A Finite Element approach for mesoscopic modelling of fracture

C. La Borderie & collaborators

SIAME-EA4581
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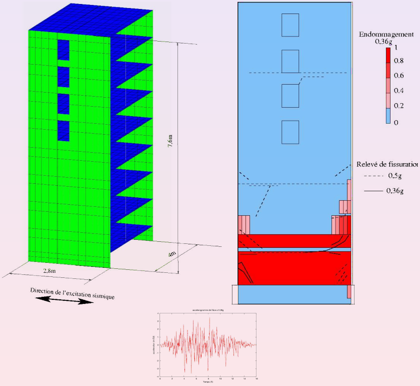
Introduction : Scales of modelling

Scales of Modelling

- Structure $> 10m$
- Macroscopic $\approx 1 - 10m$
- Mesoscopic $\approx 1 - 10cm$
- Microscopic$< 1cm$



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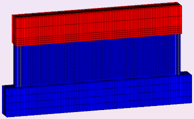

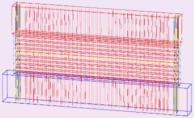

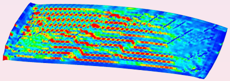

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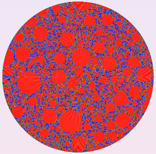
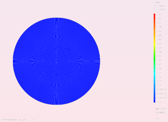
Splitting test





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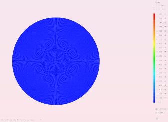

Crack width

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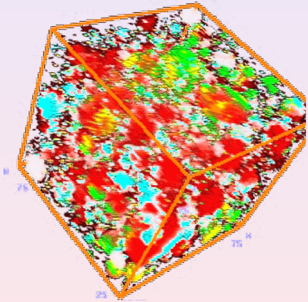
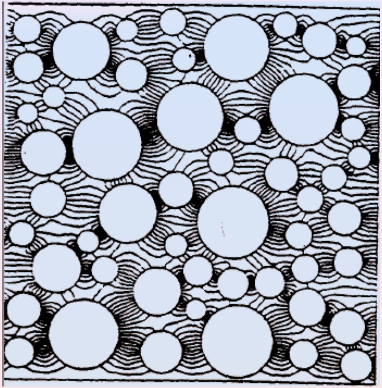
Cement paste $E/C = 0.45$



from D.P. Bentz (NIST, CEMHYD3D)

Introduction : mesoscopic models

- Witmann 1988 : Application to drying of concrete
- Mounajed, Menou & La Borderie ≈ 2002 : Symphonie, concrete at high temperatures
- Implementation into Cast3M : 2007
- Smooth method : 2010



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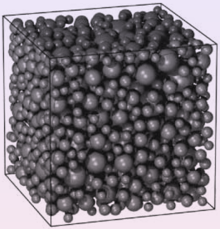

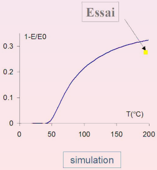

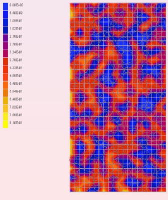

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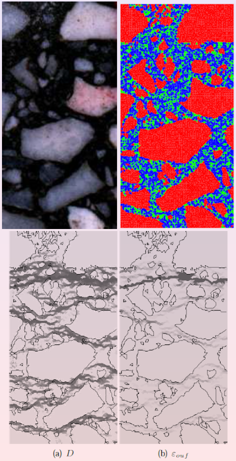

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specifications

- 2D or 3D random generation
- granular compactness
- ITZ
- Shape of aggregates

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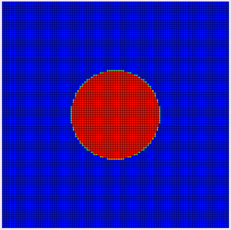
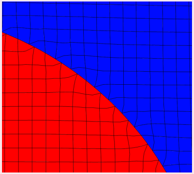
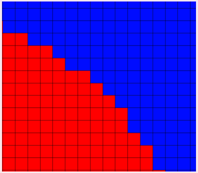
The smooth meshing method

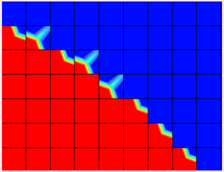




exact



discrete

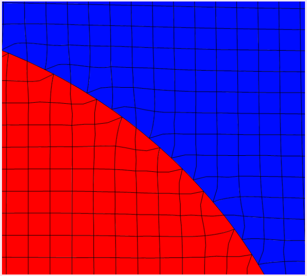


smooth

Meshing methods

Exact method

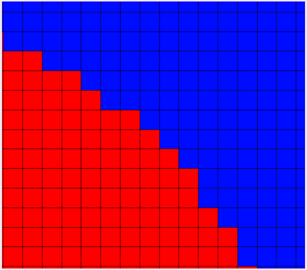
- Each aggregate is meshed separately, then the matrix is meshed
- Doesn't work in case of small and large aggregates, particularly in 3D
- ITZ can be modelled (but which parameter ?)



Meshing methods

Discrete method

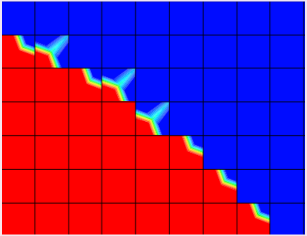
- Aggregates properties are projected on the mesh elements
- Costless method, irregularities at the boundary
- Total volume of aggregates is badly modeled



Meshing methods

Smooth method

- Aggregate properties are projected on the Gauss points
- Each Gauss point owns the material properties of paste or aggregate
- Costless method, unable to model ITZ



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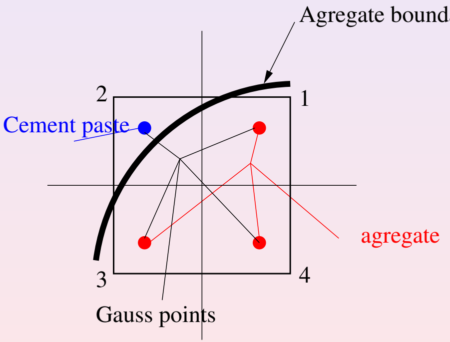
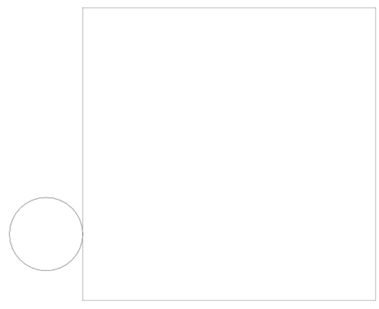
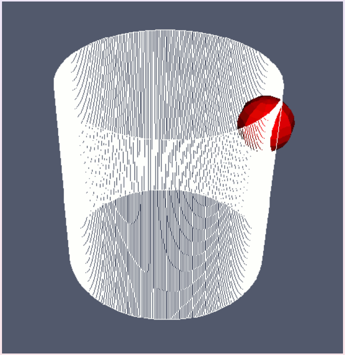
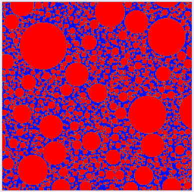


Aggregate drawing

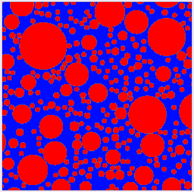




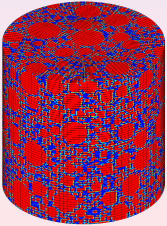
Mesh samples



$\Phi_{min} = 1mm$



$\Phi_{min} = 2.5mm$



$\Phi_{min} = 2.5mm$

Damage model

Damage model

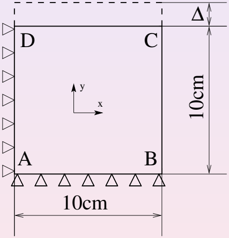
- Isotropic but unilateral (Fichant et al, 1999)
- Indirect effect of damage on en compression
- Softening in tension
  - Mazars' equivalent strain $\tilde{\varepsilon}$
  - mesh size h
  - parameters f_t et G_f

- $\bar{\sigma}_{ij} = \frac{E}{1+\nu}\varepsilon_{ij} + \frac{E\nu}{(1+\nu)(1-2\nu)}\varepsilon_{kk}\delta_{ij}$
- $\sigma_{ij} = (1-d)\langle\bar{\sigma}\rangle^{+}_{ij} + (1-d)^{\alpha_1}\langle\bar{\sigma}\rangle^{-}_{ij}$
- $d = 1 - \frac{f_t}{E\tilde{\varepsilon}} exp\left(\frac{hf_t}{G_f}\left(\frac{f_t}{E} - \tilde{\varepsilon}\right)\right)$

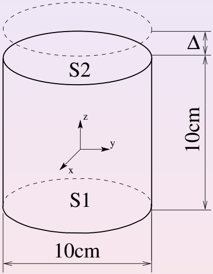
	$E(GPa)$	ν	$f_t(MPa)$	$G_f(J/m^2)$	α_1
Paste	15	0.2	3	20	10
Aggregates	60	0.2	6	60	30

Characteristics of components

Application to macroscopic behavior

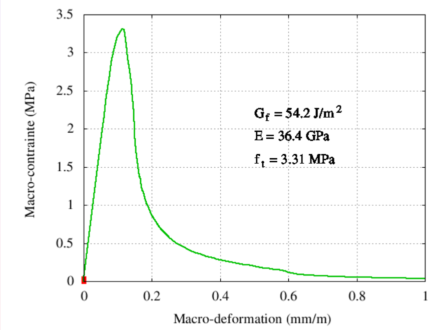


2D

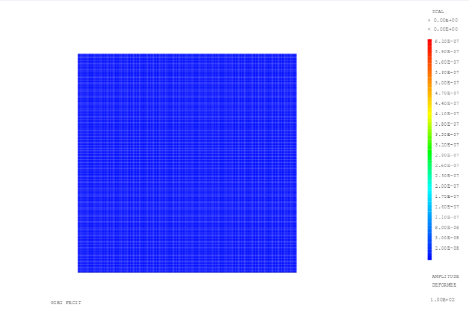


3D

Uniaxial tension

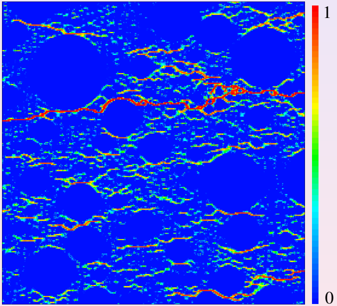


Macroscopic behavior

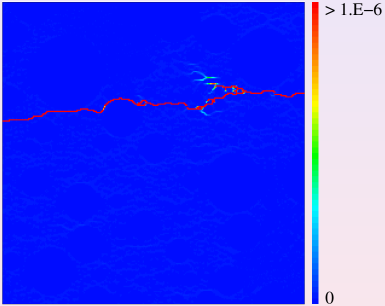


Crack width

Uniaxial tension

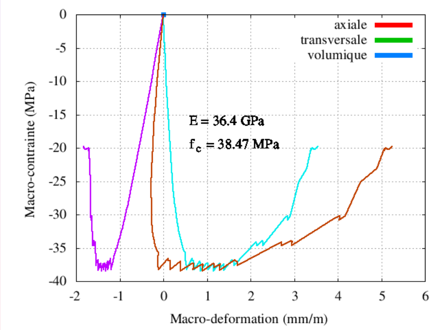


Damage field
at $E_{yy} = 1‰$

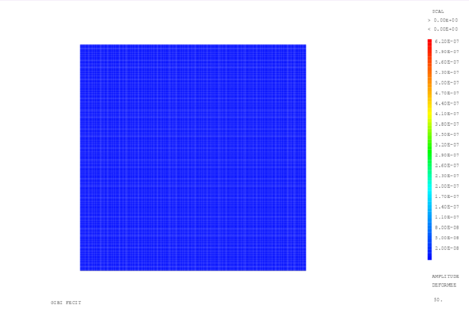


Crack width
Ã $E_{yy} = 1‰$

Uniaxial compression

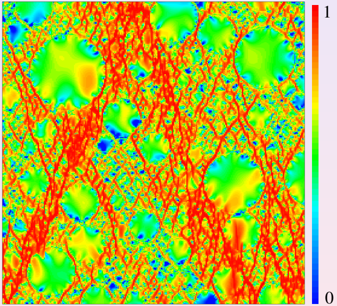


Comportement macroscopique



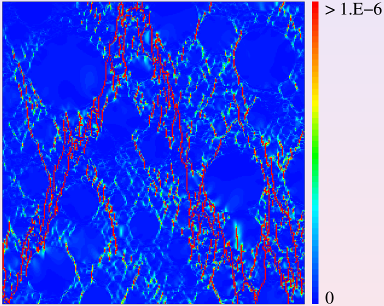
Ouverture de fissure

Uniaxial Compression



Damage field

Ã $E_{yy} = -1.83‰$



Crack width

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Effects of hydration on inner stresses

Hydration

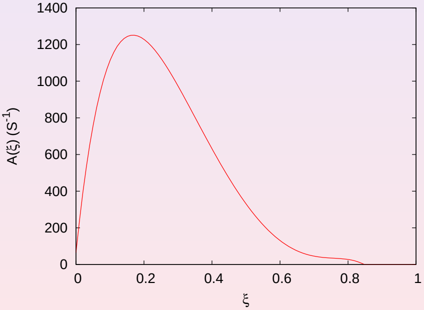
- Thermo-activation (Ulm)
- Hydration heat
- Endogenous shrinkage

$$\dot{\xi} = \tilde{A}(\xi)e^{-\frac{E_a}{RT}}$$

- ξ hydration degree
- $\tilde{A}(\xi)$ Normalized affinity function
- E_a is the activation energy ($Jmol^{-1}$)
- R is the constant of perfect gas ($8.314 Jmol^{-1}K^{-1}$)
- T is the temperature in kelvin

Effects of hydration on inner stresses

$$\tilde{A}(\xi) = \sum_{i=0}^{6} a_i x^i$$



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Effects of hydration on inner stresses

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$$C\dot{T} = \nabla(K\nabla T) + L\dot{\xi}$$

- C specific heat capacity
- K thermal conductivity $(Wm^{-1}K^{-1})$
- L is the total activation energy (Jm^{-3})

Effects of hydration on inner stresses

Hydration

- Thermo-activation (Ulm)
- Hydration heat
- Endogenous shrinkage

$$\dot{\varepsilon}_{au_{ij}} = -k\dot{\xi}\delta_{ij} \quad \textit{for } \xi > \xi_0$$

- ε_{au} autogenous shrinkage
- k shrinkage coefficient
- ξ_0 is the setting value of ξ for which the paste becomes to be elastic

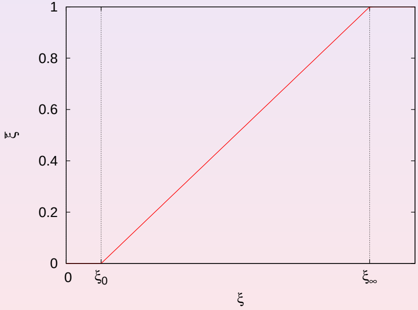
$$\dot{\varepsilon}_{th_{ij}} = \alpha\dot{T}\delta_{ij}$$

- ε_{th} thermal strain
- α coefficient of expansion

Coupling

Evolution of the mechanical parameters (from de Schutter)

- Effective coef of hydration
  $\bar{\xi} = < \frac{\xi - \xi_0}{\xi_\infty - \xi_0} >_+$
- Young's modulus $E(\xi) = E_\infty \bar{\xi}^\beta$
- Poisson's ratio
  $\nu = \nu_\infty \sin \frac{\pi * \bar{\xi}}{2} + 0.5 e^{-10 * \bar{\xi}}$
- Tension strenght $f_t(\xi) = f_{t\infty} \bar{\xi}^\gamma$
- Fracture energy $G_f = G_\infty \bar{\xi}^\gamma$



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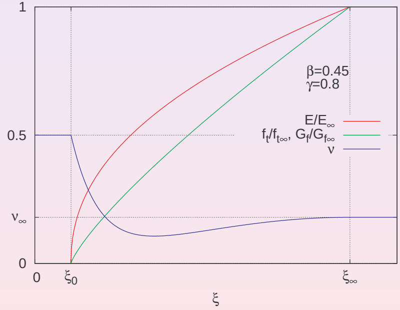
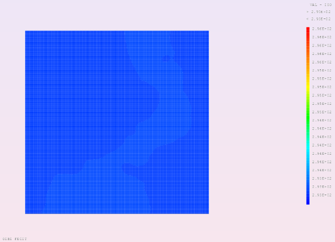
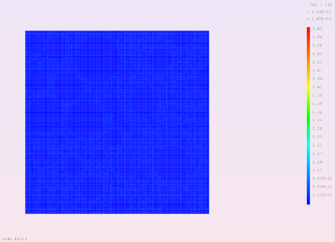


Hydration of concrete

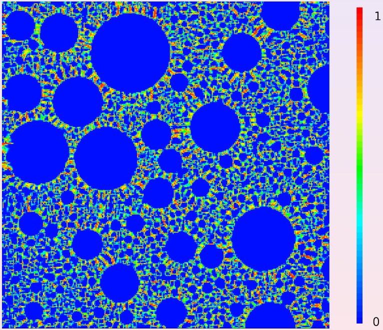


Temperature $T(K)$

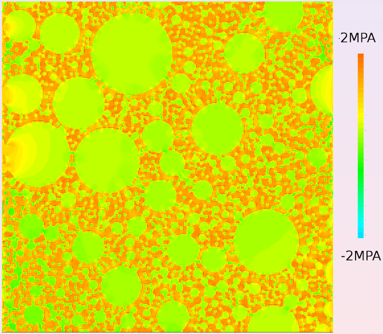


degree of hydration ξ

Hydration of concrete

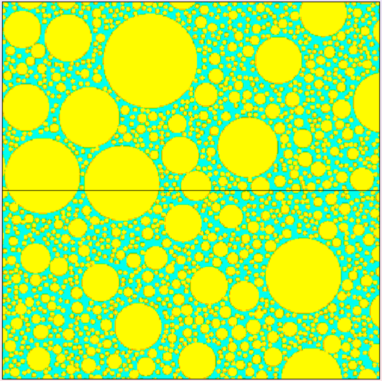


Damage

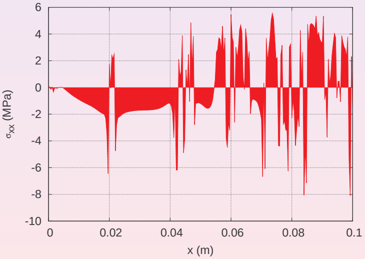


Hydrostatic stress σ_{kk}

Hydration of concrete

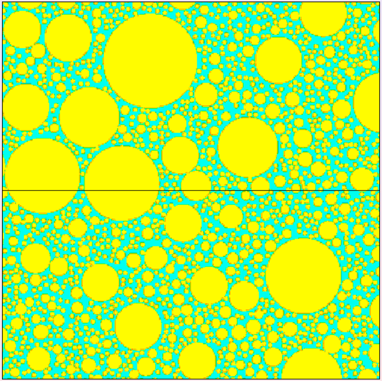


Along the middle line



meso-stress σ_{xx}

Hydration of concrete



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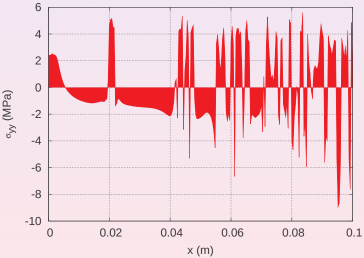


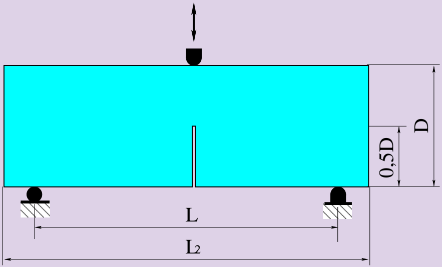
meso-stress σ_{yy}

Application to scale effects

Dimensions

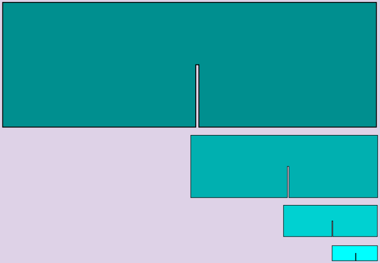
Thick (m)	L_2 (m)	L (m)	D (m)	Notch Height (m)
0,05	1,4	1	0,4	0,5D

Size of the beam



Experimental setup

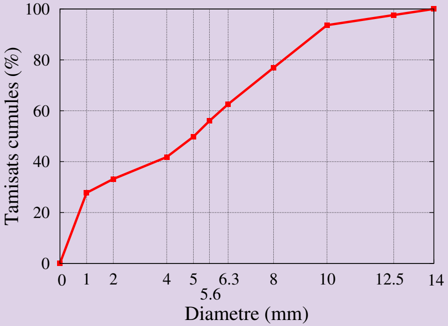
- Experiments from Rojas, Grégoire & Pijaudier-Cabot
- Homothety ratio : 1, $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$



beam size

Modeled problem

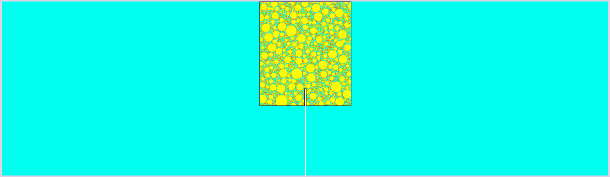
Grading curves



Model

Meshing strategy

- Notched beams of different homothety ratios $\frac{1}{2}$; $\frac{1}{4}$; $\frac{1}{8}$.
- Mix meso-macro model



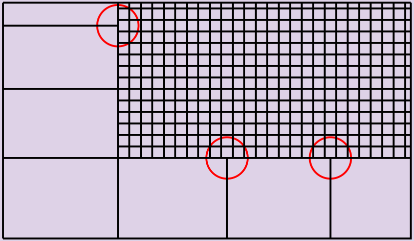
Mesh and aggregate drawing for the homothety ratio of $\frac{1}{2}$

- 3 different drawings are used for each beam.

FE Modeling

Meshing strategy

- Nodes do not match.
- Cinematic coupling.



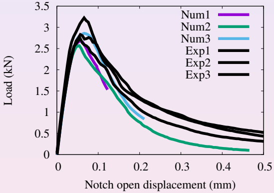
Connection

FE Modeling

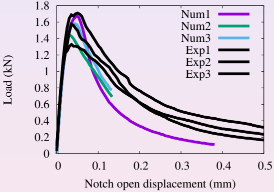
Mechanic parameters

	Young's modulus E (GPa)	Poisson's Ratio ν	Tension strenght f_t (MPa)	Fracture energy G_f (J/m^2)
Paste	25	$0,2$	3	20
Aggregates	55	$0,2$	6	60
Homogenized	$39,61$	$0,2$	-	-

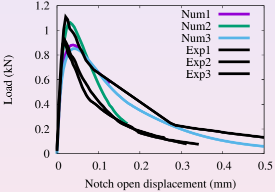
FE Results



Homothety ratio 1/2



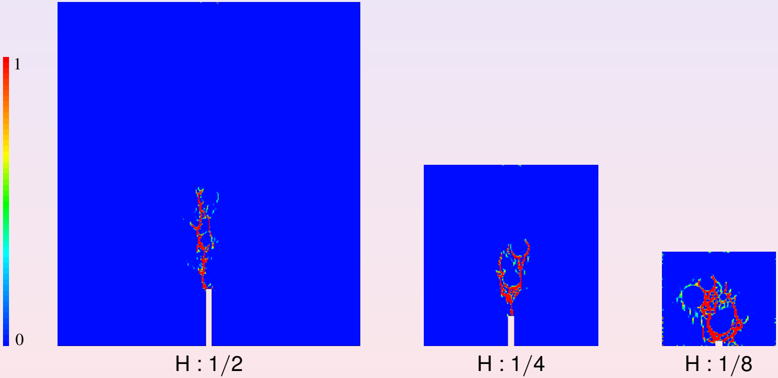
Homothety ratio 1/4



Homothety ratio 1/8

CMOD / load from experiments and simulations

Results

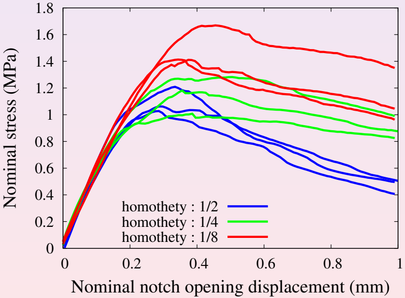


Damage at the peak load for different homothety ratio

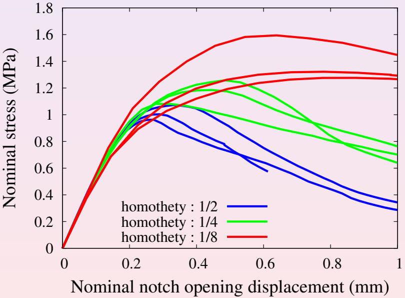
Scale effect law (Bažant, 1976)

Nominal stress : $\sigma_n = \frac{3PL}{2eD^2}$

Nominal notch opening : $U_n = \frac{U}{D}$



Experiments



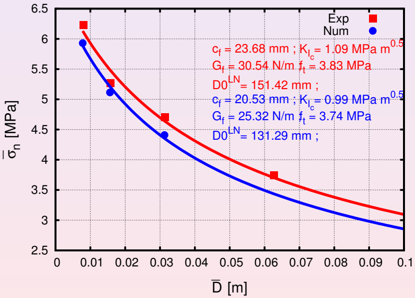
Numerical

$\sigma_n(U_n)$ curves

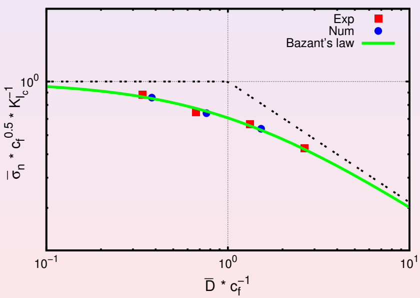
Scale effect law (Bažant, 1976)

Intrinsic size : $\bar{D} = 0.15637481182436 * D$

Intrinsic nominal stress $\bar{\sigma}_{nu} = 4.35395101484703 * \sigma_{nu}$



$\bar{\sigma}_{nu}(\bar{D})$ curve



Scale effect law from Bažant

Conclusions

Smooth FE method for mesoscopic scale

- Can be used in 2D or 3D even if 3D needs long computation time
- Take into account the granular compacity
- Useful for couplings
- Easy to use with any model as long as it is the same for aggregates and paste
- Does not account for the ITZ

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Thanks ! ! !

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