Dynamic fracture roughness in a concrete microstructure using lattice beam method

J.F. Jerier[a], C. Poinard[b], Y. Malécot[b], F. Gatuingt[c] and J.F. Molinari[a]

[a] Laboratoire de Simulation en Mécanique des Solides, EPFL CH-1015 Lausanne, Switzerland
[b] Laboratoire 3S-R, Domaine Universitaire BP53 38041 Grenoble, France
[c] Laboratoire de mécanique et technologie, 61 Avenue du Président Wilson 94230 Cachan, France

Overview and objectives

The scaling properties of fracture surfaces have been investigated since the last two decades. Experimental results show that fracture surfaces obtained in mode I for concrete samples (see Fig. 1) are self-affine and anisotropic [1]. At a large scale, the roughness exponent (H) is 0.45 due to pinning and de-pinning phenomena. Recently, using the lattice beam model and a large system size, a crack roughness close to 0.45 has been recovered [2]. **Using this numerical method, we investigate the influence of hard inclusions and macro-porosities on the fracture surface roughness based on the material properties in table 1.**

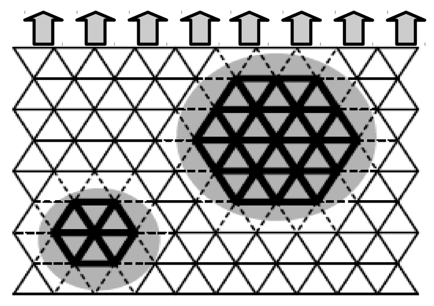


Figure 1: Lattice element properties according to phase composition of the concrete mesostructure

	E(GPa)	ν	σ_f (Mpa)
Aggregate	75	0.2	10
Matrix	25	0.2	5
Interface	25	0.2	2.5

Table 1: Material properties for the different beams composing the numerical concrete sample

Beam Model

$$F^i_N = \alpha(u^j_x - u^i_x)$$

$$F^i_{Tz} = \beta(u^j_z - u^i_z) - \beta\frac{L}{2}(\theta^j_z + \theta^i_z)$$

$$M^i_{Bz} = \frac{\beta L}{2}(u^j_y - u^i_y + L\theta^j) + \delta L^2(\theta^j_z - \theta^i_z)$$

$$M^i_T = \frac{GI_o}{L}(\theta^j_x - \theta^i_x)$$

$$\alpha = \frac{EA}{L},\quad \beta = \frac{1}{\frac{L}{GA} + \frac{L^2}{12EI}},\quad \delta = \beta\left(\frac{EI}{GAL^2} + \frac{1}{3}\right)$$

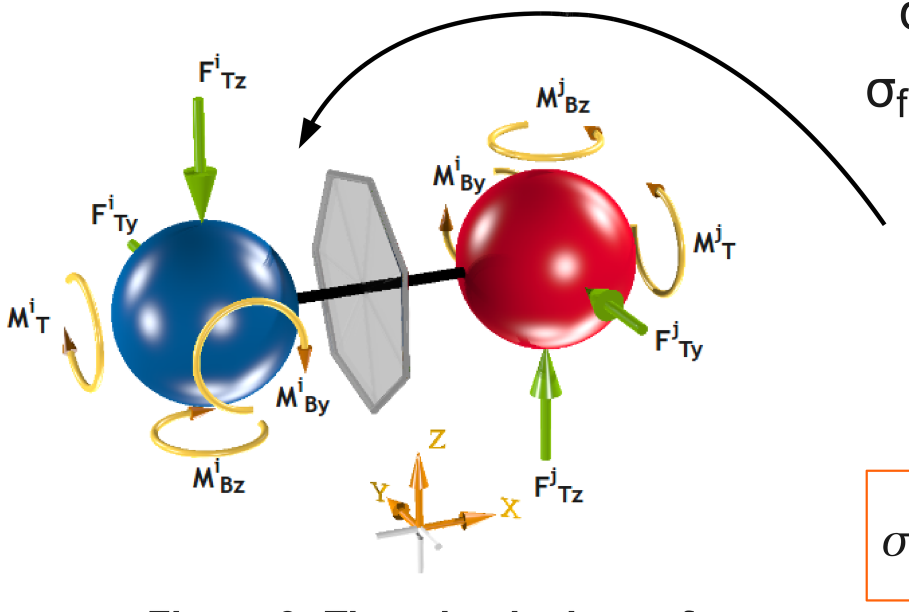
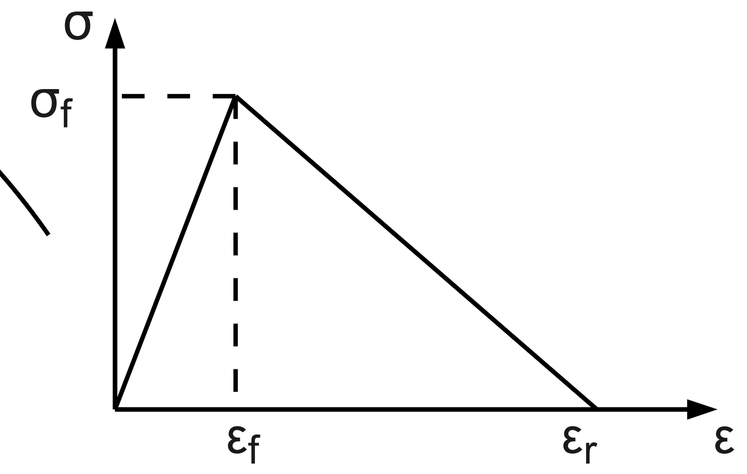


Figure 2: Timoshenko beam for the inter-sphere interactions



$$\sigma = \left(\frac{F}{A}\right) + 0.05A\,\frac{max(|M_B|,|M_T|)}{\pi I}$$

Figure 3: Damage law implemented into the beam element

The used lattice beam model is a discrete method based on an explicit time integration scheme. This method is intensively used to investigate fracture processes [3]. In our study, the numerical sample is represented by an assembly of 500.000 polydisperse spheres and 4 million beams . They are connected via damageable beam elements based on the Timoshenko beam theory [4] (see Fig. 2).

Macro-porosities and aggregates

From the X-ray tomography image, we can model via a sphere assembly the concrete material structure with the complex shapes of aggregates and macro-porosities (see Fig. 4).

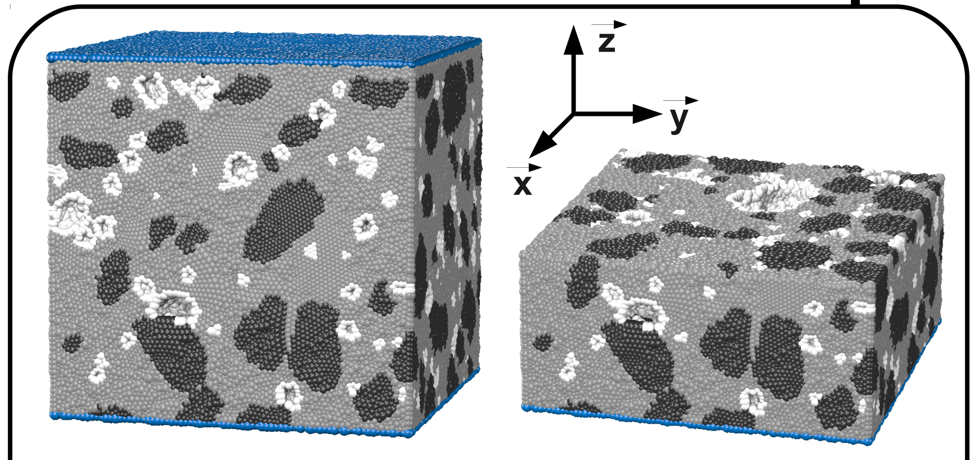


Figure 4: Numerical concrete sample based on a X-ray microtomography image (25mm^3)

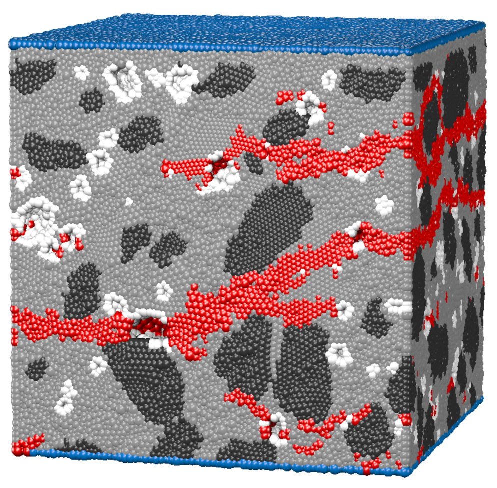


Figure 5: The crack paths (in red) crossing the concrete sample

The fracture was mimicked by removing beam elements from the original lattice according to a strength criterion (see Fig. 3). The main crack surface is extracted from the most stretched damaged beams. The crack surface is reconstructed with a percolation algorithm on a regular grid so as to be analysed (see Fig. 9). Scaling of crack width w(l) with window size l in the x and y direction shows an anisotropy of the crack surface when the heterogeneities are included (see Fig. 7).

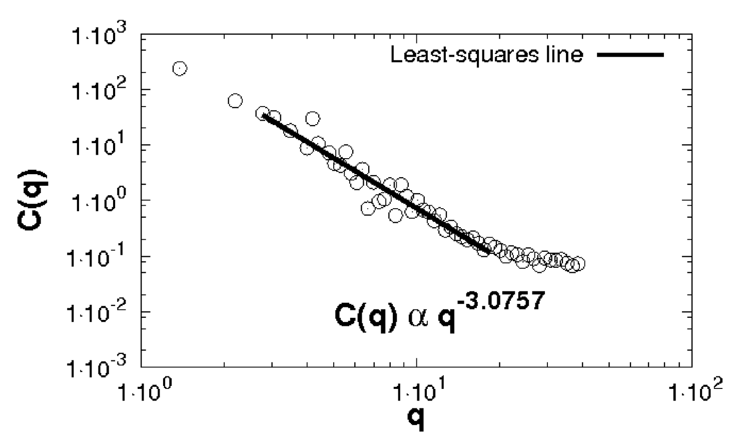


Figure 6: Roughness exponent in 2D plotted in a log-log diagram (H=0.5)

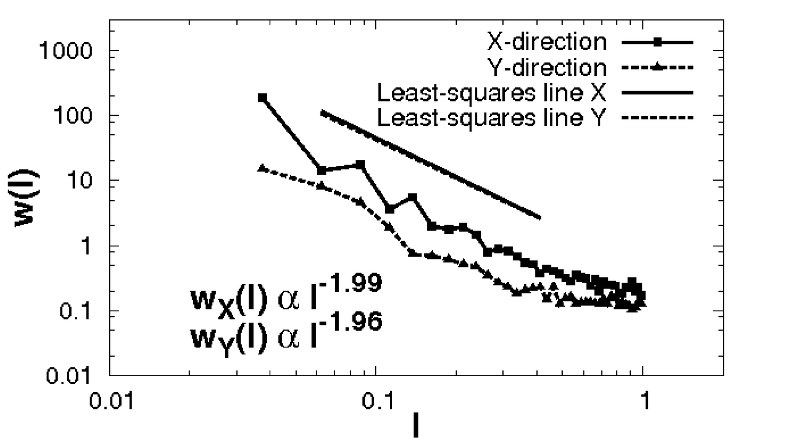


Figure 7: Local roughness exponents in both x and y directions

Macro-porosities only

The same numerical sample is used for this simulation. However, the beam material properties are changed (no aggregates).
We notice that the porosities initiate the cracks (see Fig. 8). Consequently, the main crack surface passes through the largest macro-porosities (see Fig. 9).

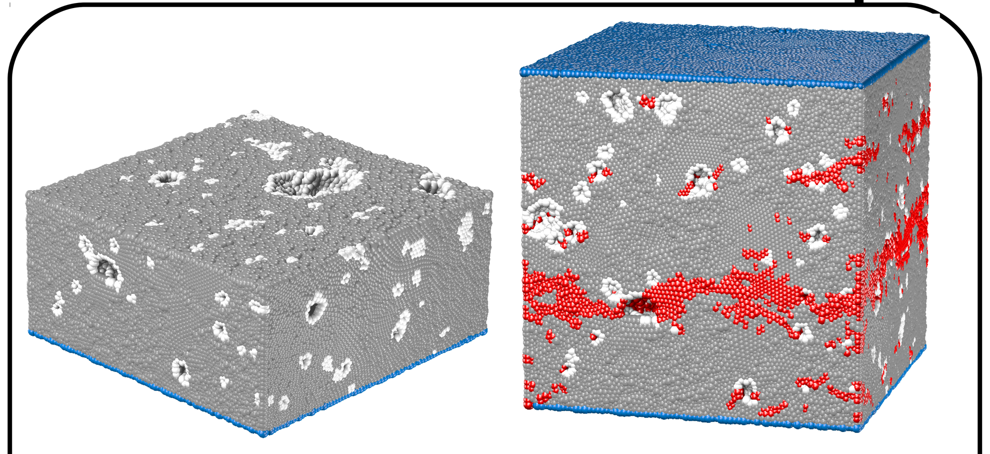


Figure 8: Sample with only macro-porosities. The different crack paths are represented.

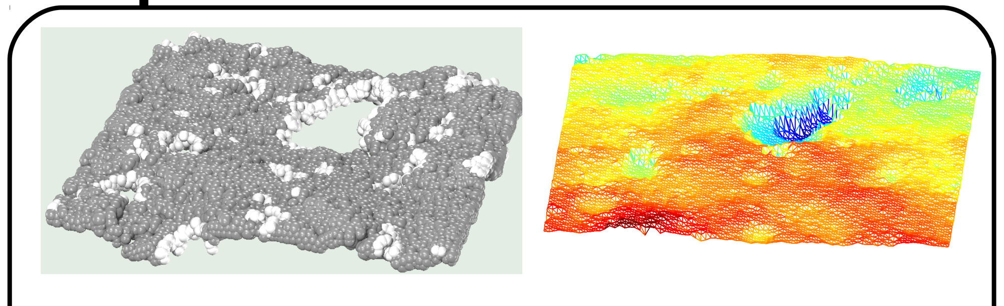


Figure 9: The main crack surface is extracted and reconstructed from a regular grid to be analysed

For this specimen, the main crack surface contains large holes due to the presence of the macro-porosities. In order to analyse geometrically this surface, the holes defined from white spheres are filled with a percolation algorithm (see Fig. 9).

The roughness exponent H computed from the scaling of power spectrum in 2D C(q) is equal 0.46. The local roughness exponent (1D) in x and y direction are equal to 0.55, but a slight gap remains.

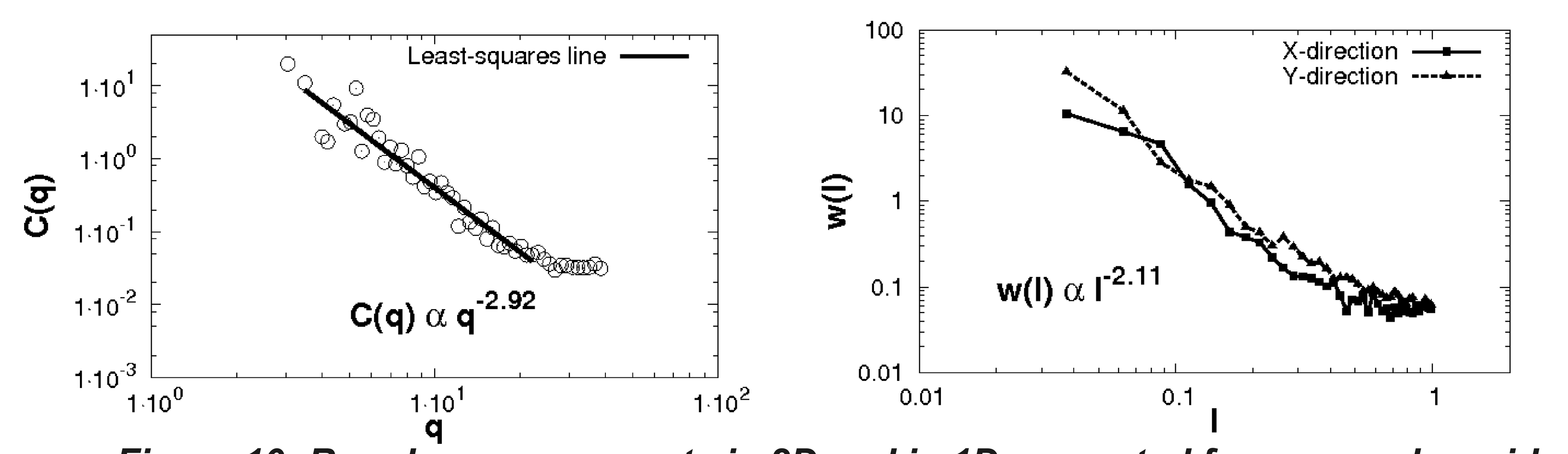


Figure 10: Roughness exponents in 2D and in 1D computed from a regular grid with a size of 80x80 nodes

No macro-porosities and no aggregates

In the case without aggregates and without macro-porosities, the power spectrum in 1D in x and y direction are superposed. The local roughness exponents are equal 0.46 (see Fig. 11). In this case, the crack surface is isotropic.

a) **b)**

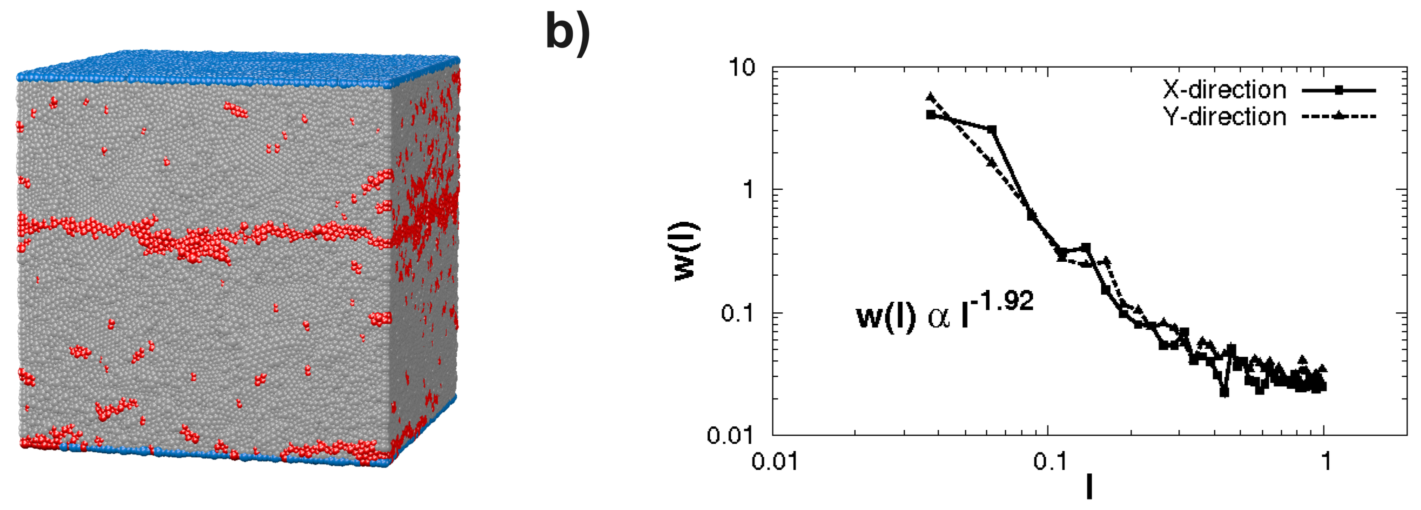


Figure 11: a) A sample constitued only by matrix is cracked after a simulation in mode I. b) Local roughness exponents in both x and y directions are superposed.

Conclusion

This study exhibits that the crack profiles obtained in fracture simulations on a real microstructure or a homogeneous network by using a lattice beam method have a roughness exponents of 0.5±0.05.
We also show that the inclusion of complex shapes of aggregates and macro-porosities into the concrete sample generates an anisotropic crack surface. The experimental results [1] have reported such anisotropy. Thereby, our work demonstrate the importance of including real heterogeneities into the simulations to capture accurate fracture surfaces.

Bibliography

[1] **L. Ponson, D. Bonamy, H. Auradou, G. Mourot, S. Morel, E. Bouchaud, C. Guillot and J. P. Hulin**, *Anisotropic self-affine properties of experimental fracture surfaces*, Int. J. Fract., 140 (2006) 27-37.
[2] **K.V.V. Nukala, P. Barai, S. Zapperi, M.J. Alava and Srđan Šimunović**, *Fracture roughness in three-dimensional beam lattice systems*, Phy. Rev. E, 82 (2010) 1-10.
[3] **G. Lilliu, J.G.M. van Mier**, *3D lattice type fracture model for concrete*, Engrg. Fract. Mech. 70 (2003) 927–941.
[4] **G. D'Addetta, F. Kun, E. Ramm, H. Herrmann**, *From solids to granulates - Discrete element simulations of fracture and fragmentation processes in geomaterials*, Lect. Notes Phys, (2001) 231-258.

Mail: jean-francois.jerier@epfl.ch

Laboratoire de Simulation en Mécanique des Solides
Ecole Polytechnique Fédérale de Lausanne