Modeling of fluid transfer in concrete: experimental constitutive laws and numerical probabilistic strategies

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Layout

1. Aim of the work
2. Probabilistic strategies for modeling fluid flows through cracking concrete
3. Real time water permeability evolution of localized crack in concrete under loading
4. Model validation
5. Conclusion and prospectives

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Motivation

A concrete structure has to ensure functions that go beyond the sole mechanical resistance

The description of cracks in concrete plays a crucial role when dealing with **life expectancy and durability** of concrete structures:


Nuclear power plants


Dams


Storage structures

Main factors influencing concrete durability:

- **concrete porous structure**:
  - penetration of pollutant species
  - deterioration of material characteristics: armature corrosion, degradation of the matrix structure, ...
- **concrete heterogeneity**:
  - micro cracks (small loads, early age, ...)
  - macro cracks

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Motivation and finalities

Interactions between cracking and transport phenomena in concrete and concrete structures

Modeling of cracking (Rossi 1989; Rossi et al, 1992; Rossi, 1994; . . . ; Tailhan et al, 2010)

Purely mechanical problem described using a **probabilistic approach**.

- cracking processes
- scale effects
- heterogeneity

Main finalities

Further research efforts are required:

- to investigate a probabilistic strategy for thermo-hydro-mechanical (THM) analysis of cracking concrete
- to investigate physical mechanisms related to transport phenomena in cracked concrete

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Concrete treated as a porous medium

State quantities

$$\underbrace{\boldsymbol{u} = \boldsymbol{u}(\boldsymbol{x}, t)}_{\text{displacement field}} \quad \underbrace{p_w = p_w(\boldsymbol{x}, t)}_{\text{pressure field}}$$

Linear momentum balance

$$\nabla \cdot \boldsymbol{\sigma} = 0$$

- effective stress tensor can be defined as $\boldsymbol{\sigma}' = \boldsymbol{\sigma} - \alpha p_w \mathbf{I}$

Mass balance equation

$$\nabla \cdot \left(\frac{\boldsymbol{k}}{\mu_w} \nabla p_w \right) + \frac{1}{M} \frac{\partial p_w}{\partial t} + \alpha \frac{\partial \boldsymbol{\varepsilon}_v}{\partial t} = 0$$

where:

- μ_w is the water dynamic viscosity
- ε_v is the total volumetric strain;
- $\boldsymbol{k} = \boldsymbol{k}(\boldsymbol{x}, t) = \boldsymbol{k} = k_c \mathbf{I}$ is the second order permeability tensor.
- The coupling coefficient M, under saturated conditions, is : $1/M = \phi/K_w + (\alpha - \phi)/K_s$.

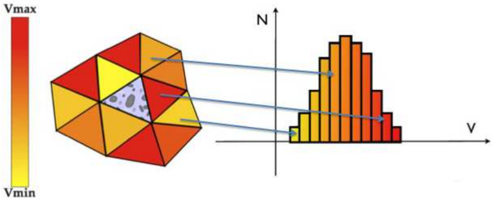
Probabilistic approach to concrete cracking

Material heterogeneity and *size effects* are taken into account via a randomly distributed mechanical properties on all the mesh, using experimentally derived probabilistic distribution laws.

Main assumption (Rossi 1989; Rossi et al, 1992; Rossi, 1994; . . . ; Tailhan et al, 2010)

Each Finite Element is considered as a volume of heterogeneous material

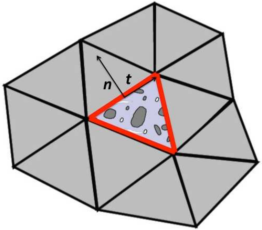
Key aspects



- Mean values and standard deviations of Young modulus E and tensile strength f_t distributed as function of the ratio V_s/V_g and of the compressive strength of concrete f_t.
- A Monte Carlo-like method is used to statistically validate the results via a large number of computations.

Numerical modeling strategies

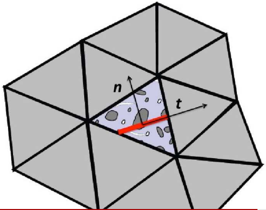
Discrete-explicit probabilistic approach



- Massive elastic elements with elastic behaviour.
- HM two noded zero-tickness interface elements with random mechanical properties:

$$k_t = k_f(\mathbf{I} - \boldsymbol{n} \otimes \boldsymbol{n}) \quad k_n \to +\infty$$

Macroscopic approach



- Cracks are embedded into massive probabilistic elements via a Rashid-like approach
- The longitudinal water flow through a single crack is uniformly distributed within the cracked element

$$k = \underbrace{k\boldsymbol{n} \otimes \boldsymbol{n}}_{\boldsymbol{k}_n} + \underbrace{\tilde{k}_f(\mathbf{I} - \boldsymbol{n} \otimes \boldsymbol{n})}_{\boldsymbol{k}_t}$$

What about the fracture permeability?

Consitutive law for k_f

The permeability k_f of crack is commonly assumed to be dependent on the square fracture aperture a according the so called **parallel plates model**

$$\underbrace{k_f = \frac{a^2}{12}}_{\text{standard}} \quad \text{or} \quad \underbrace{k_f = \frac{wa^2}{12\alpha} \qquad k_f = \frac{a_h^2}{12}}_{\text{modified}}$$

Questions ...

- what are the *physical mechanisms* related to transport phenomena in cracked concrete?
- is the cubic law *valid* in order to model fluid flow through a cracking concrete?
- is it possible to *modify the cubic law* in order to take into account these phenomena?

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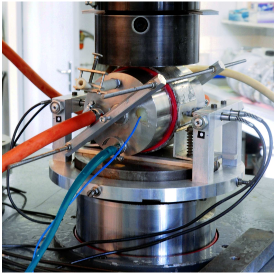
Real-time evolution of transfer properties

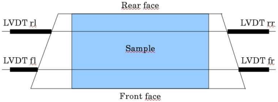
Classical permeabiity estimations (on unloaded specimens)

Permeability estimations are made on **residual cracks** (unloaded specimens)]

A different experimental protocol (on specimens under loading)



- The test is controlled in real-time using the mean diameter variation Δd [Boulay09]



- The mass of water M flowing through the sample is monitored *in real-time* during the hydro-mechanical loading

In order to estimate a transmissivity/permeability the *crack geometry* has to be characterized . . .

Real-time evolution of transfer properties: the protocol

Finality

Real-time evolution of water permeability in cracking concrete (**under load**)

- Step 1 – Hydro-mechanical protocol

Real-time evolution of transfer properties: mass flux through the crack

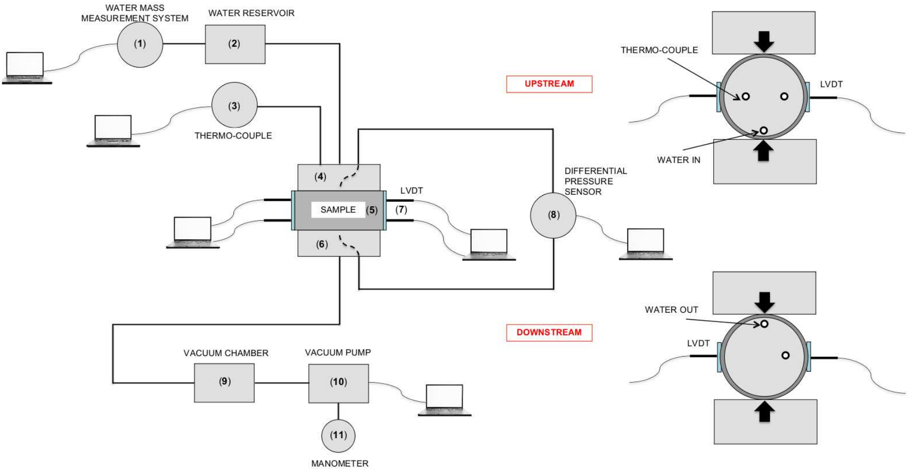
- Step 2 – Mechanical protocol

Geometrical statistical characterization of the crack (LVDTs + DIC technique)

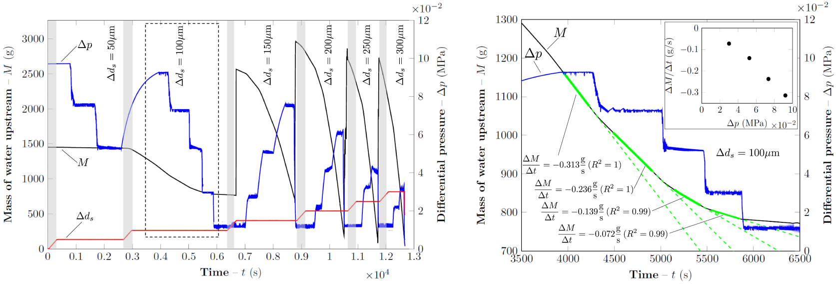
- Step 3 – Permeability estimation

Transfer properties (step 2) are correlated to the crack geometry (step 1) in real-time

Hydro-mechanical protocol: schematic view



Hydro-mechanical protocol: flux measurements



How to estimate the hydraulic transmissivity using these results?

- Assuming valid the Darcy's law:

$$k_f = -\frac{Q}{A_f}\frac{\mu}{\rho}\left(\frac{\Delta p}{\Delta x}\right)^{-1} \tag{1}$$

- In order to estimate a hydraulic transmissivity/permeability of the crack, some crack geometrical informations are required ...

Mechanical protocol: crack apertures computed from LVDTs measurements

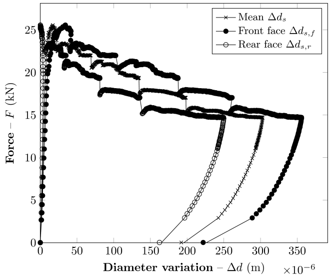
The only information we have about the crack geometry from LVDTs measurements is the crack aperture at mid-height a_m of the sample

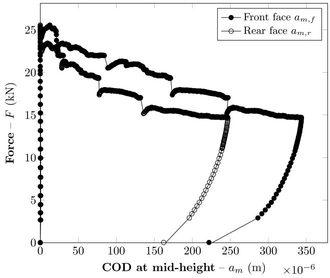
Assumption

After the peak load, the sample is split into two elastic blocks

The aperture $a_{m,\bullet}$ is calculated from LVDTs measurements:

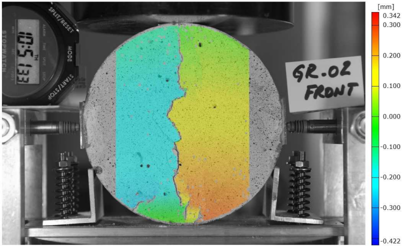
$$\boxed{a_{m,\bullet} = \Delta d_\bullet - \Delta d^e_\bullet}$$

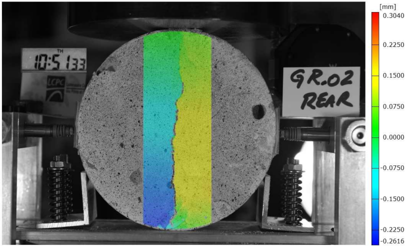




Mechanical protocol: Digital Imaging Correlation (DIC)

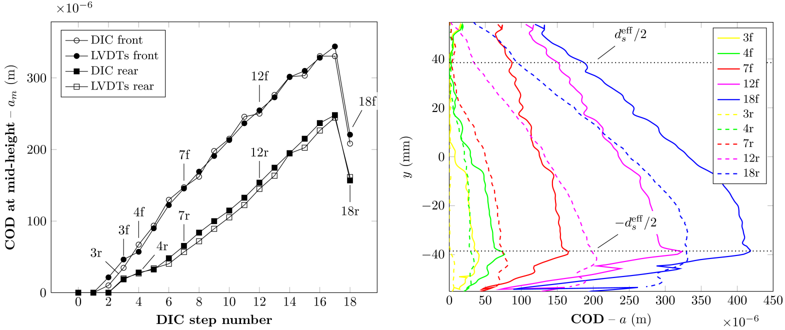
Complete description of the displacement field





Mechanical protocol: Digital Imaging Correlation (DIC)

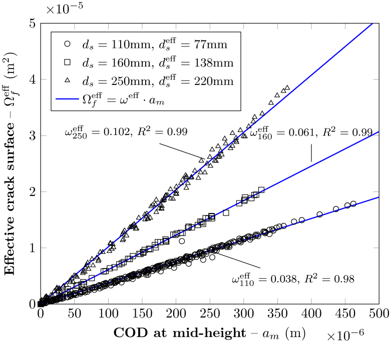
Crack aperture at mid-height of the sample obtained with LVDTs measurements and DIC computations



Mechanical protocol: (measured COD - surface of the crack) relationships

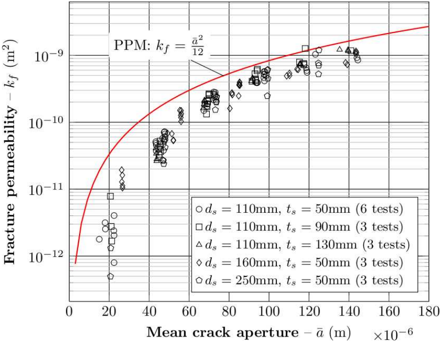
- The surface of the crack Ω_f on each face of the sample can be computed
- Analytical (linear) relationships $\Omega_f = \alpha \times a_m$ between COD at mid-height of the sample and crack surface can be obtained

(a_m, Ω_f) relationship



Permeability estimations: crack permeability vs crack aperture

A_f and a representative crack aperture are estimated in function of the measured Δd_s using DIC results;



Main result:

A suitable for numerical implementation fracture permeability - aperture relation

$$k_f = k_f(\bar{a})$$

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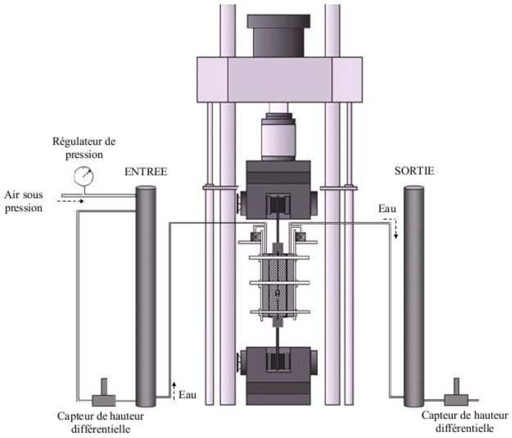
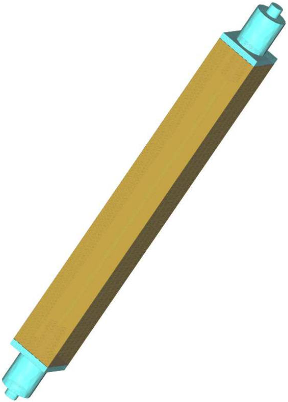
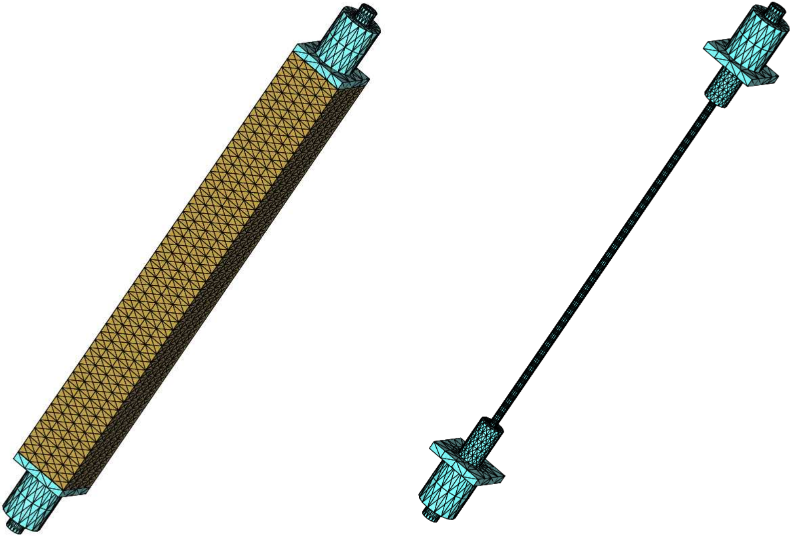
Reference experimental tests (Desmettre and Charron, 2010, 2012)

- Tie-specimens
- Cross sectional area: 90 mm × 90 mm;
- Length 610 mm



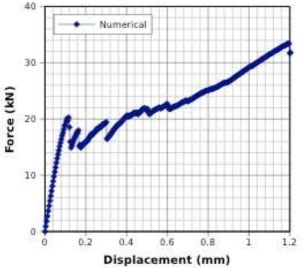


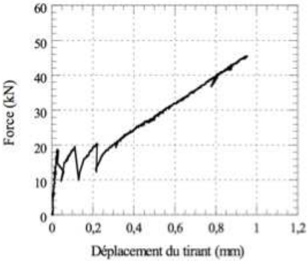
Computational mesh

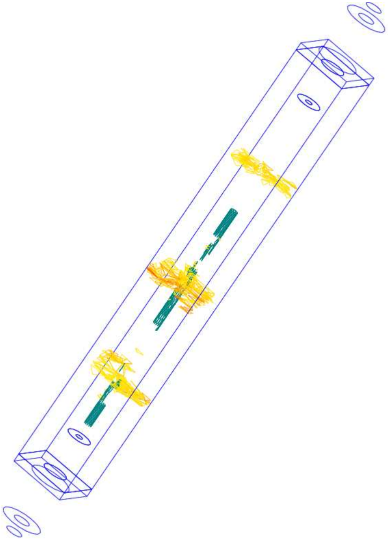


16842 massive tetrahedral probabilistic elements, 2732 probabilistic 3D interface elements

Mechanical computation







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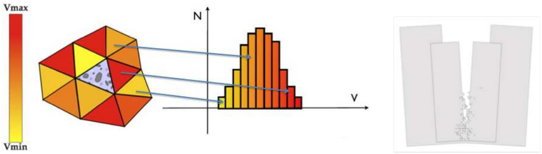
Numerical modeling of concrete cracking . . .

- A *new (Fortran) FEM code* for coupled THM analysis of porous media has been developed.
- Cracking is modeled by means of the probabilistic approach developed by Rossi, Tailhan, . . .



- The mechanical probabilistc models have been extended to HM coupled analysis

Experimental analysis

- A protocol for real time minitoring of water permeability of localized cracks in concrete under loading has been developed
- An analytical relationship between k_f and a has been pointed out

Model validation. Work in progress . . .

- Model validation via the simulation of real structural elements under coupled HM loading conditions.

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Thank you very much for your attention!

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