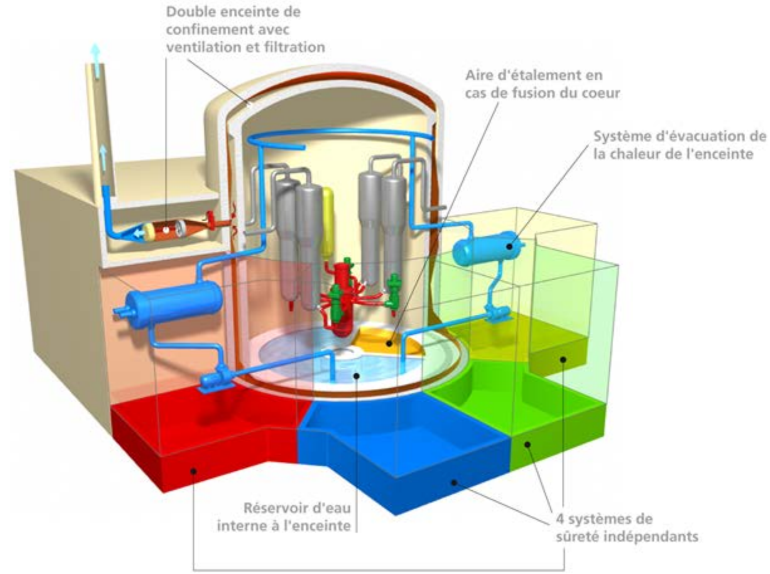
COUPLING BETWEEN MECHANICAL STATE AND PERMEABILITY FOR CONCRETE

Mohamad Dandachy

3SR, University of Grenoble, France

Introduction & context

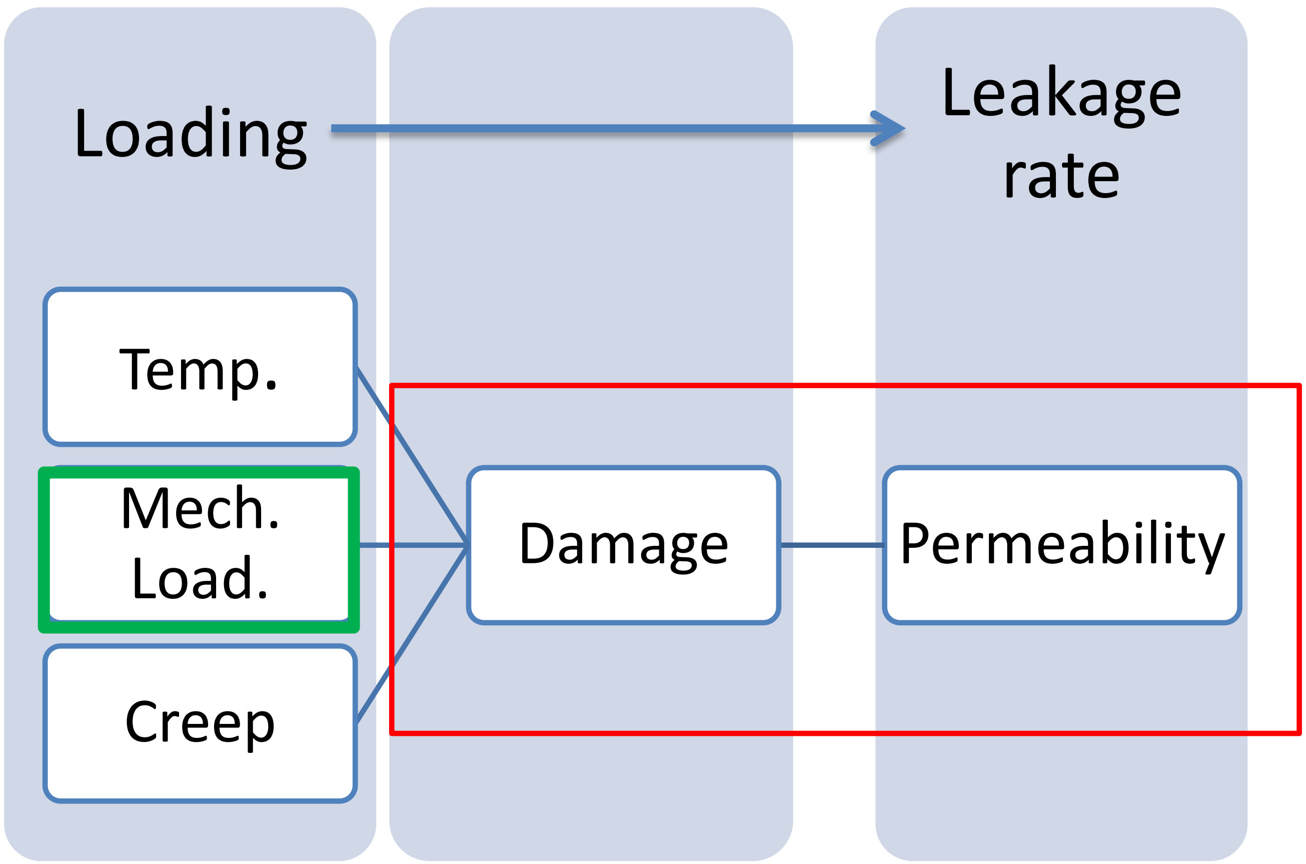


- Sealing has to be guaranteed for 40 years.
- **Diffuse damage (microcracking) and/or localized (macrocracking)**
- **Estimation of the evolution of transfer properties (structural durability analysis)**

Objectif:

Propose/validate numerical tools to predict/estimate leakage rate in a cracked structure.

Numerical modelling



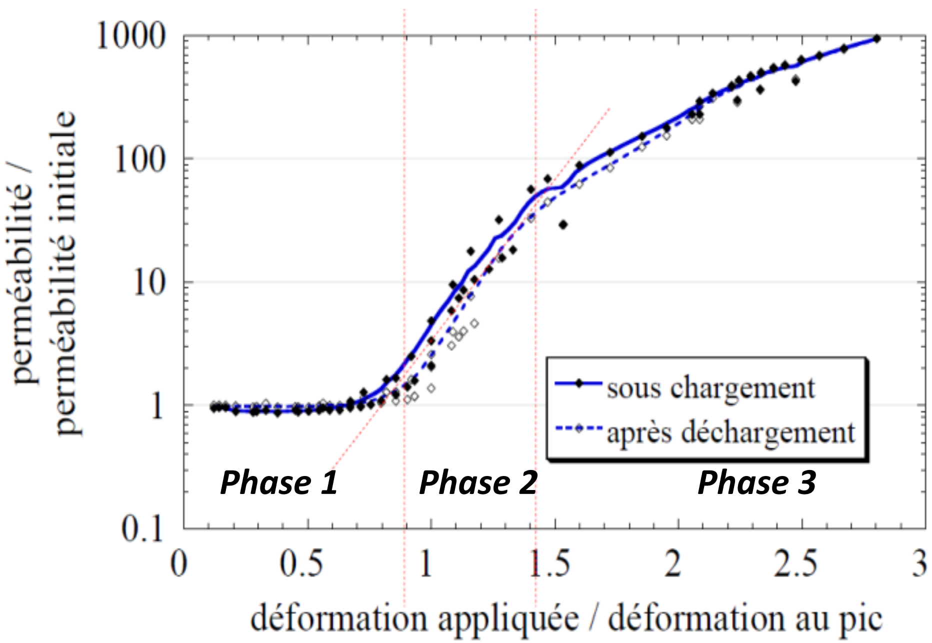
Here we focus on studying the effect of mechanical damage on the permeability of concrete.

Outline

- - **Bibliography**
- - Hydro-mechanical modelling
- - Application: Brazilian test
- - Conclusions
- - Perspectives

Effect of the mechanical load on the permeability of concrete

[Hearn 1999] [Aldea 2000] [Picandet 2001, 2009] [Biparva 2005] [Choinska 2007] [Dal Pont 2011 (HDR)] [Rastiello 2014]



Permeability evolution of concrete during compression test [Choinska et al. 2007]

Phase 1

- Low evolution of sample permeability
- Permeability governed by Darcy's law

$$k_m = \mu \frac{Q}{A}\left(\frac{\Delta P}{\Delta x}\right)^{-1}$$

Phase 2

- high permeability evolution
- Crack connectivity

Phase 3

- Permeability increased by 3 orders of magnitude
- Governed by Poiseuille's law

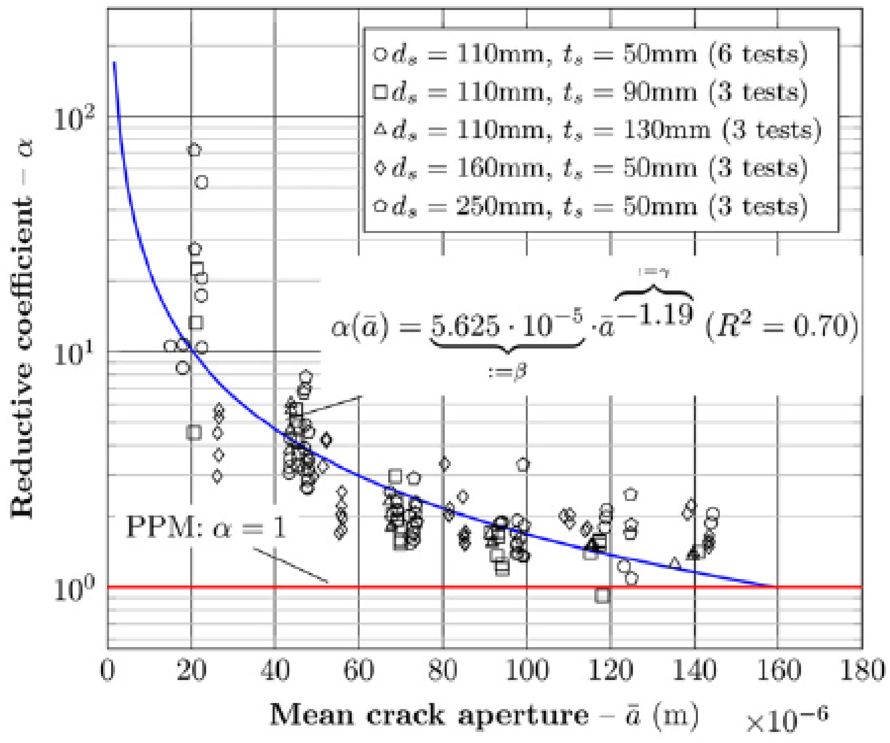
$$k_P = \frac{[u]^2}{12\alpha}$$

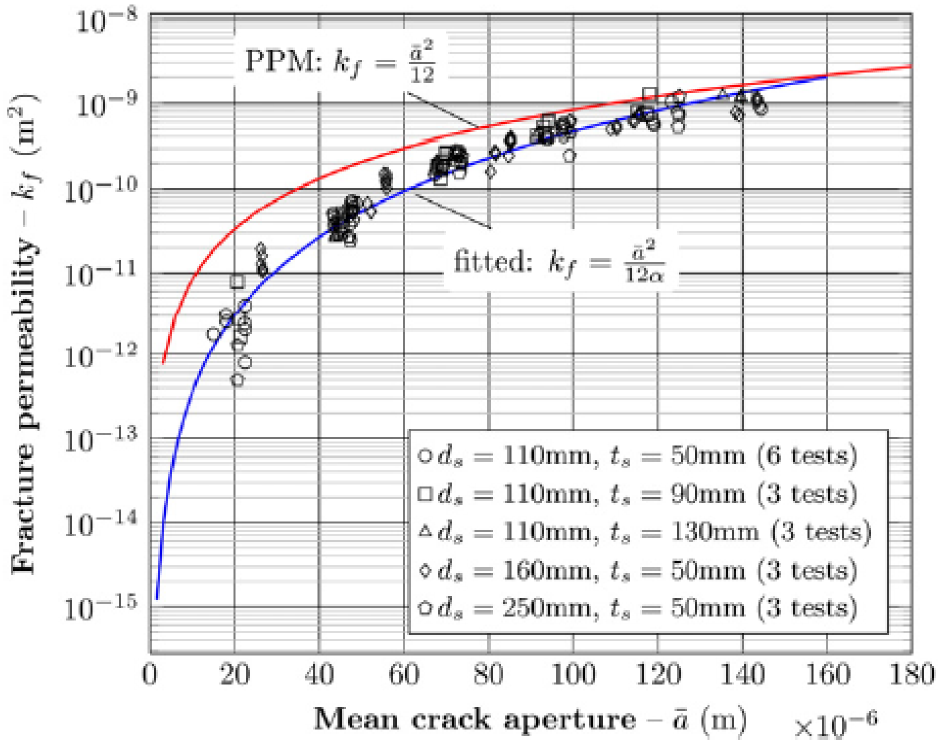
α :crack roughness, turtuosity and bridging

- **Difficulty to perform the coupling during the three phases with the same model**

Discussion on the correction factor α

[Hearn 1999] [Aldea 2000] [Picandet 2001, 2009] [Biparva 2005] [Choinska 2007] [Dal Pont 2011 (HDR)] [Rastiello 2014]





a) Correction factor versus mean crack aperture

[Rastiello et al. 2014]

b) fracture permeability estimation via the experimentally corrected parallel plates model

- **Correction factor is adopted in the numerical simulations**

Continuous modelling: damage model

Isotropic damage model

Local model

$$\varepsilon_{eq} = \sqrt{\sum_{i=1}^{3} < \varepsilon_i >_+}$$

Mazars 1986

- Can be applied at the scale of the structure.
- Simple, time cost is reasonable and accurate mechanical description.
- Crack opening can be calculated.
- No need before mechanical description information about the crack.

Nonlocal integral model

Pijaudier-Cabot and Bažant 1987

$$\phi_0(\boldsymbol{x}, \boldsymbol{s}) = \exp\left(-\left(\frac{4\|\boldsymbol{x} - \boldsymbol{s}\|^2}{l_c^2}\right)\right)$$

Stress based nonlocal model

Giry et al. 2011

$$\phi_0(\boldsymbol{x}, \boldsymbol{s}) = \exp\left(-\left(\frac{4\|\boldsymbol{x} - \boldsymbol{s}\|^2}{l_c^2(\boldsymbol{x}, \boldsymbol{\sigma}_{prin}(\boldsymbol{s}))}\right)\right)$$

$$\overline{\varepsilon_{eq}}(\boldsymbol{x}) = \frac{\int_\Omega \phi_0(\boldsymbol{x}, \boldsymbol{s}).\varepsilon_{eq}(\boldsymbol{s})d\boldsymbol{s}}{\int_\Omega \phi_0(\boldsymbol{x}, \boldsymbol{s})d\boldsymbol{s}}$$

Coupling between permeability and mechanical state (Continuous approach) [Pijaudier-Cabot et al, JEM (2009)]

(For each element i)

$$\log K_i = D log K_P + (1 - D) log K_D$$

Poiseuille's Permeability:
(Mean Permeability of a cracked element)

$$K_P = \xi \frac{(\lambda l_c)^3}{12 l_e} (F^{-1}(D) - Y_{D0})^3$$

$$F^{-1}(D) = Y_{D0} - \frac{\ln(1 - D)}{B_t}$$

ξ : correction factor for Poiseuille's Law (Roughness, Turtuosity, etc..)

Picandet's Permeability:
(Permeability of a microcracked element)

$$K_D = K_0 f(D) = K_0 \exp\left((\alpha D)^{\beta}\right)$$

K_0 : Permeability of a sound material

α, β: Fitted parameters

D : Damage Field

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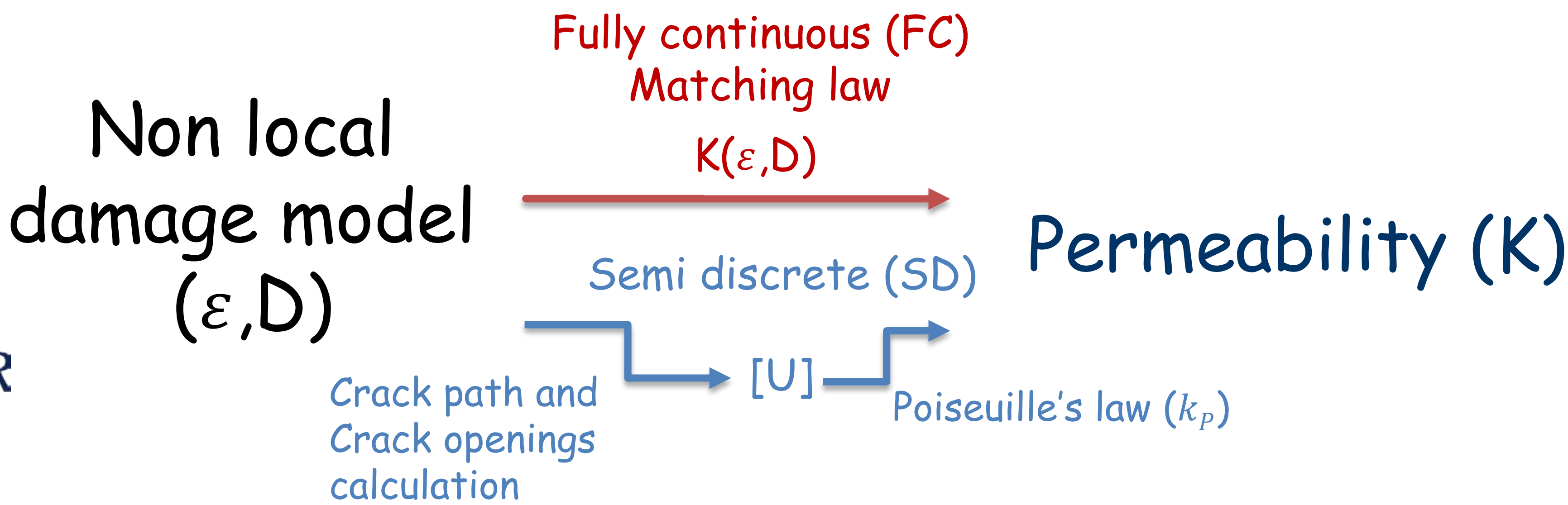
Coupling by means of two approaches



- **FC approach can be directly applied once the mechanical problem is solved.**
- **SD approach requires crack tracking and crack opening assessment**

Coupling by means of two approaches

Fully continuous approach — **Semi discrete approach**

Diffuse damage

$k_D^e = k_0 f(D^e) = k_0 \exp\left((\alpha D^e)^\beta\right)$ **Picandet et al. 2001**

$D^e \leq l$ $(l = 0{,}15\ for\ instance)$

Localized damage (Poiseuille k_P^e)

Fully continuous approach

$$k_P^e = \frac{(l^e)^{2-\gamma_r}}{12\beta_r}(\varepsilon_{n^e} - \varepsilon_{D0})^{3-\gamma_r}$$

ε_{n^e} : Maximum principal strain

ε_{D0} : Strain at first crack initiation

l^e : Average length of the FE ($\sqrt[3]{V^e}$)

$\xi = \mathrm{f}([\mathrm{u}], \beta_r, \gamma_r)$ **Rastiello et al. 2014**

$$\boldsymbol{K}_m^e = (k_D^e)^{1-D} \times (\boldsymbol{K}_P^e)^D$$

Semi discrete approach

- $k_P^e = \dfrac{[u_{n^e}^e]^{3-\gamma_r}}{12\, l^e\, \beta_r}$
- Crack path (Topological search, **Bottoni et al. 2015**)

$$[u_{\mathbf{n}^e}^e]_{strong} = \frac{(\varepsilon_{FE} * \emptyset)(x_0)\ \int_\Gamma \emptyset(x_0 - x)ds}{\emptyset(0)}$$

Dufour et al. 2008

Sum of fluxes $\mathbf{Q} = \boldsymbol{Q}_{bulk} + \boldsymbol{Q}_{crack}$

$$\boldsymbol{K}_m^e = k_D^e \boldsymbol{I} + k_P^e \boldsymbol{R}^{\mathrm{T}}(\boldsymbol{I} - \boldsymbol{n}^e \otimes \boldsymbol{n}^e)\boldsymbol{R}$$

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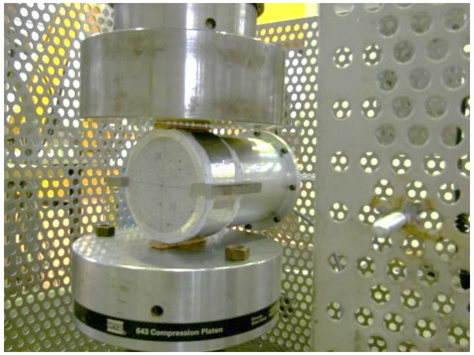
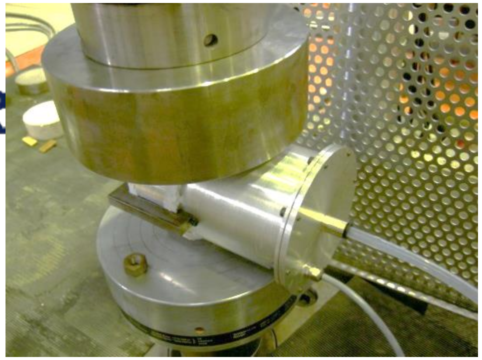
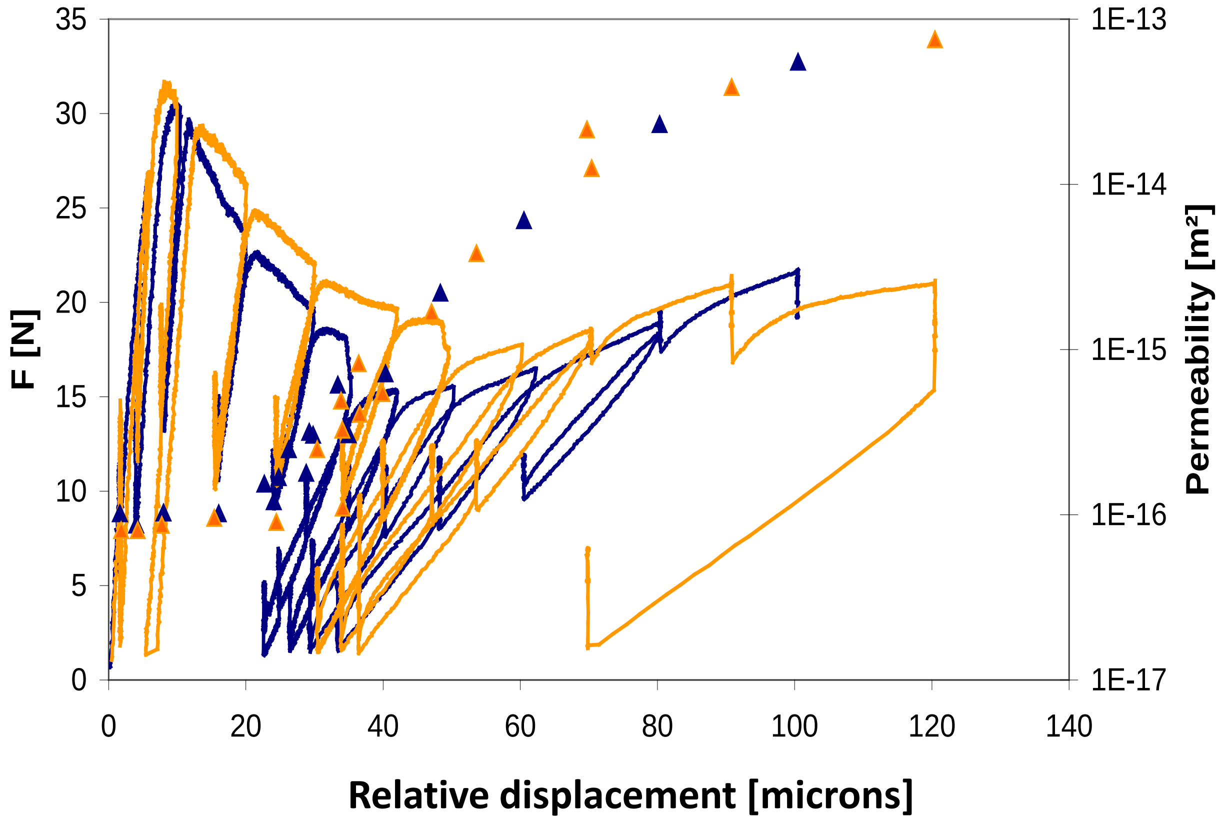
- - Bibliography
- - Hydro-mechanical modelling
- - Application: Brazilian test
  - Physical experiment
  - FE simulation
- - Conclusions
- - Perspectives

Physical experiment (Hydro-mechanical behaviour)

(Controlled by COD)



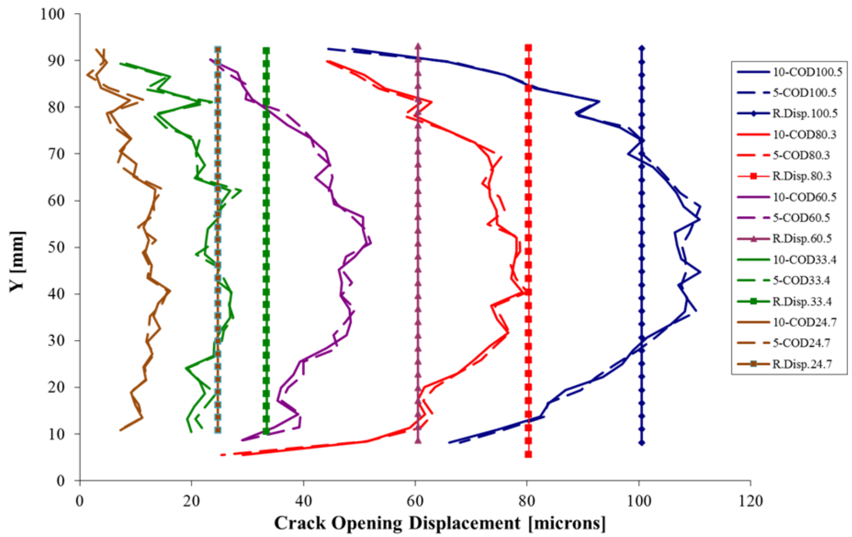


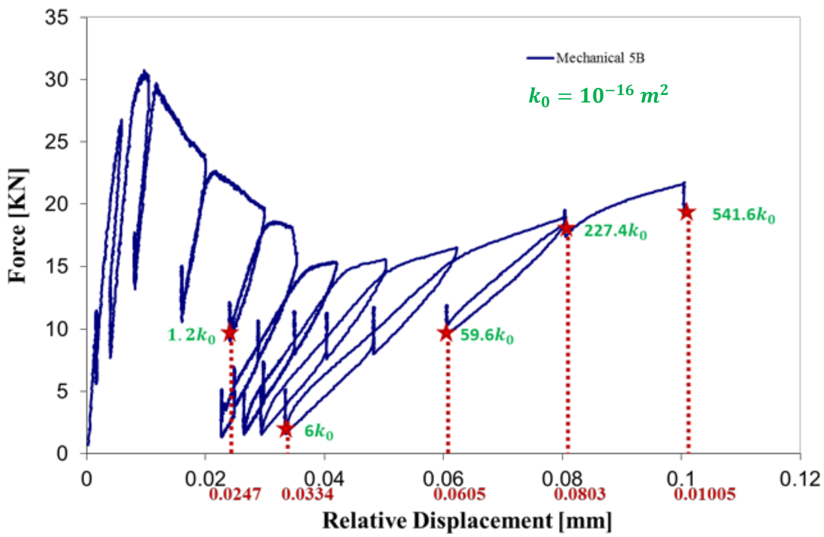


Gas permeability of mortar under splitting test determined when partially unloaded.

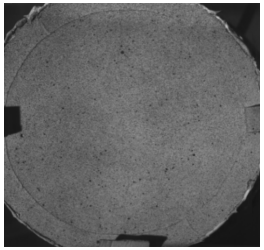
Dufour 2007 (HDR)

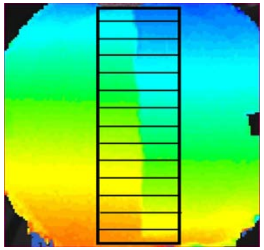
Physical experiment (Crack opening assessment)



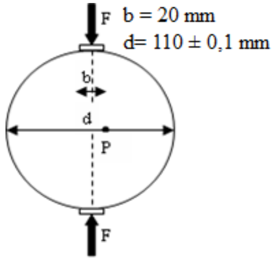


Face S_s





Face S_b



S_b : surface with larger diameter

P: on S_b, disp. sensor

- **3D effect seen on the cracking patterns due to geometrical effect.**

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  - Physical experiment
  - **FE simulation**
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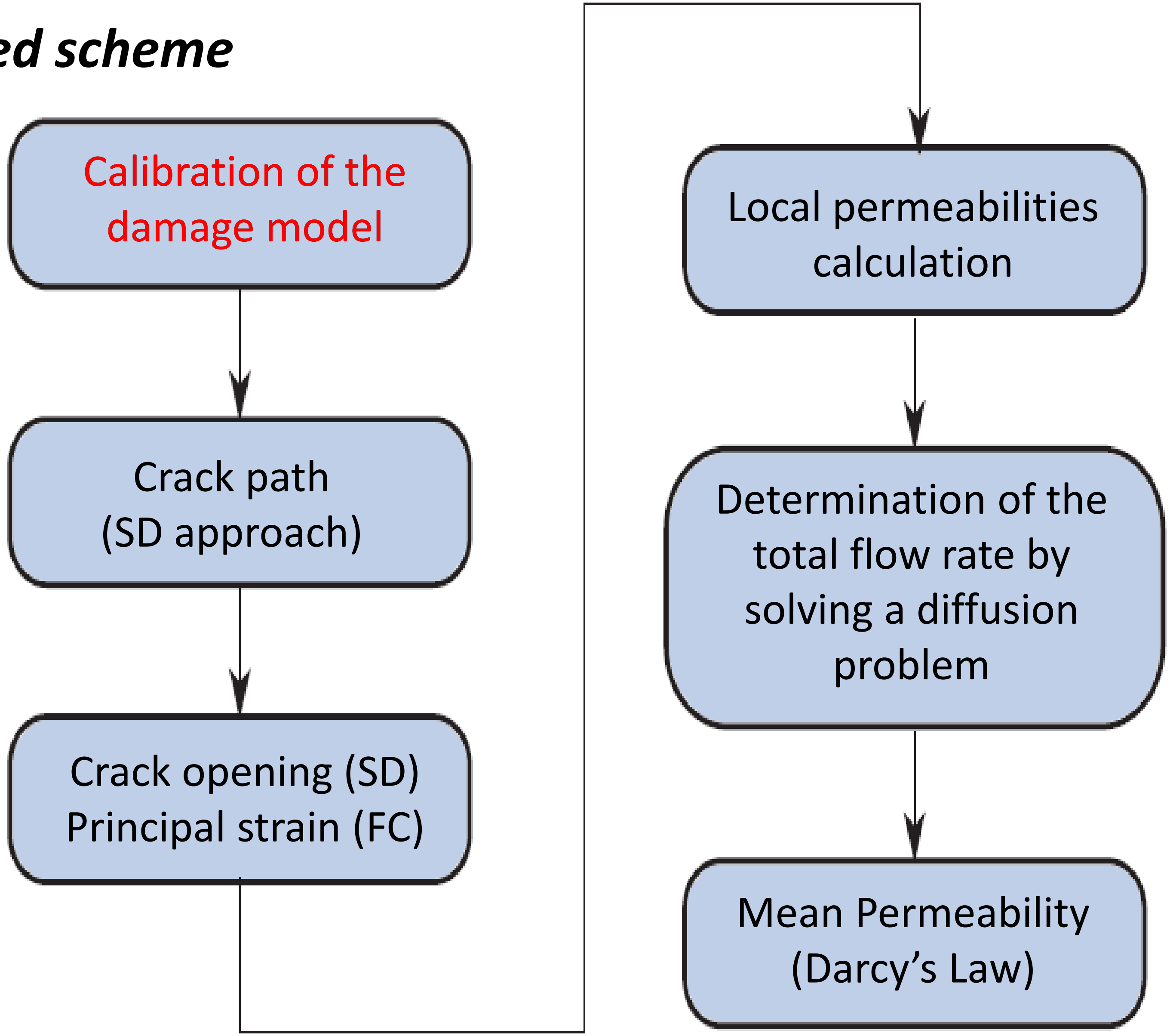
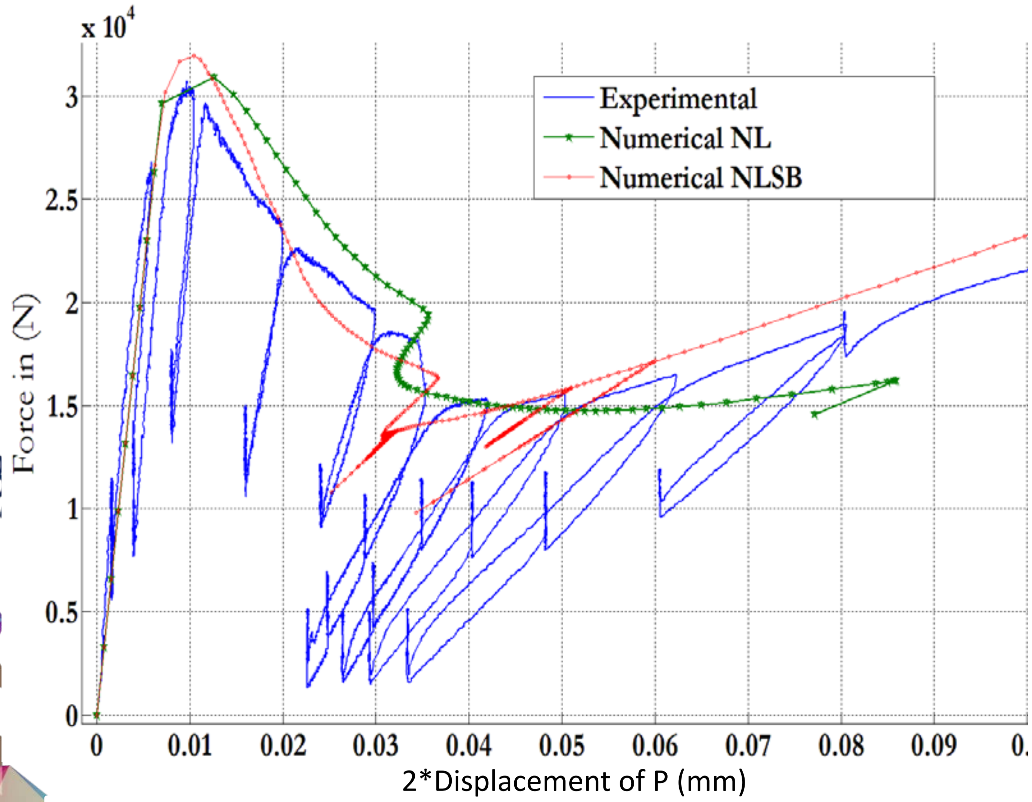
Staggered scheme (weak)

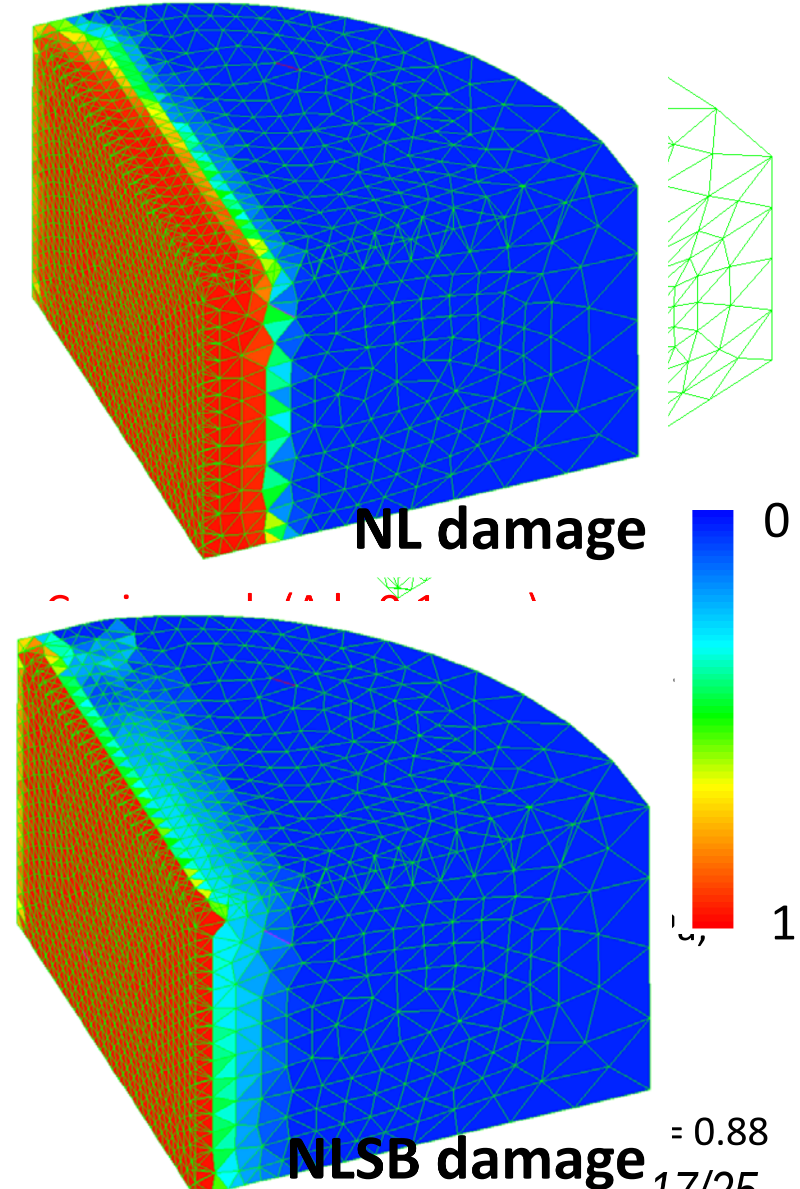


Calibration of 3D mechanical model

Arc-length control by maximum strain

(Force-Disp snap back)



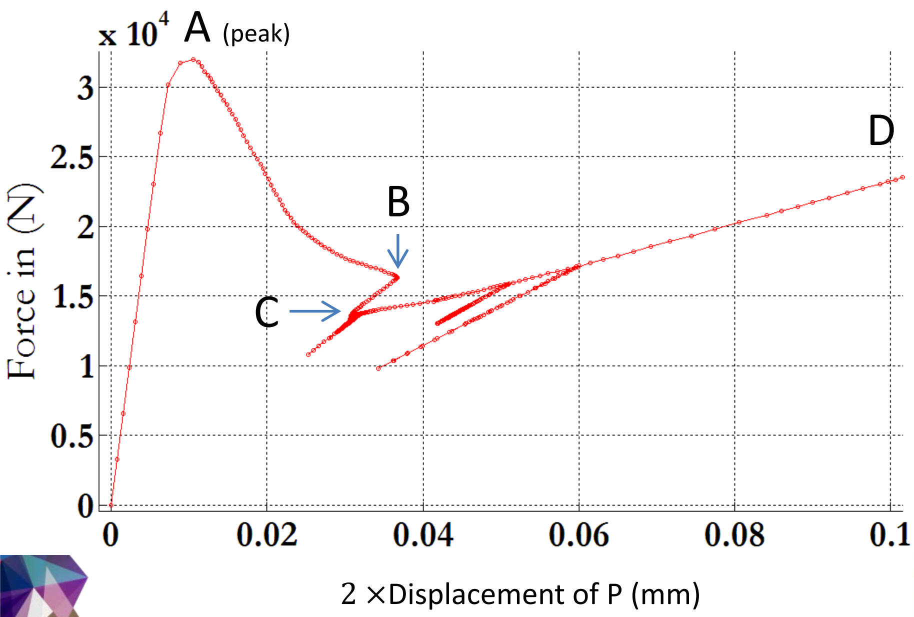


- **Better behavior after the splitting phase.**
- **More realistic damage field.**

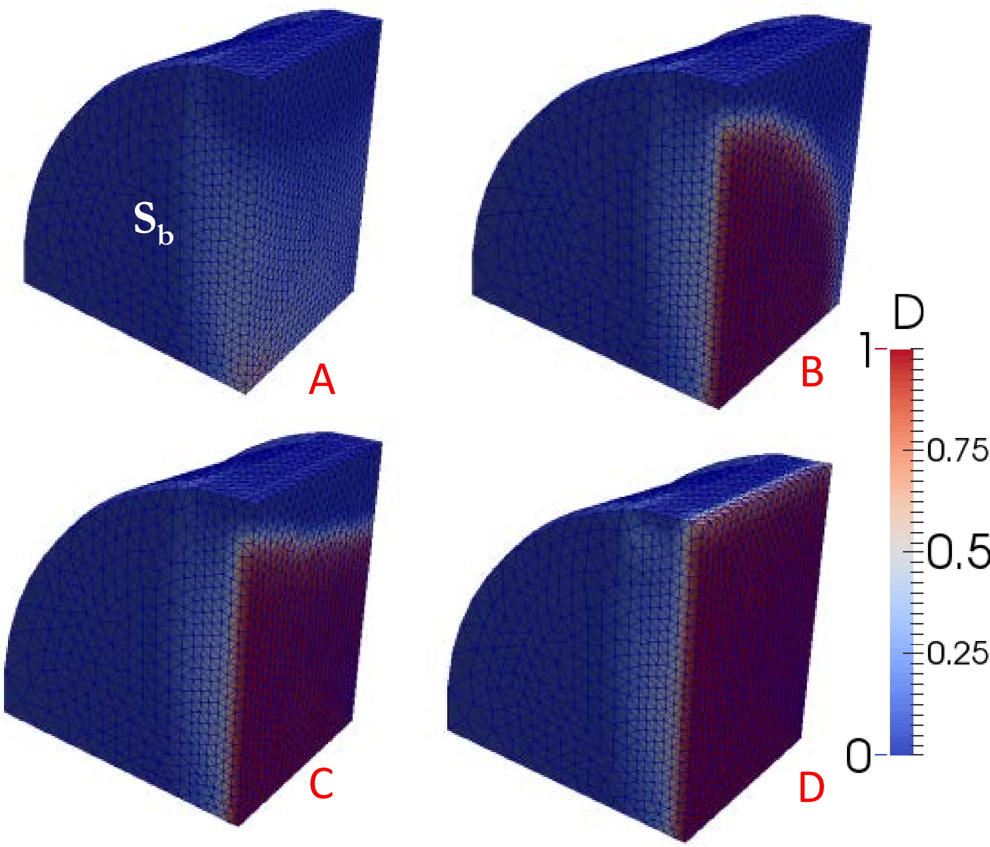
➡ **NLSB**

Damage Profiles

NLSB model

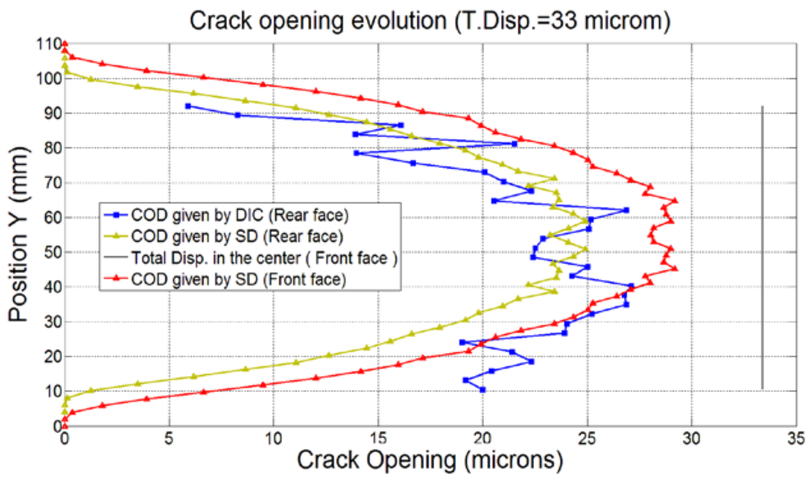


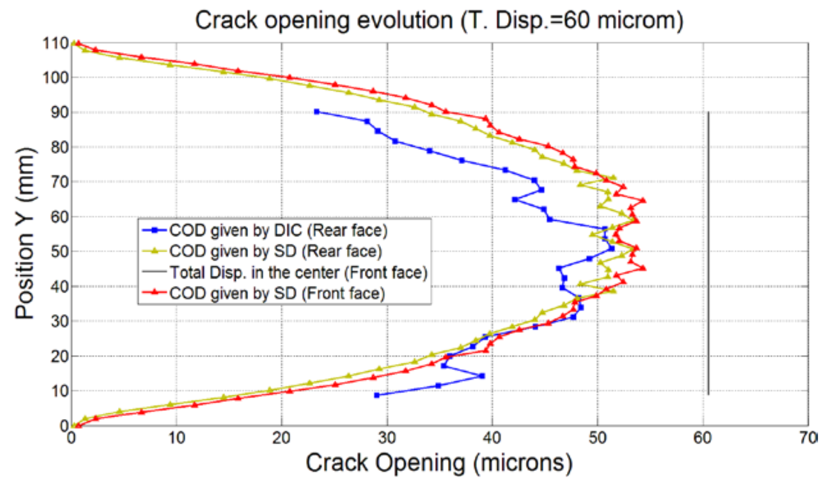
S_b : surface with larger diameter

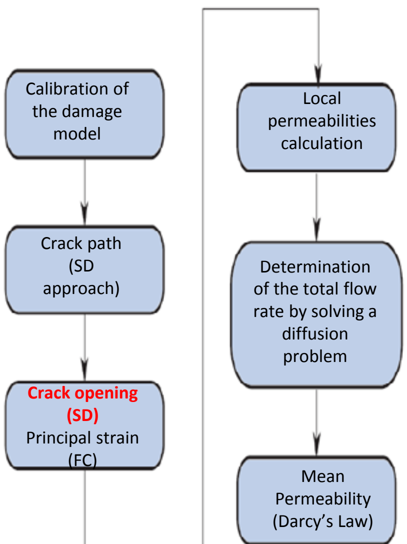


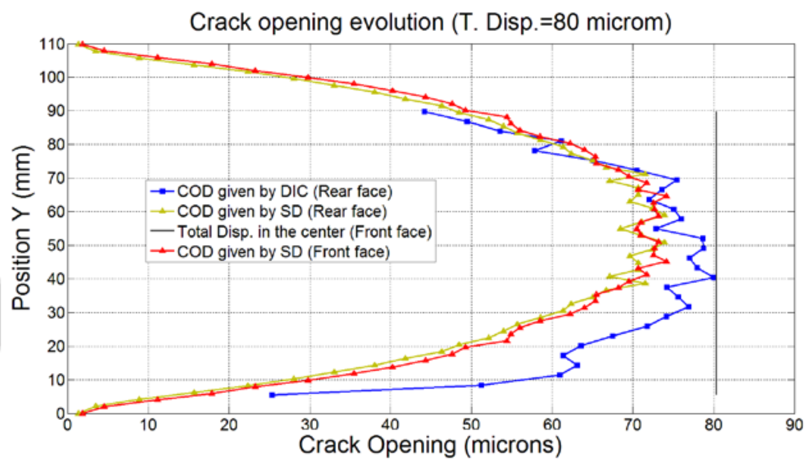
- **The 3D simulation highlights the damage (crack) propagation in the longitudinal direction.**

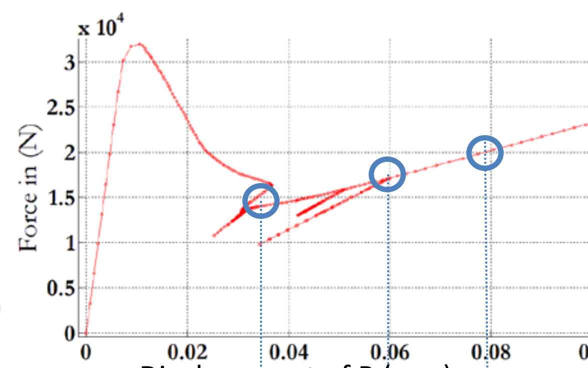
Crack opening assessment



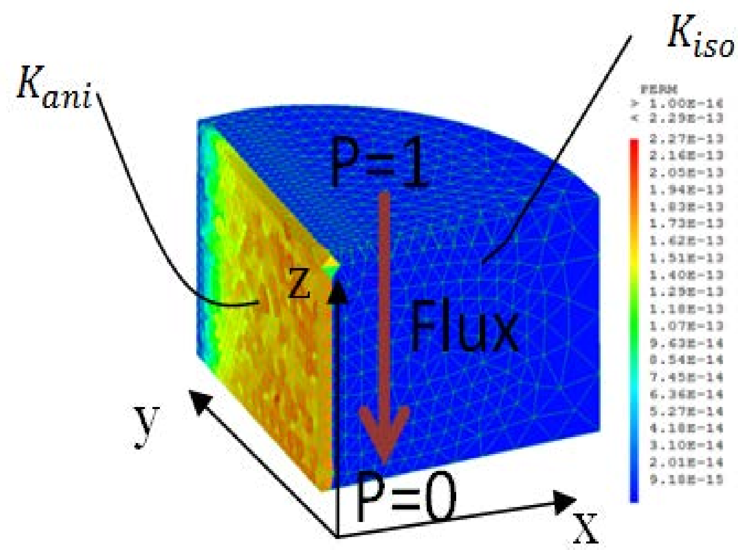


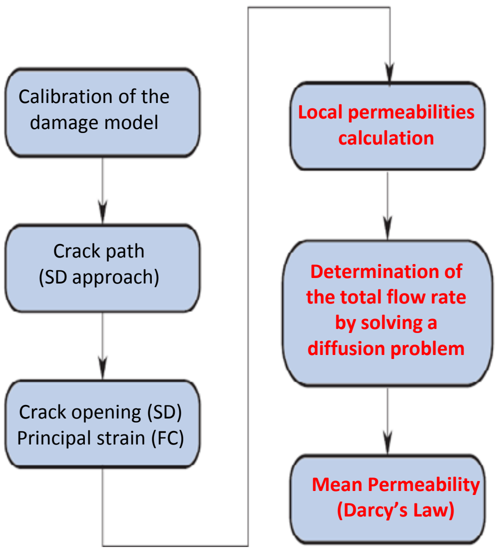






Local and structural permeabilites calculation

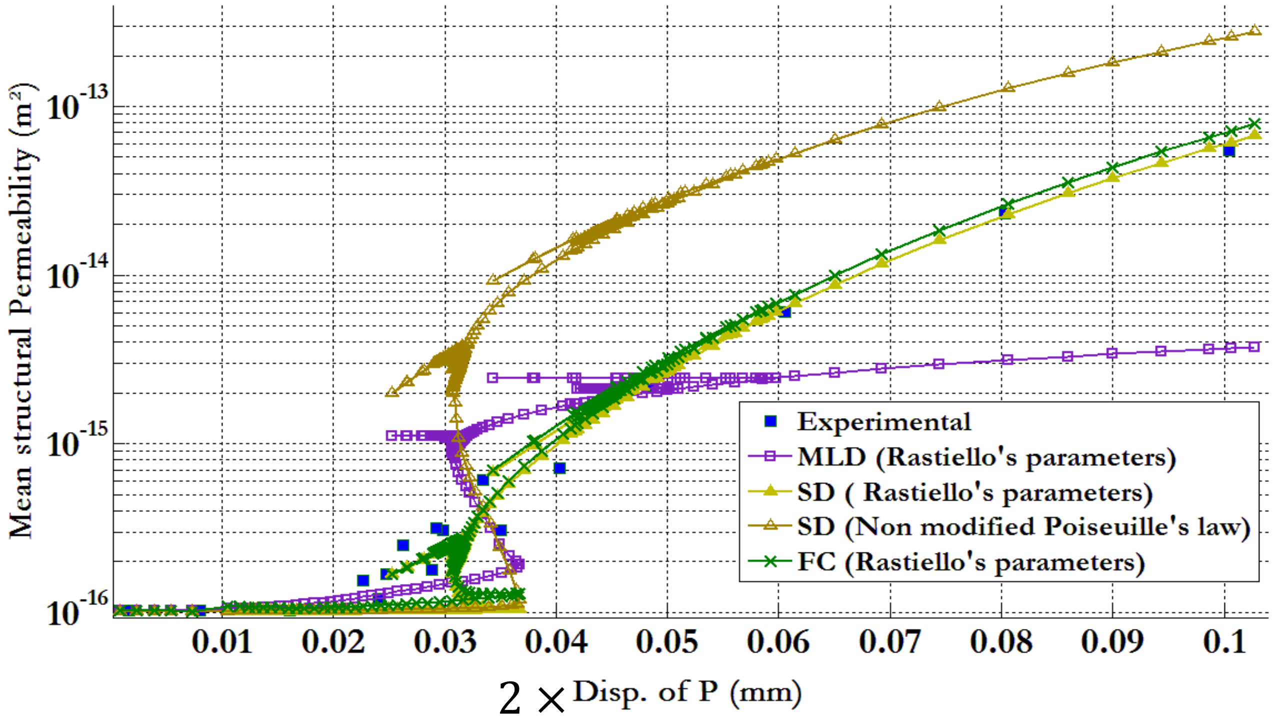




Solving the diffusion problem by applying a pressure gradient.

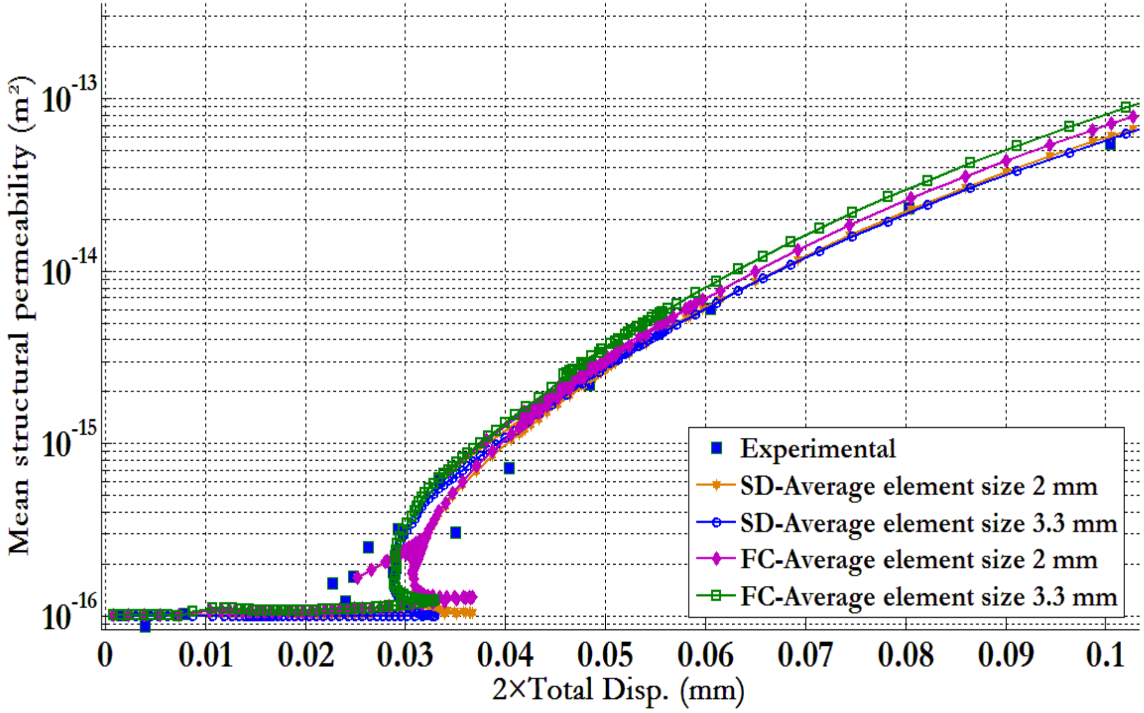
$$\Rightarrow \quad Q \text{ is computed and } \quad k_m = \mu \frac{Q}{A}\left(\frac{\Delta P}{\Delta x}\right)^{-1}$$

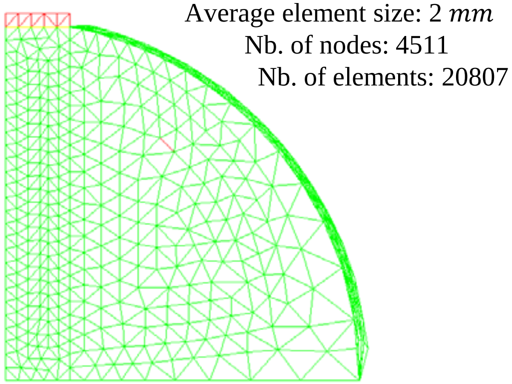
Coupling between permeability and mechanical state

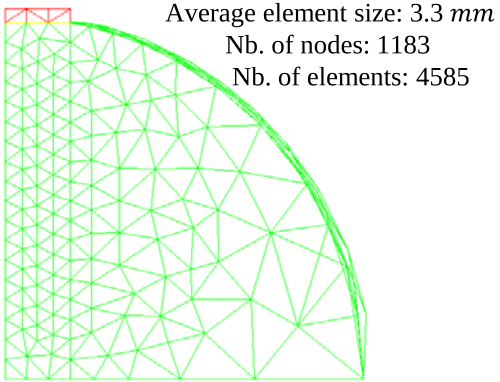


1. **Damage (permeability) stabilizes around 1 and do not evolves when unloading (MLD)**
2. **Poiseuille's law (ksi=1) overestimates the crack permeability**
3. **Good agreement between the proposed models and experimental data**
4. **Rastiello's parameters are valid for an OC/mortar up to COD of 0.1 mm**

Mesh sensitivity







Mesh independent results obtained with the proposed approaches

Outline

- - Bibliography
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- - Application: Brazilian test
- - **Conclusions**
- - **Perspectives**

Conclusions:

- The NL stress based is proven to be better than the original NL on the Global scale as well as on the local one.
- With (MLD), damage (permeability) stabilizes around 1 and do not evolves when unloading.
- The crack opening assessment is obtained accurately using the Strong Discontinuity approach applied in the post processing phase.
- It is shown that the proposed parameters of Rastiello that intervene in the relation between the correction factor and the crack opening, γ and β, are valid for an ordinary concrete/mortar.
- The coupling using two approaches is validated on the splitting test.
- Mesh independent results are obtained.

Perspectives :

- Coupling permeability with thermal and/or creep damage.
- Other applications (steel-concrete interface for instance).
- Generalize the approaches to structure elements.
- Consider slip flow (apparent permeability) in the hydraulic models.

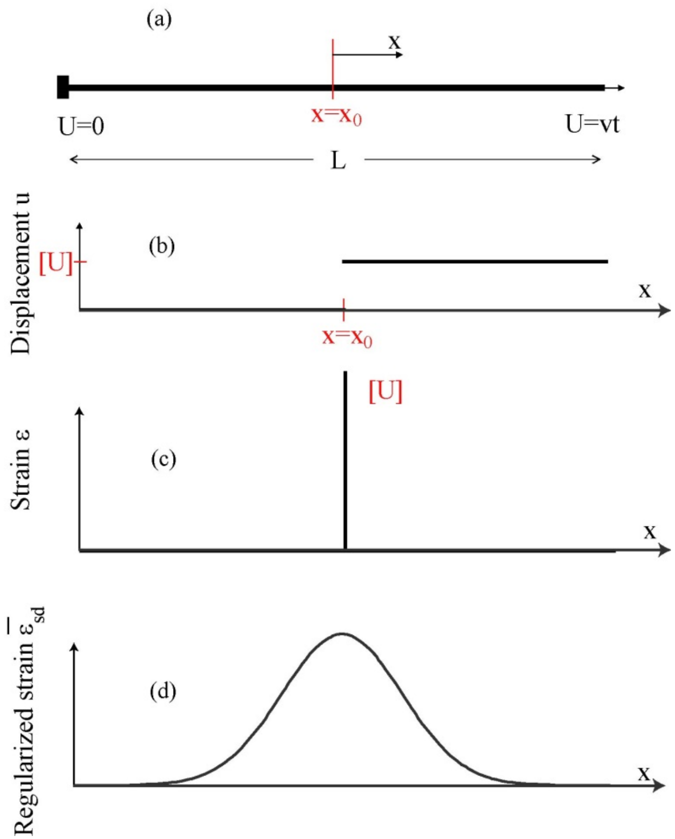
Thank you for your attention

Crack location and opening

Crack path

• Trivial in the actual test (Plane of symmetry parallel to the loading).

Crack opening along the path



Strong DiscontinuityApproach : Equalityof numericaland analytical profiles at their maximum x_0

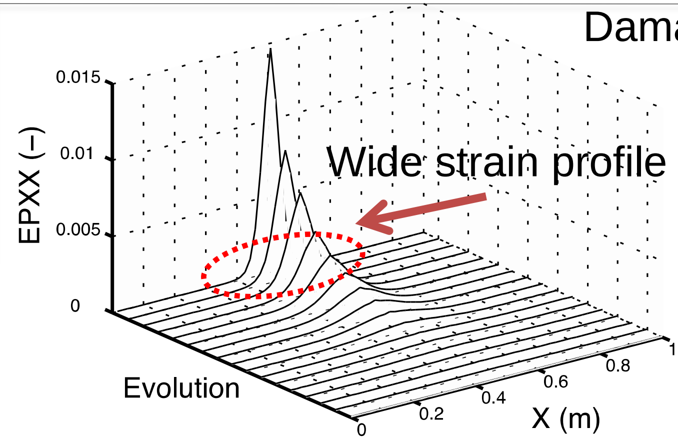
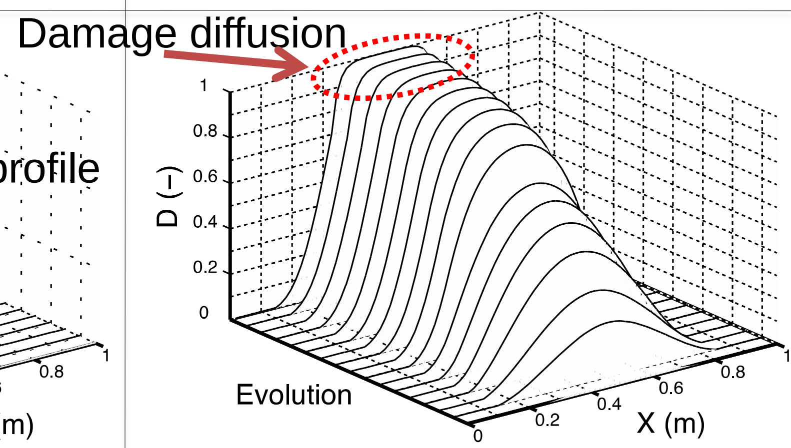
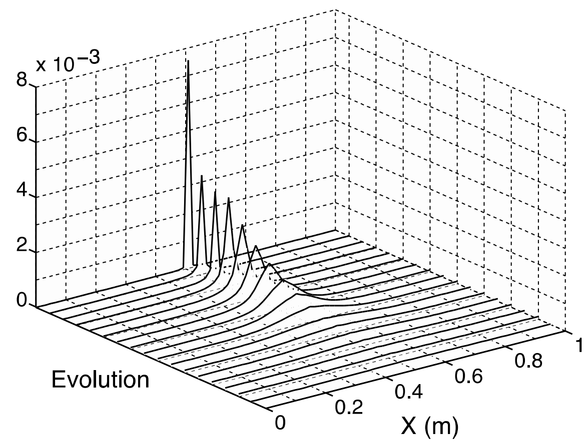
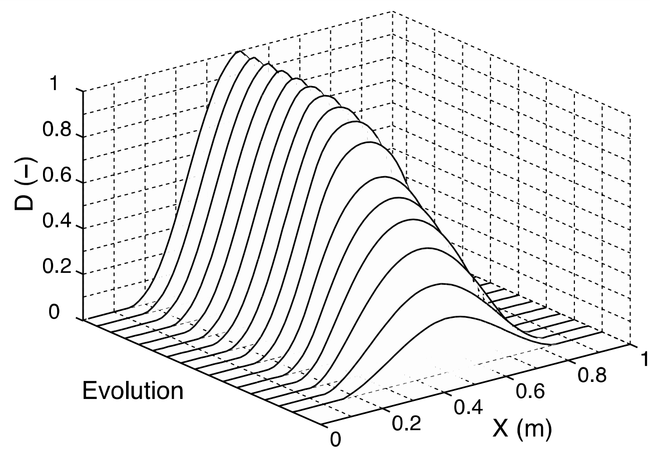
$$\bar{\varepsilon}_{sd}(x_0) = \bar{\varepsilon}_{eq}(x_0)$$

Crack opening

$$[U]_{strong} = \frac{(\varepsilon_{FE} * \phi)(x_0) \int_{\Gamma} \phi(x_0 - x)dx}{\phi(0)}$$

Dufour et al. 2008

Evolution of the localization at failure

	Strain field	*Damage field*
Original nonlocal model		
Stress based nonlocal model		

Applying the SD Method

→ **Crack path is taken as the green crack surface**

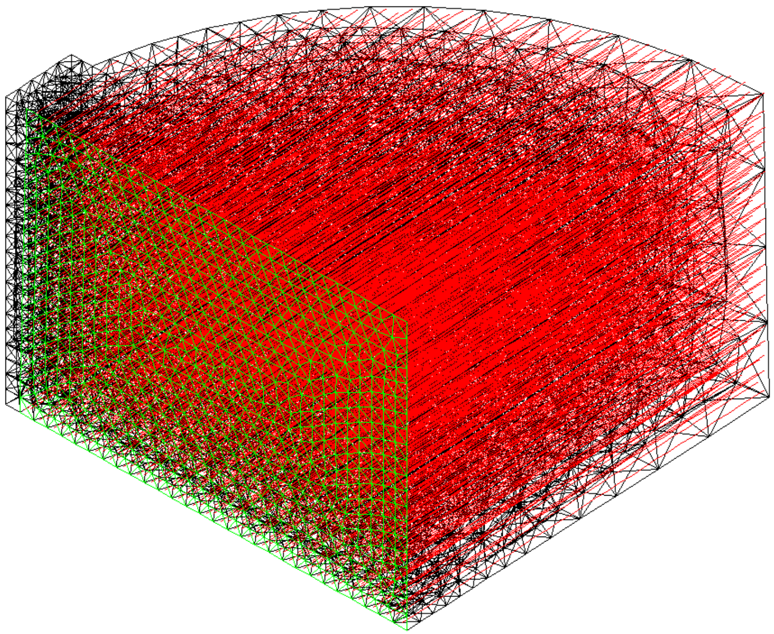
→ **Convert the medium to 1D profile along a line orthogonal to the crack surface.**

→ **Projection of strain field on the 1D profile.**

$$\varepsilon_N = \vec{N}.\varepsilon.\vec{N}$$

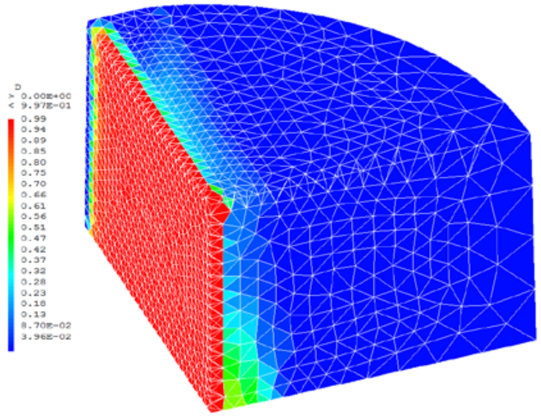
→ **Equality of numerical and analytical profiles at their maximum x_0**

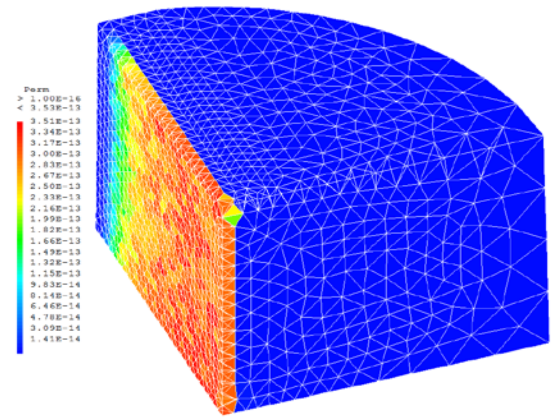
$$\bar{\varepsilon}_{sd}(x_0) = \bar{\varepsilon}_{eq}(x_0)$$



Coupling by means of two approaches

Pijaudier-Cabot et al, JEM (2009)





Matching Law

K(D)

Damage (D) → Permeability (K)

$$\log K = D \log K_p + (1-D)\log K_D$$

Crack openings calculation

[U]

Poiseuille's law

(K_P)

$$[U]_{strong} = \frac{(\varepsilon_{FE} * \emptyset)(x_0) \int_\Gamma \emptyset(x_0 - x)ds}{\emptyset(0)}$$

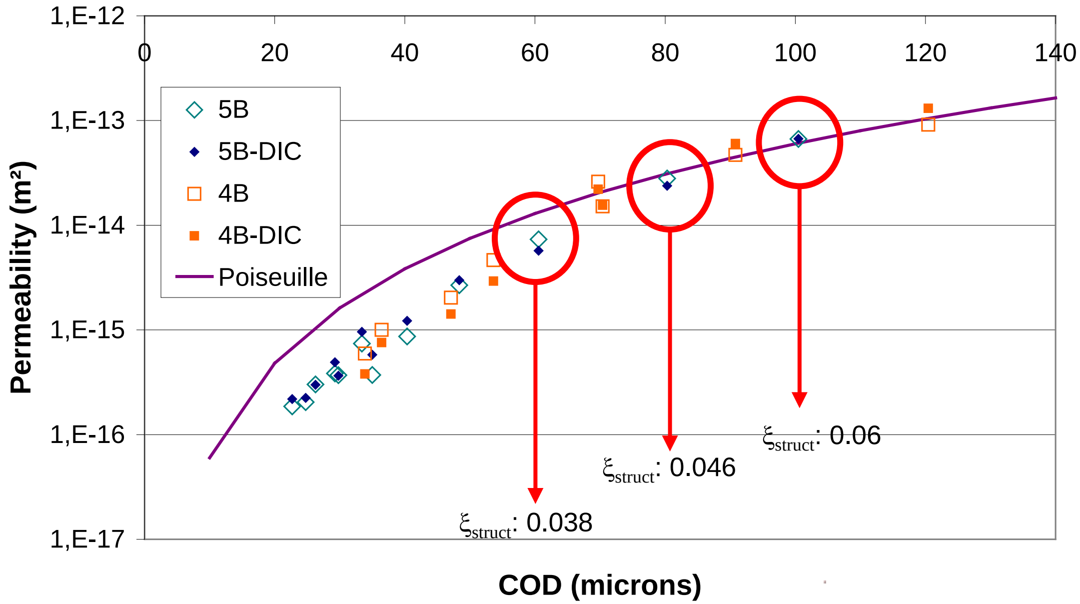
Dufour et al. 2008

$$K_P = \frac{[U]^2}{12\alpha}$$

$$[U]_{weak} = \frac{\iint_\Gamma (\varepsilon_{FE} * \emptyset)(s)ds}{\int_\Gamma \emptyset(x - x_0)\,ds}$$

Dufour et al. 2012

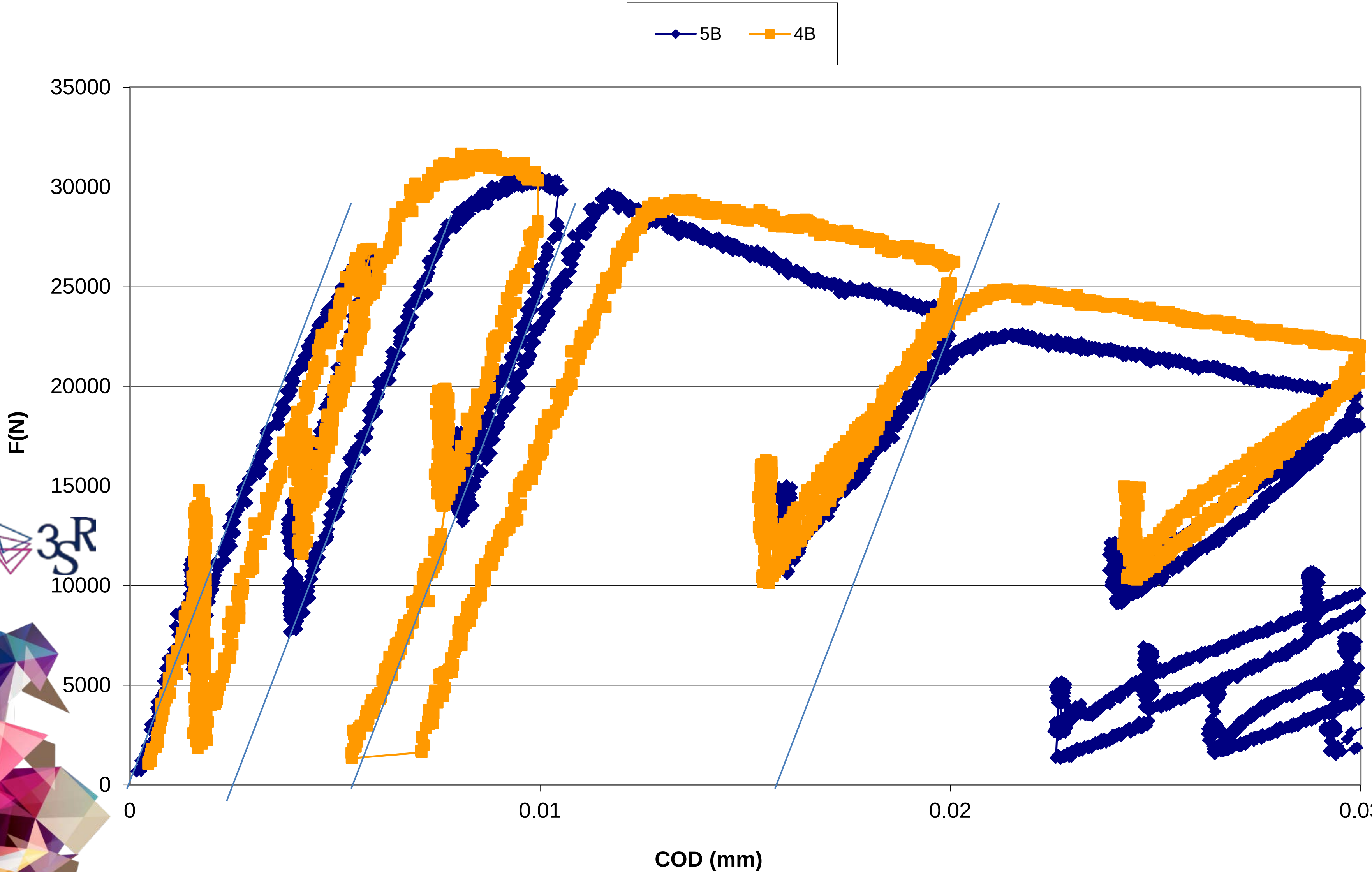
Correction factor for Poiseuille's law



Poiseuille's law (permeability of a crack)

Structural or mean permeability $$K_m = K_P \frac{[u]_m . \varphi}{S_{struct}} = \frac{\xi_{struct}}{S_{struct}} \frac{{[u]_m}^3 . \varphi}{12}$$

$$\xi_{struct} = \frac{1}{\beta \overline{[u]}^{\gamma}} \quad \begin{cases} \beta = 5{,}625 \times 10^{-5} \\ \gamma = -1{,}19 \end{cases}$$


5B
4B
35000
30000
25000
20000
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10000
5000
0
F(N)
0
0.01
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COD (mm)