American Concrete Institute

Statistical Physics for Quasi-Brittle Fracture

Ariel Attias, Franz-Josef Ulm

Introduction

- Concrete is the **most widely** used material in the world
- Great mitigation potential of its environmental impact through:
  a) Resilience.
  b) GHG emissions.

- How to assess the performaces of a fracture method ?
  a) Fracture load/pattern predictions.
  b) Size-effect.

- Why come with **another** fracture method ?

The SGCMC model: From Finite Elements to Statistical Physics

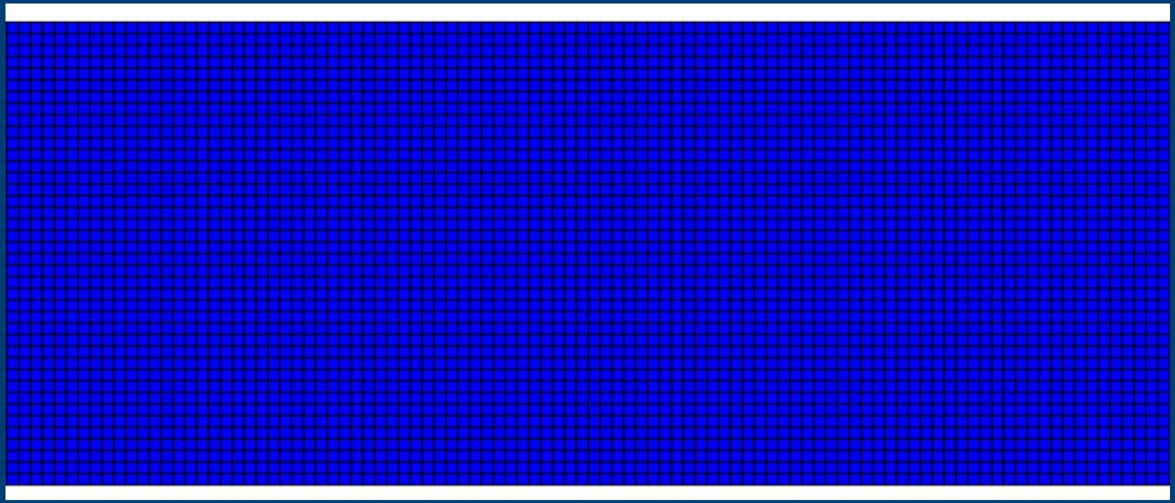


Figure: FE regular square mesh

Fracture site

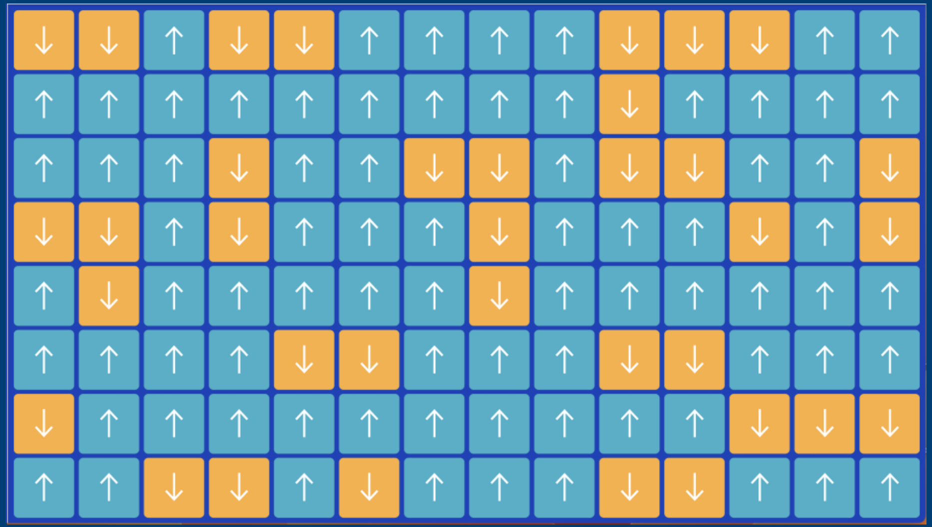


Figure: Ising Lattice model

- Fracture (**spin**) dynamics is governed by probability (**semi-grand ensemble**).
- Element fracture potential: the **ground-state energy** ϵ_0.
- Basis for reduced units analysis (ϵ_0,R)

The SGCMC model: Energy Dissipation Regularization

- Fracture is a surface process $\neq \epsilon_0$ (volumetric)
- Regularization of the crack with a ϵ-rationalization C_ϵ $(\epsilon > R)$

$$\epsilon_0^{eff} = \epsilon_0 \frac{\Delta C_\epsilon}{2\epsilon}$$

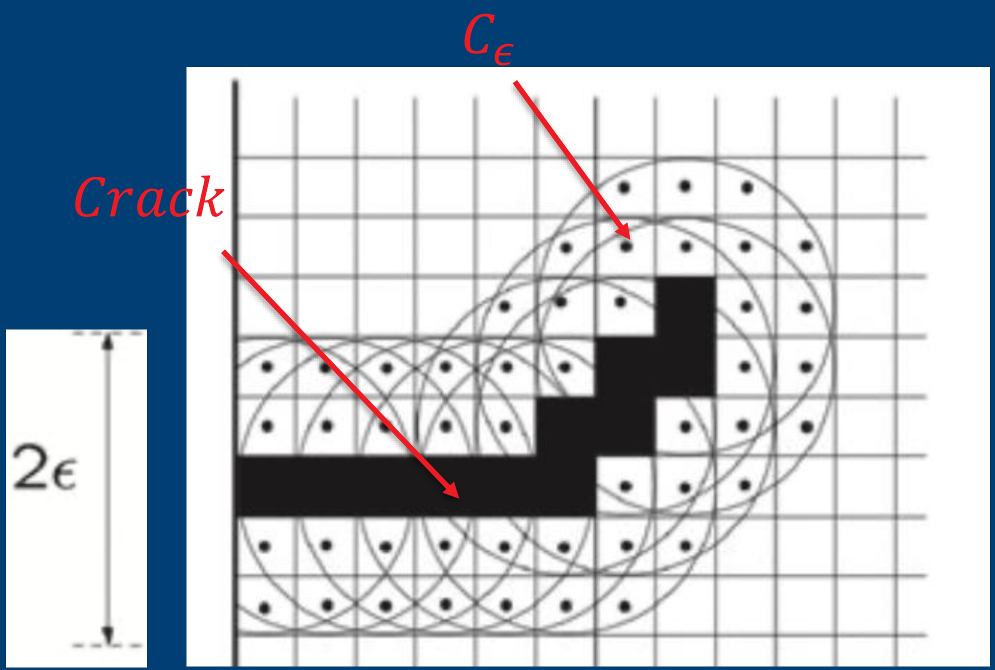


Figure: Square mesh with existing crack

Fracture propagation

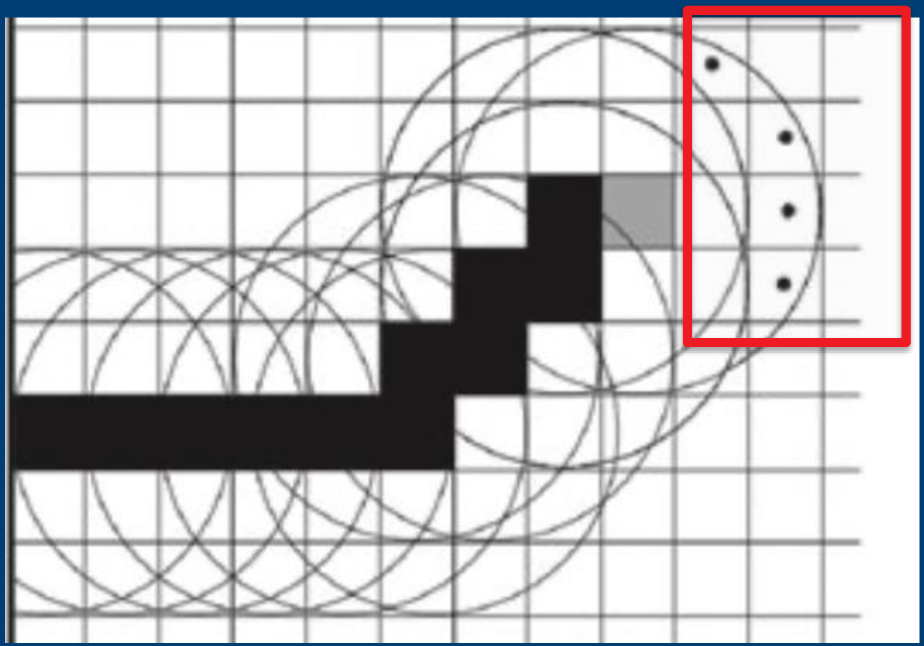
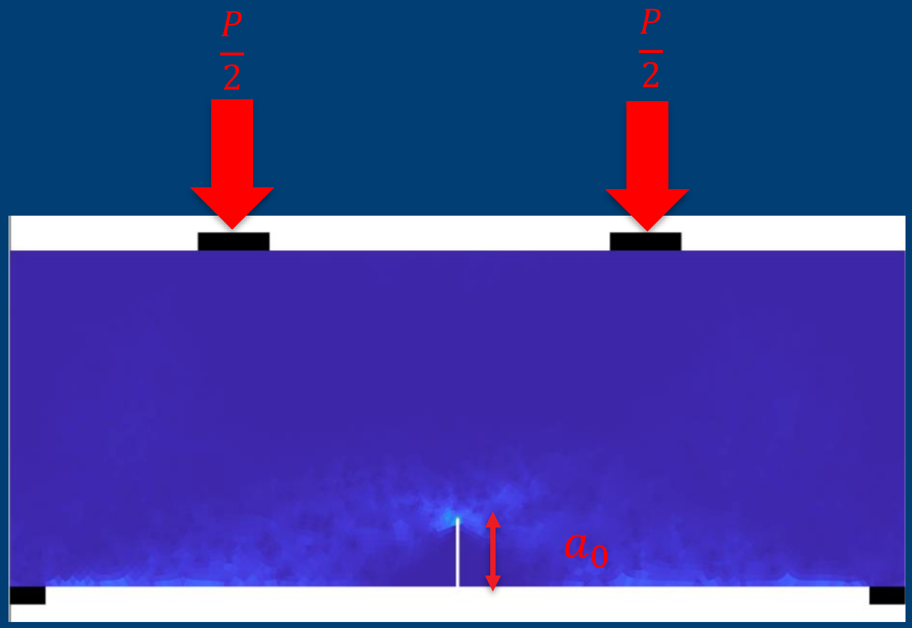
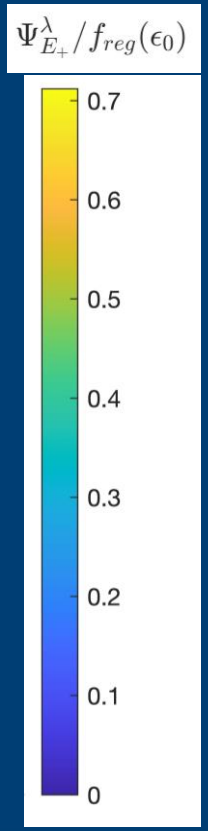


Figure: Square mesh with updated crack

A 4-pt bending beam: Fracture pattern

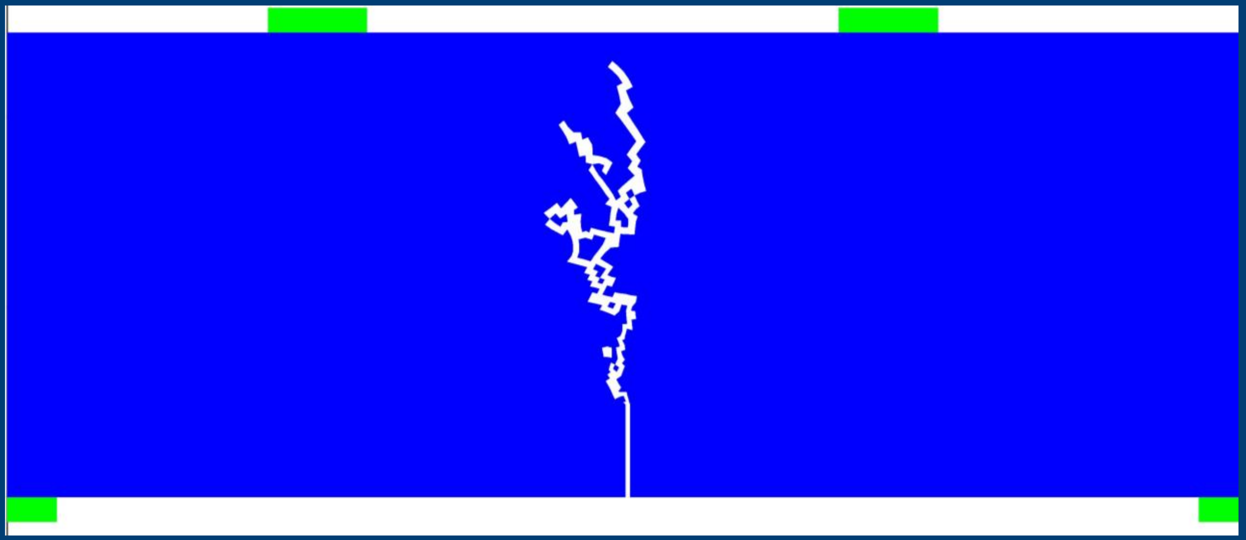
- $\epsilon_0^e = \int \frac{f_t^2}{E} \; d\,\Omega_\mathrm{e}$
- Tension-compression asymmetry.





<u>Figure</u>: Initial Fracture Likelihood

- Fracture micro-states respect the **Ergodicity** principle.
- Fracture analysis beyond average response.



<u>Figure</u>: a Fracture Micro-State

A 4-pt bending beam: Fracture Propagation & Phase transition

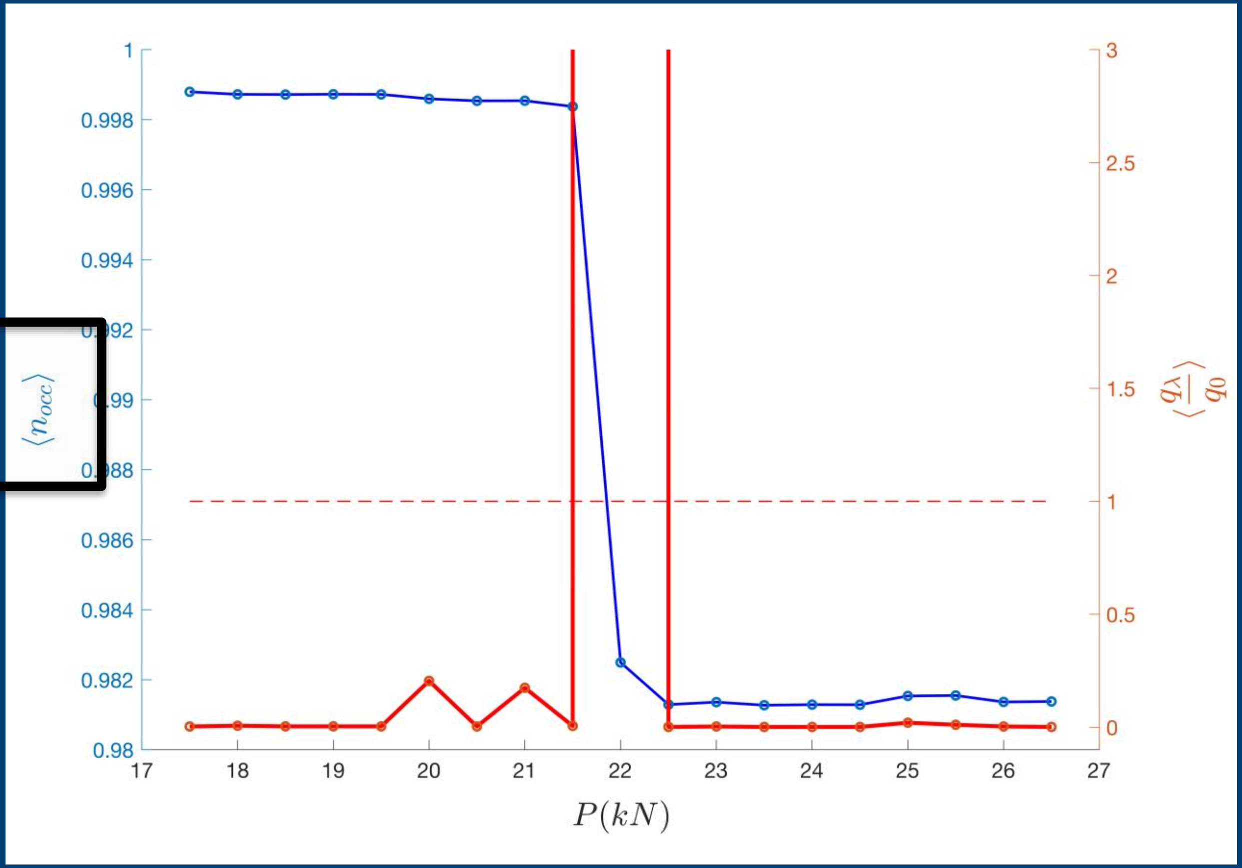


Figure: Critical load detection ($\frac{a_0}{H} = 0.2$)

- Fracture is a **first-order** phase transition (n_{occ} discontinuity).
- Heat of element rupture: $\frac{q_\lambda}{q_0}$

a) $q_i = \frac{\partial U_i}{\partial N_i}$ *determined by statistics*

b) in-situ measurement of fracture propagation (balance)

A 4-pt bending beam: Fracture load

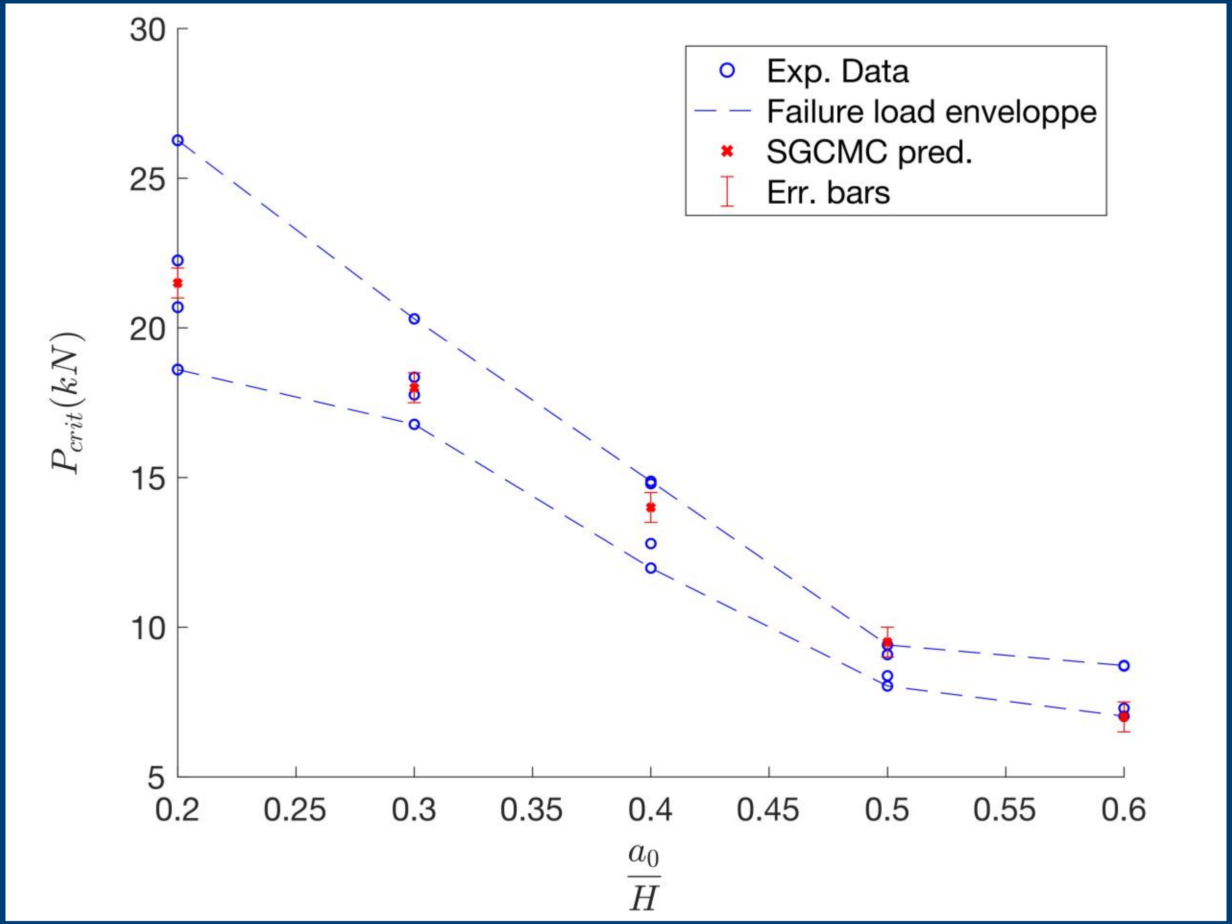


Figure: Fracture load predictions [2]

- Predict fracture load in the experimental range of observed values.
- Span a large number of geometries.
- Visit different fracture micro-states for each $\frac{a_0}{H}$.

A 4-pt bending beam: Size-effect

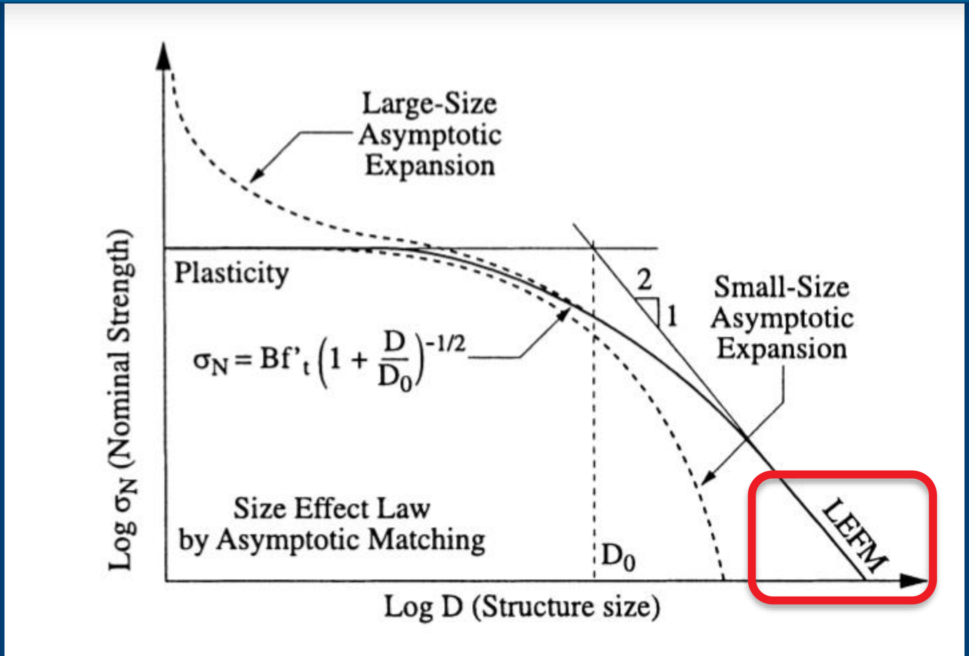


Figure: Bazant's Type II SEL

- Reduced-Units does not allow to reproduce size-effect.
- Need for rescaling of the ground-state energy

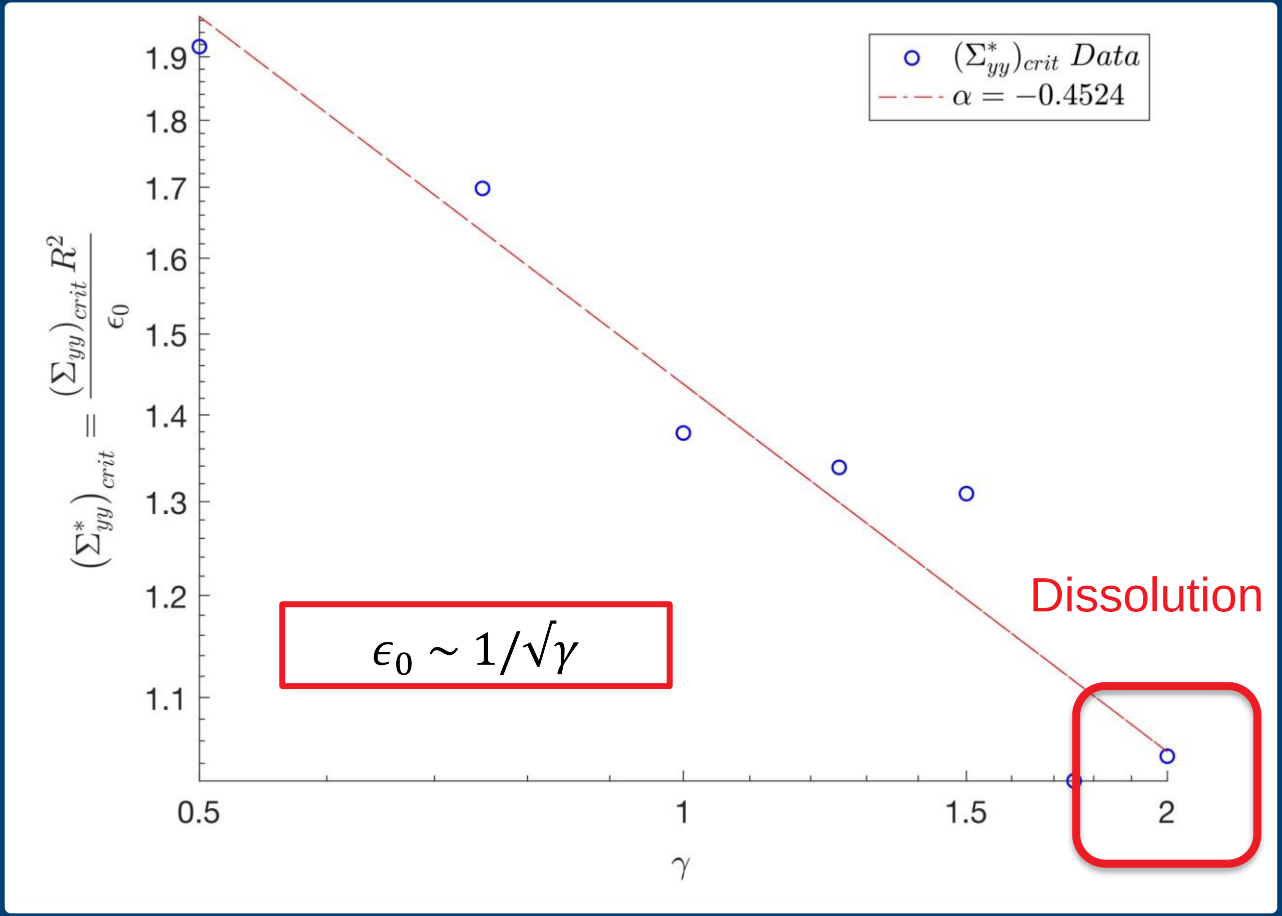


Figure: SEL *LEFM (previous research)*

A 4-pt bending beam: Size-effect (2)

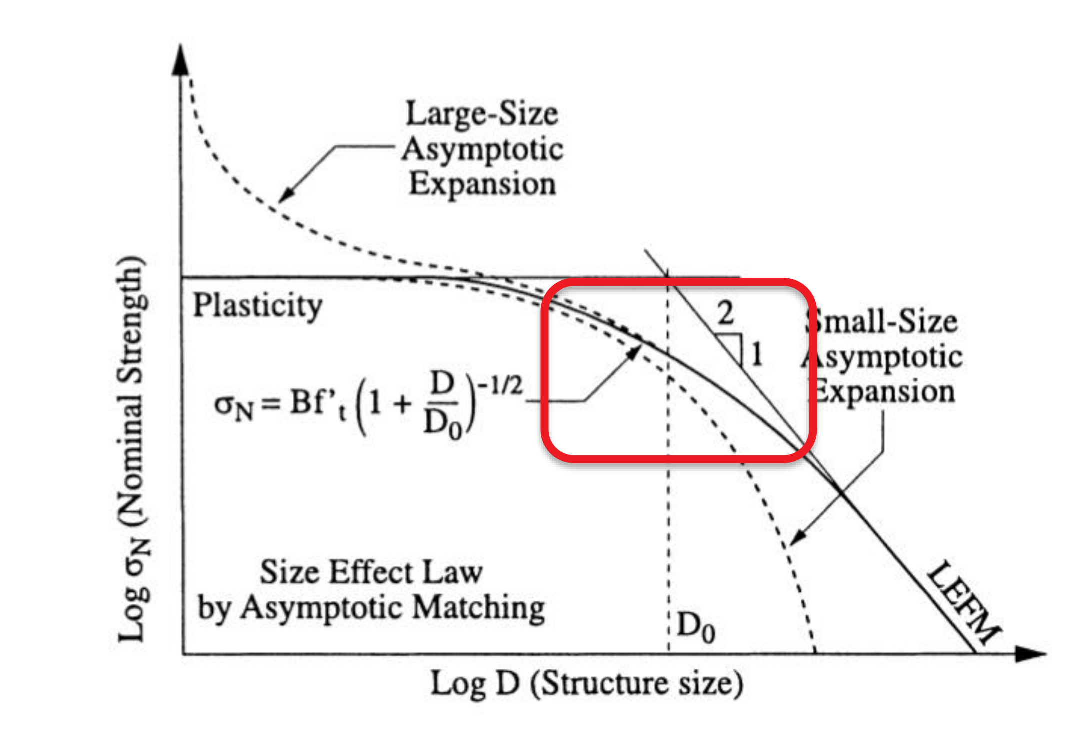


Figure: Bazant's Type II SEL

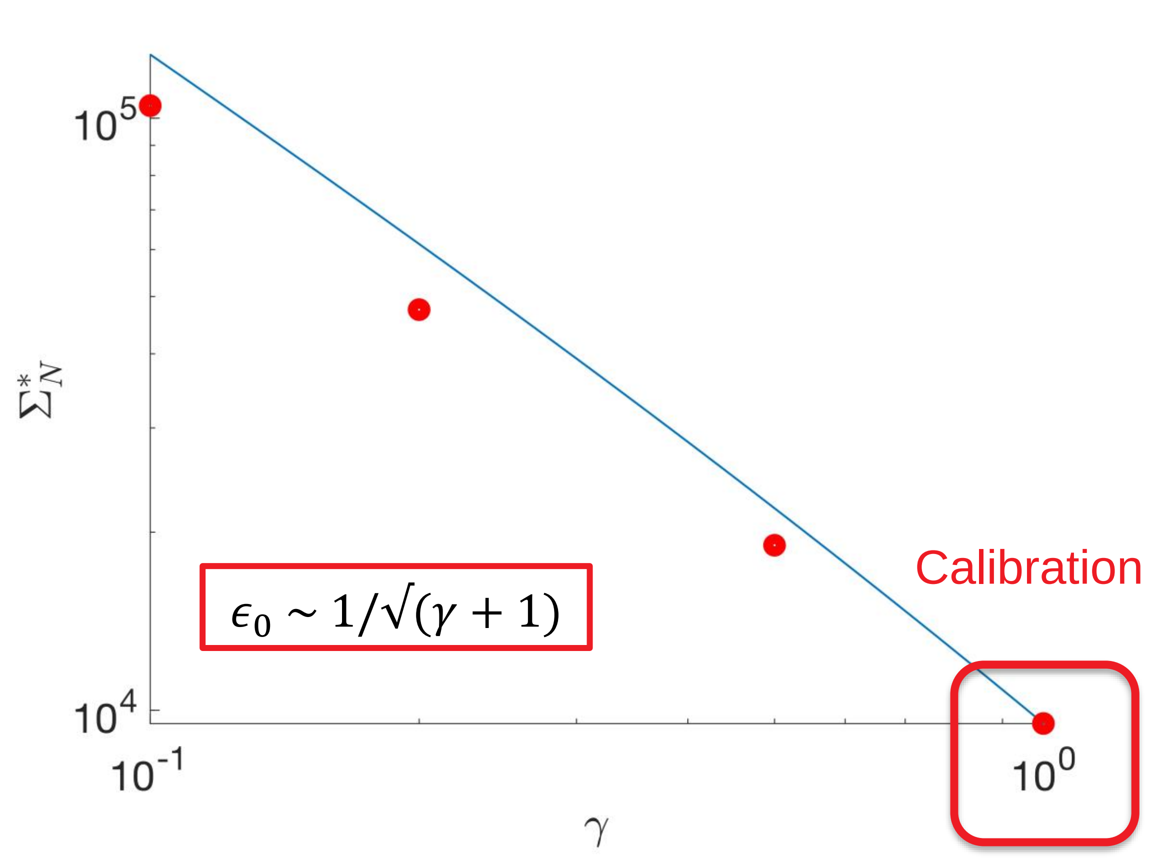


Figure: Type II SEL

Iosipescu test: From Mode I fracture to Mode II fracture

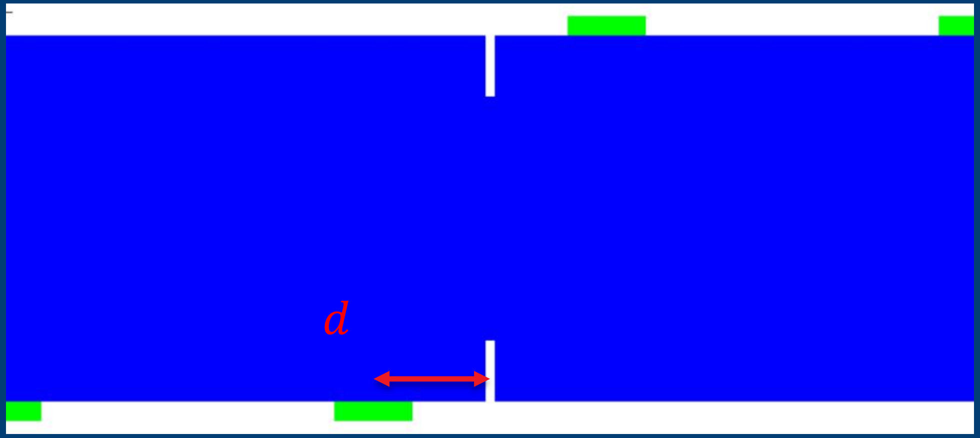


Figure: Iosipescu beam geometry

- Compressive loads on the two central pads.
- Fracture mechanism varies as a function of the load eccentricity.

  a) d large (Mode I) : opening
  b) d small (Mode II): sliding

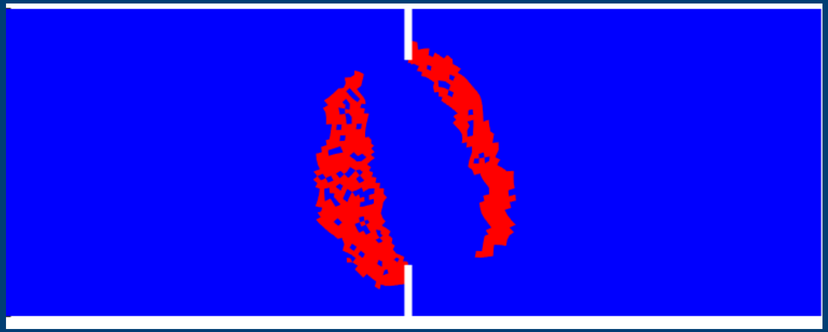


Figure: Mode I fracture

VD split

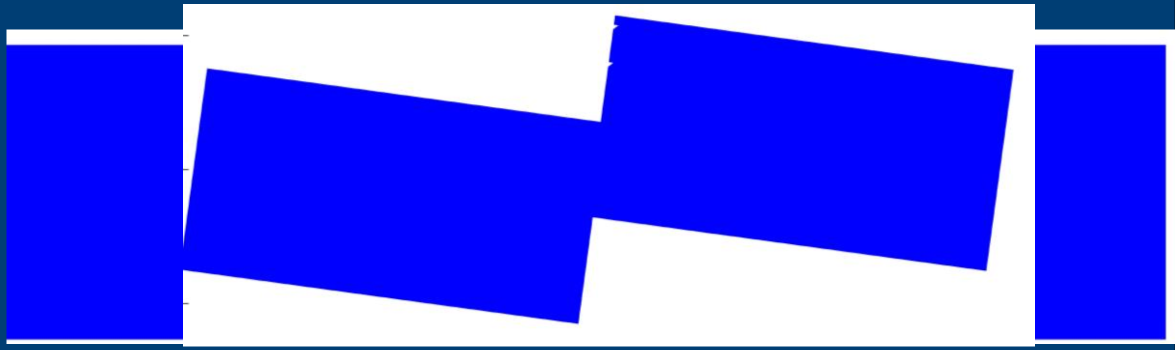


Figure: Mode II fracture

Inform stakeholders on the performances of a mix

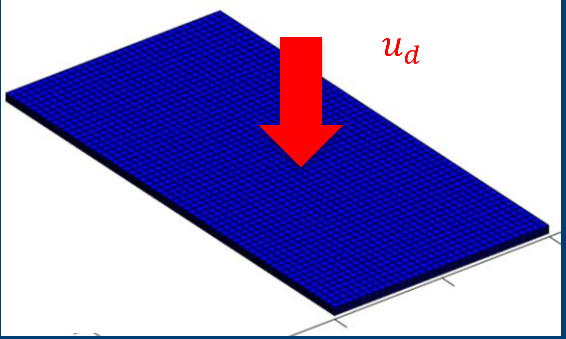


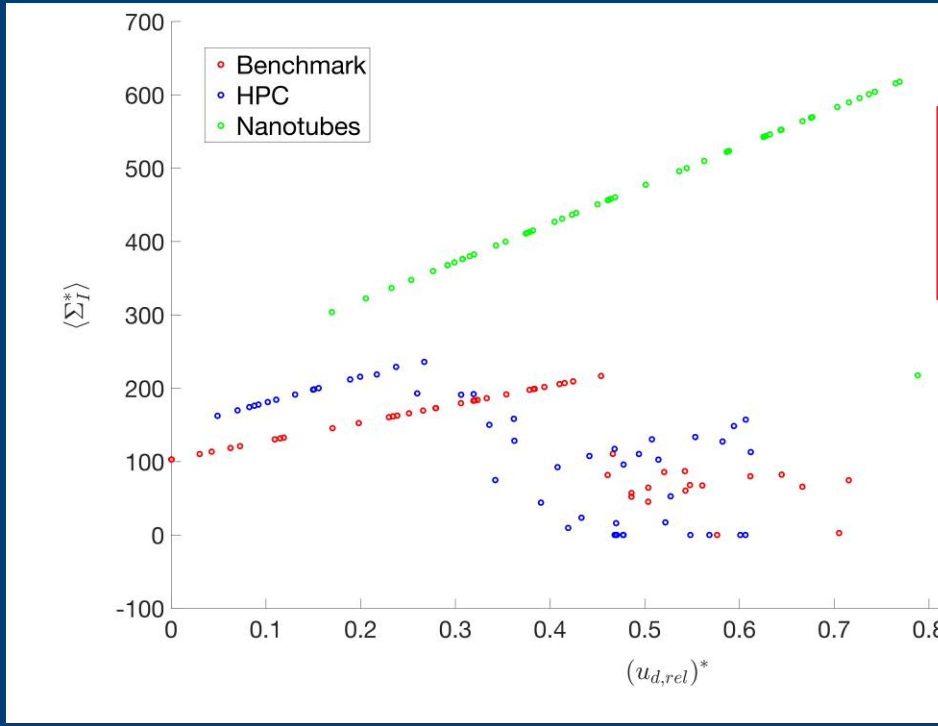
Figure: 3D plate geometry

- Key example for pavement and structural components (floor/wall) design.
- Informed choice through multi-parameter modelling

Material	ε_c	ν	$du_{rel} = \frac{f_t \times f_c^{ref}}{f_c \times f_t^{ref}}$	GHG (kg CO_2e/m^3)
Bench	0.1296×10^{-3}	0.17	1	355
HPC	0.1256×10^{-3}	0.15	0.7	400
Nanotubes	0.1032×10^{-3}	0.15	1.35	368

Figure: Mix Performances

Inform stakeholders on the performances of a mix



$$\frac{\Sigma_I^*}{\Sigma_{I,el}^*} < \frac{1}{2}$$

Figure: stress-displacement realisations

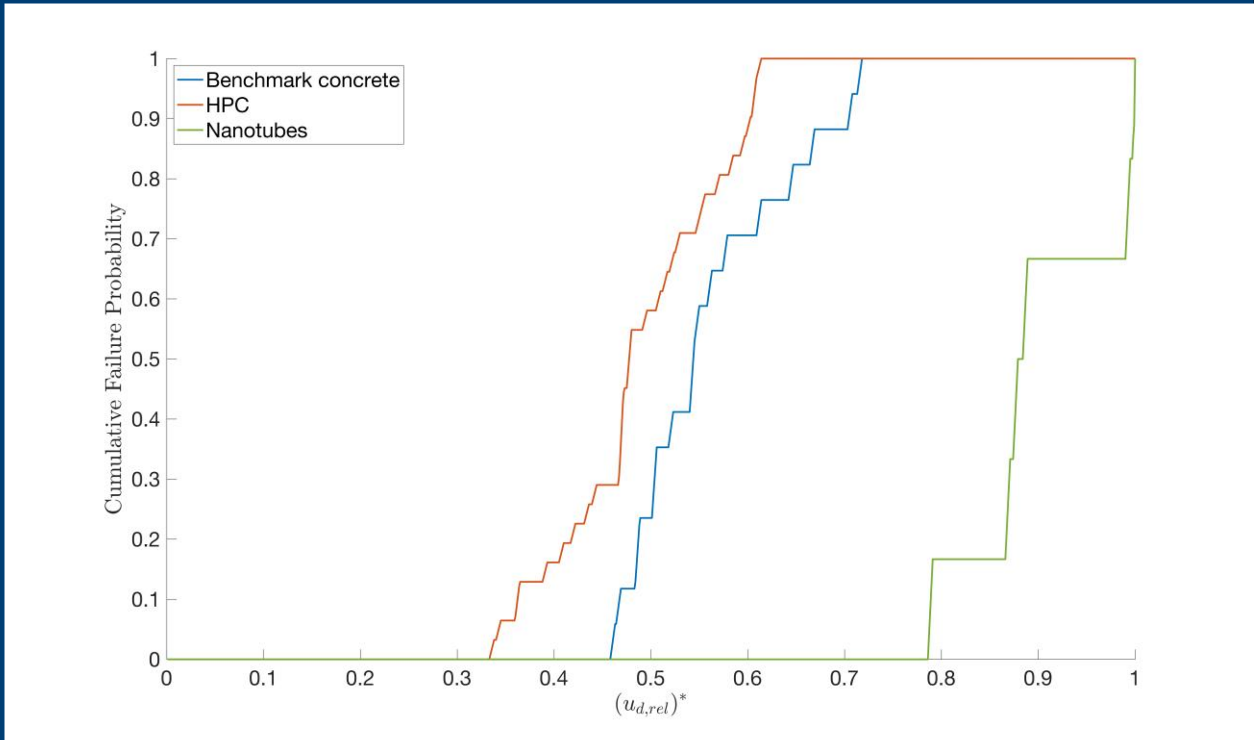


Figure: Fragility curves

Conclusions & Perspectives

- The SGCMC is a probabilistic fracture for (quasi)-brittle materials which:
  a) Enlarges fracture tracking by going beyond average responses.
  b) Predicts fracture loads for several geometries.
  c) Reproduces Type II size-effect.
  d) Describes complex fracture pattern

- The method can help the stakeholders make informed choices through the modelling of fragility curves for different mixes.

- Combining structural performances & GHG emissions can help optimize structures' design.

Thank you

For the most up-to-date information please visit the American Concrete Institute at: www.concrete.org

Questions: aattias@mit.edu