paths, as suggested by Vonk [2]. Numerical results of the four meshes subjected to pure tension in the x and y directions are presented and discussed.

Resumen: Siguiendo el trabajo de Stankowski [1], una probeta de hormigón de 14×14cm se representa en 2-D mediante dos disposiciones alternativas de 16 o 36 piezas de árido de forma irregular, embebidos en una matriz de mortero. En el análisis por elementos finitos, los elementos de medio continuo se suponen elásticos y la posibilidad de fisuración se introduce insertando elementos interfase a lo largo de todos los contactos entre elementos árido-mortero y mortero-mortero. Para la interfase se supone un modelo elasto-plástico con superficie de rotura en función de la tensión normal y tangencial y reblandecimiento por trabajo de fractura. Para la matriz de mortero de cada disposición de áridos, se consideran dos mallas distintas: la propuesta originalmente, y una segunda que permite trayectorias de fisuras menos tortuosas en la línea propuesta por Vonk [2]. Se presentan y comparan algunos resultados numéricos de las cuatro mallas sometidas a tracción pura en las direcciones x e y.

1 INTRODUCTION

Detailed understanding of complex aspects of fracture of composite materials may be improved with explicit consideration of their components and microstructure. Some studies of this kind, using the FEM, can be found in the literature of concrete [1-3]. In this paper, on-going research being carried out at ETSECCPB-UPC along this line is summarized, and some results are presented. This paper updates previous results described in [4]. Two aggregate arrangements are borrowed from [1], with 16 (4 × 4) or 36 (6×6) irregular pieces which are surrounded by a mortar matrix. Aggregates and mortar are discretized with triangular finite elements with linear elastic behavior. The FE mesh also includes zero-thickness interface elements with two pairs of nodes each, along all mortar-aggregate and some mortar-mortar inter-element boundaries. The use of interface elements for fracture analysis was proposed in [5] and developed later in [6-11]. 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 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 where interfaces have been inserted. Due to that, one can expect the results to be sensitive to the mesh layout in the mortar matrix, and the selection of element boundaries in which interface elements are inserted. Two different discretizations have been considered for each aggregate arrangement. The original one proposed by Stankowski, which was not conceived to be used with interfaces within the matrix because the mortar itself was considered elasto-plastic, and a new one inspired in the work of Vonk [2], in which element boundaries follow much less tortuous paths to connect aggregate corners. The original mesh was used initially in this study to obtain a first batch of results [4], and has also been used for the study of sulphide-induced differential expansions in the concrete of two gravity dams [12]. Fig. 1 depicts the 4×4 aggregate arrangement with the new FE discretization. Fig. 2 shows the interfaces inserted into the new and old 6×6 meshes and the old 4×4 mesh respectively. Note that in the new mesh, interfaces are located only along main element boundaries allowing the least tortuous connection between cracks initiated at the matrix-aggregate boundaries, while in the old mesh they have been inserted between all mortar elements. The new 4×4 mesh has 715 triangles, 435 interface elements and 997 nodes, while the 6×6 contains 1642 triangles, 998 interface elements and 2263 nodes. Calculations have been run with the FE code DRAC and represented with the post-processor DRAC-VIU, both fully in-house developed at the ETSECCPB-UPC [13].

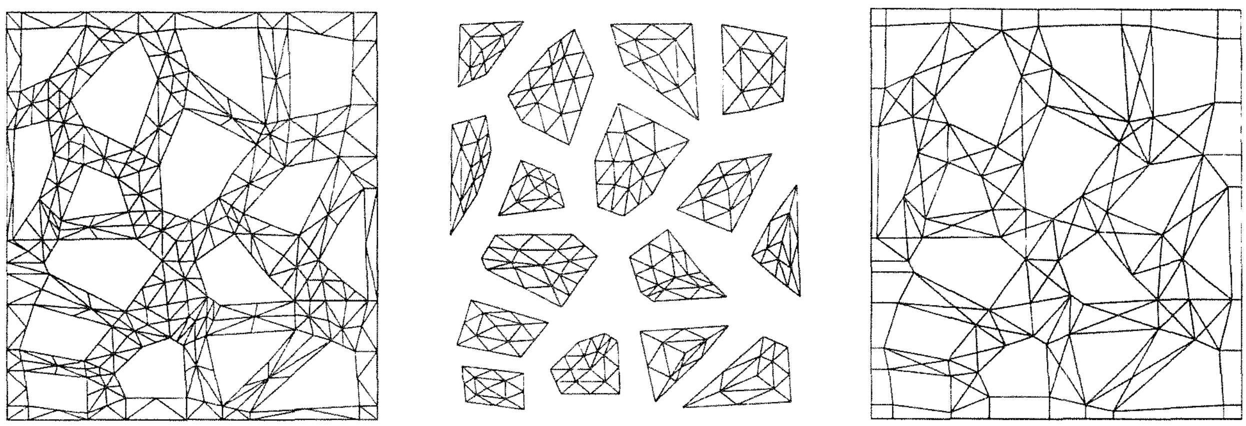

Fig. 1. New FE discretization of the 4×4 arrangement: matrix (left), aggregates (center) and interfaces inserted (right).

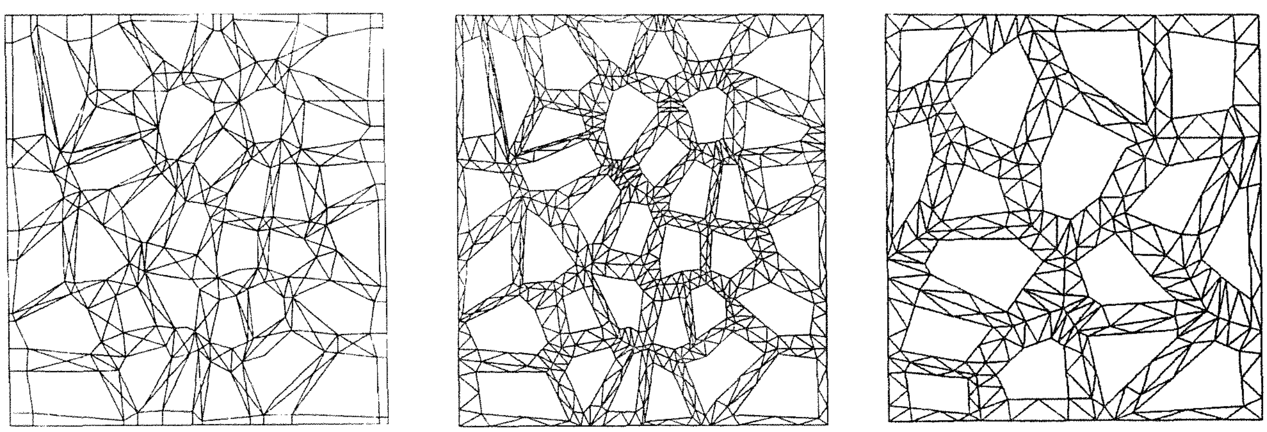

Fig. 2. Interface elements in the new and old 6×6 and old 4×4 meshes (left to right).

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 [14-18] . 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. 3. The initial loading (failure) surface $F=0$ is given as a three-parameter hyperbola (tensile strength χ, c and tanϕ; Fig. 3a). The model is associated in tension ($Q = F$), but not in compression, where dilatancy vanishes progressively for $\sigma_N \rightarrow \sigma^{\text{dil}}$. Classic Mode I fracture occurs in pure tension. A second Mode IIa is defined under shear and high compression, with no dilatancy allowed (Fig. 3b). The fracture energies G_f^I and G_f^{IIa} are two model parameters. After initial cracking, c and χ decrease (Fig. 3d), and the loading surface shrinks, degenerating in the limit case into a pair of straight lines representing pure friction (Fig. 3c). 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 $W^{\text{cr}}=G_f^I$, and residual friction ($c=0$) is reached for $W^{\text{cr}}=G_f^{IIa}$.

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 [19].

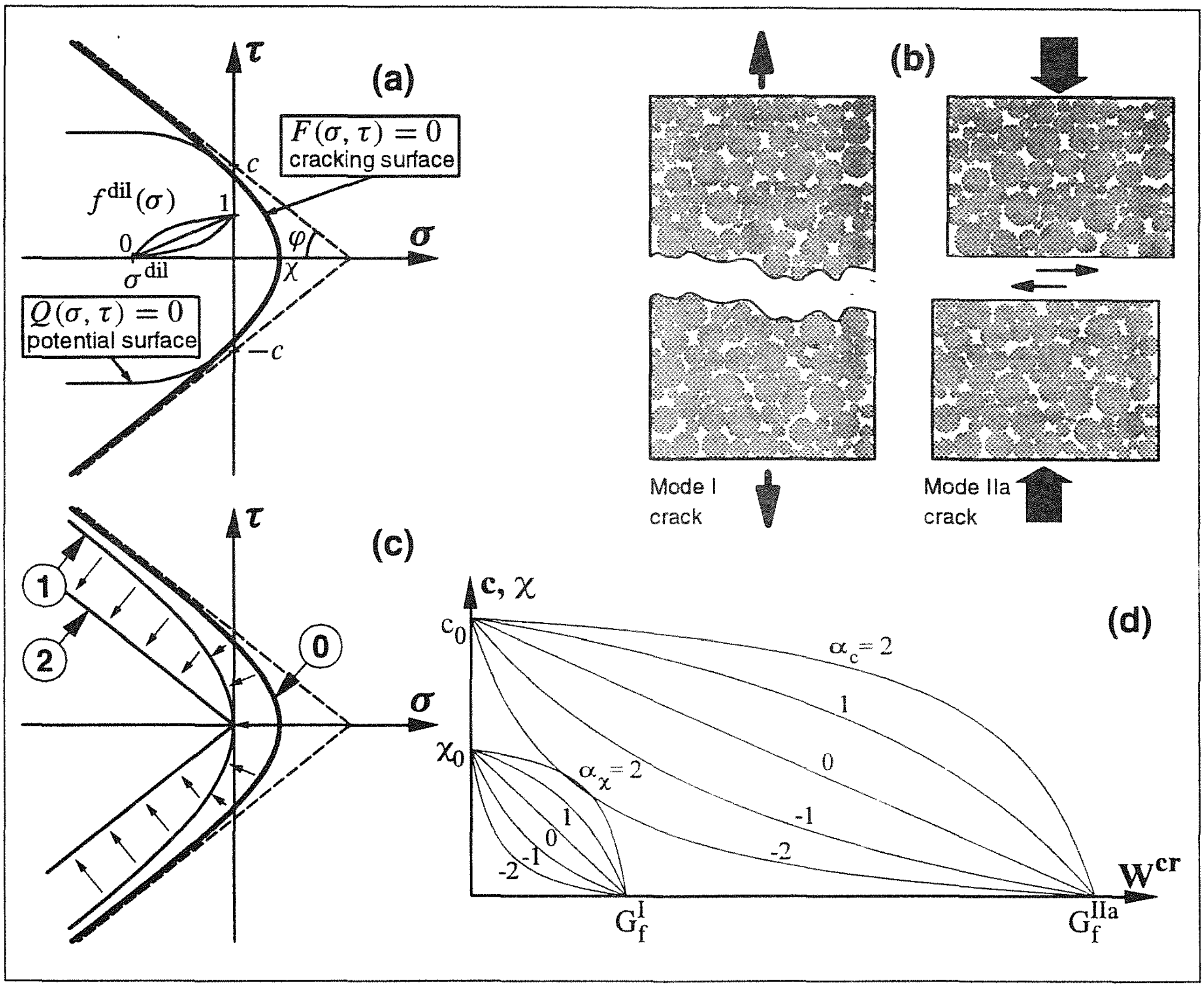

Fig. 3 — Interface model: (a) failure surface and plastic potential, (b) basic modes of fracture, (c) softening laws, and (d) evolution of the failure surface.

3 NUMERICAL RESULTS

The results presented correspond to the four meshes of figures 1 and 2 (all with the corresponding discretization of the aggregates), subject to uniaxial tension along x-axis and y-axis. In each case, uniform displacements are prescribed to all nodes of the corresponding specimen edges, while transverse displacements are left free. Average stresses are obtained by summing nodal reactions and dividing by specimen size. The material parameters are, for the continuum elements: $E = 70,000$MPa (aggregate), $E = 25,000$MPa (mortar), $\nu = 0.18$ (both); for the aggregate-mortar interfaces: $K_N = K_t = 10^9$MPa/m, tensile strength $\chi_0 = 3$MPa, $c_0 = 4.5$MPa, $\tan\phi = 0.8$, $G_f^I = 0.00003$MPa×m, $G_f^{IIa} = 10G_f^I$ $\sigma^{dil} = 7$MPa; same for mortar-mortar interfaces except for $\chi_0 = 6$MPa, $c_0 = 9$MPa and $G_f^I = 0.00006$MPa×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 [10], which seems necessary to obtain convergence near and after the peak load. Resulting average stress-average strain curves for all meshes and loading directions are represented in Fig. 4. In the figure, it is clear that the curves obtained with the new modified meshes exhibit a lower residual stress than their conunterparts obtained with the original Stankowski's discretizations. This reflects a less tortuous crack path that eliminates spurious residual friction at advanced stages of the separation process. More insight into the results may be gained with the detailed representation of the crack patterns through the mesh in figures 5 to 8. Fig. 5 depicts the deformed mesh of the 4×4 and 6×6 new meshes at some advance stage (about five times the peak strain) of x and y loading.

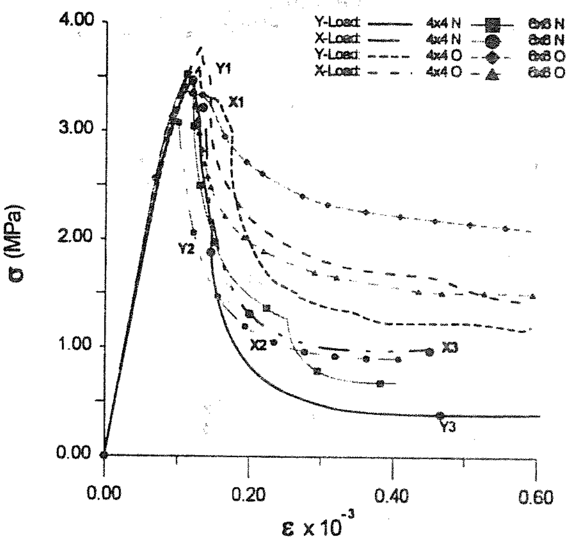

Fig. 4 — Average stress-average strain curves.

The evolution of the cracking process is represented in figures 6 and 7 in terms of the fracture energy spent W^{cr}. Each vertical sequence corresponds to three stages of the loading along y (left diagrams) and x (right diagrams). From the figures it is apparent that an initially distributed crack pattern turns, at some point near the peak load, into a highly localized state, with a single crack developing through the specimen, and all other existing cracks unload. Also, the figures exhibit branching and bridging of cracks (except perhaps on the y loading of the 4×4 mesh) which are phenomena causing longer tails in the resulting average stress–strain diagrams.

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 the compressive loading, for which preliminary results showed too high peak loads due to excessive internal friction. Additional interfaces in between continuum elements inside the aggregates themselves, are also being considered. These should provide the possibility of aggregate tip cut-off, 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.

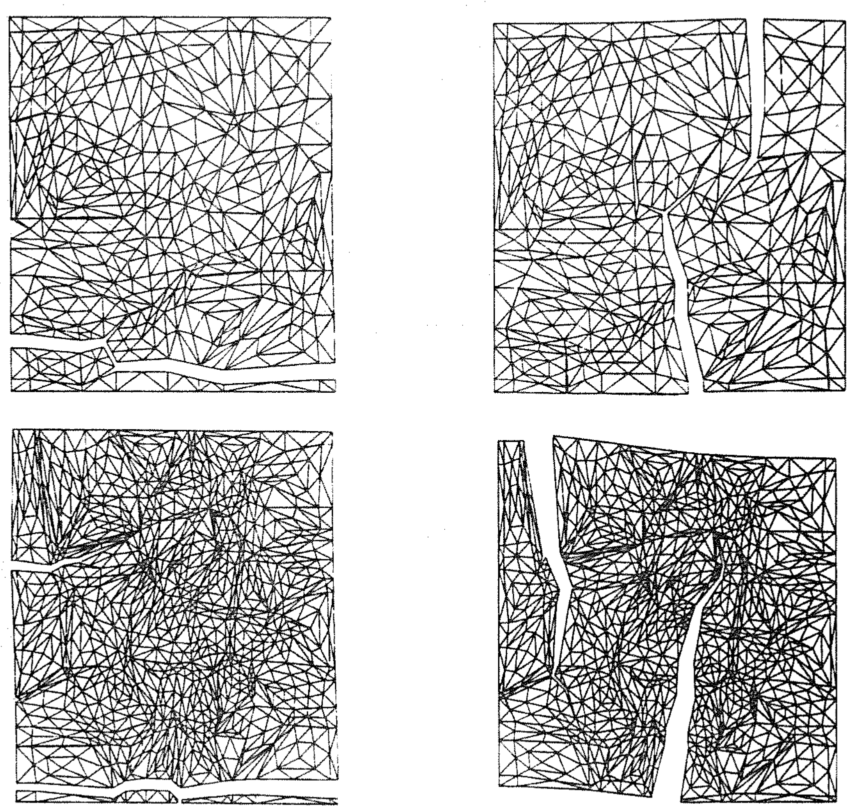

Fig. 5 — Deformed mesh at advanced y (left) and x (right) loading stages for the 4×4 (up) and 6×6 (down) meshes.

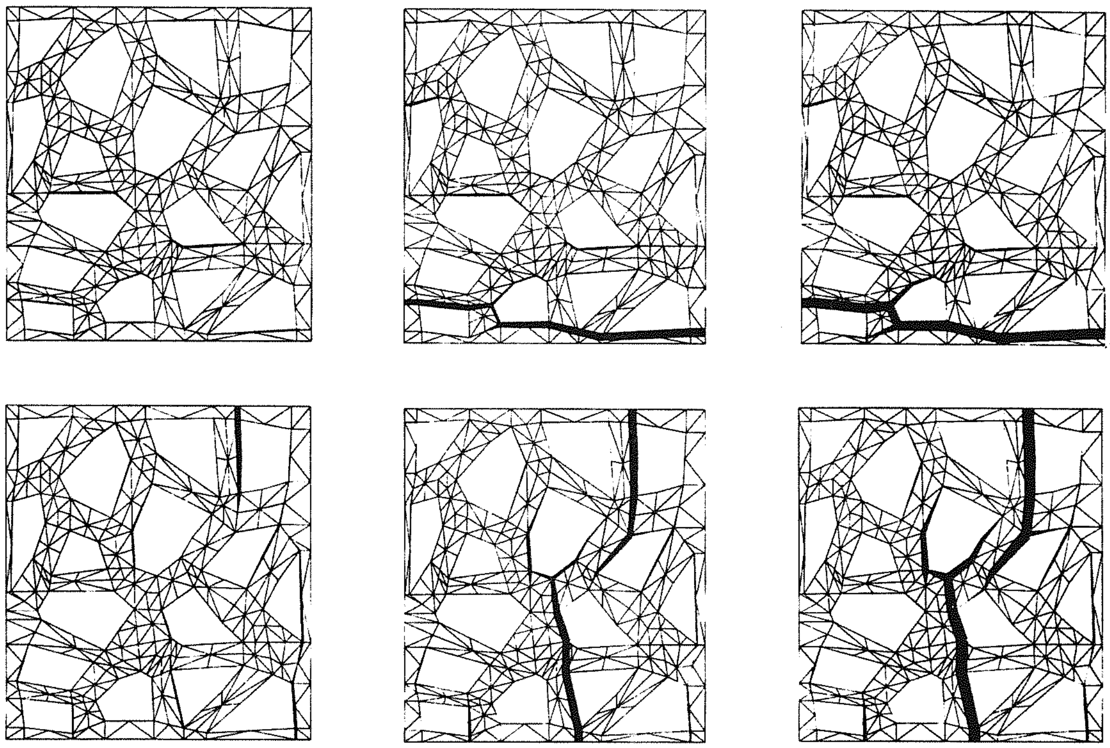

Fig. 6 — Progressive cracking of the 4×4 mesh (left to right), represented by amount of energy spent upon y (up) and x (down) loading.

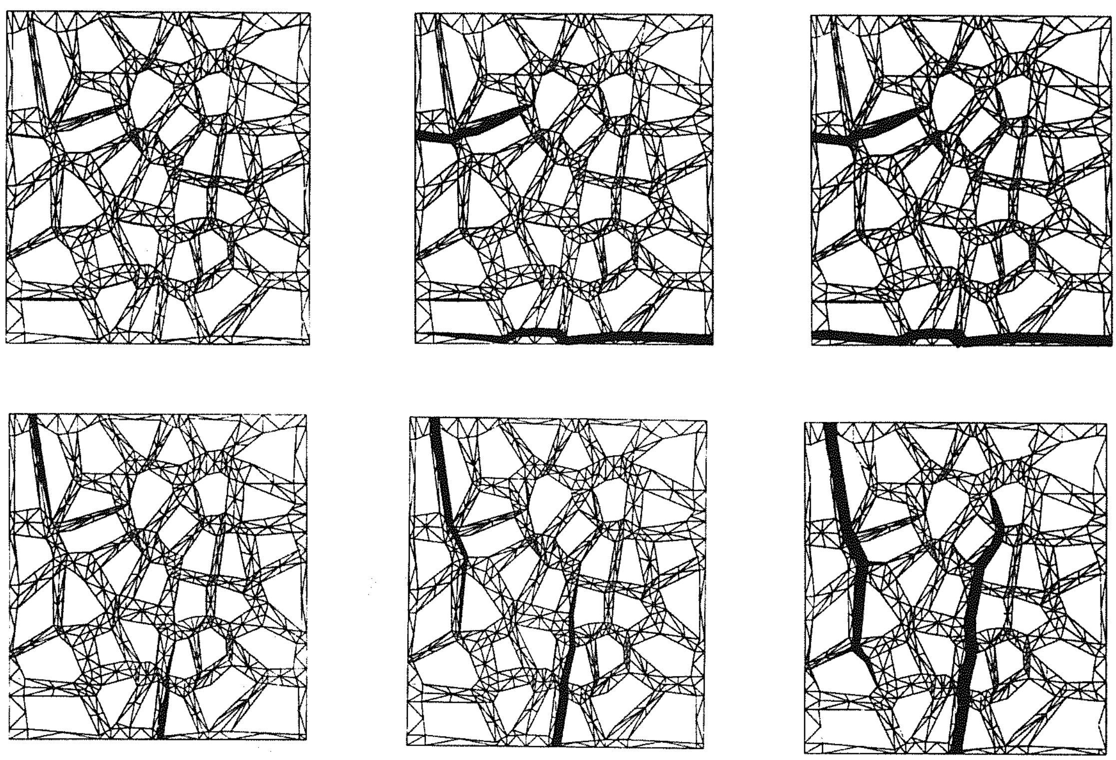

Fig. 7 — Progressive cracking of the 6×6 mesh (left to right), represented by amount of energy spent upon y (up) and x (down) loading.

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