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MESO-MACRO NUMERICAL APPROACH TO MACROSCOPIC PERMEABILITY OF FRACTURED CONCRETE – COMPLAS XI

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Abstract. In this paper, a sequential multi-scale framework to solve mass (air or water) transfer problems is described. Numerical results are checked against mechanical and permeation experimental datas from a reinforced concrete specimen under tensile load designed by C. Desmettre and J.P. Charron [2]

1 Introduction

The durability of reinforced concrete structures is strongly linked to its porosity and moreover to its cracks pattern which can be anisotropic in many realistic contexts. Created by mechanical loading or unfavorable thermo-hydrical environment, those cracks increase the penetration of water and aggressive agents within the material which can severely weaken its mechanical behavior. It is therefore obvious that being able to compute the flow going through concrete structure is a big issue for numerous applications : concrete made bridges or CO_2 storage as well as civil nuclear industry. Thanks to a mechanical model able to represent the cracks opening in heterogeneous materials [3], we then compute a mass (air or water) transfer problem within concrete and deal with permeability on isotropic as well as anisotropic crack patterns. The experimental permeability datas obtained on a tie-specimen under uniaxial loading described by C. Desmettre and J.P. Charron in "novel water permeability device for reinforced concrete under load"[2] is then checked against our numerical results.

The section 2 of this paper focuses on the sequential multi-scale framework, dealing with the cracks FE modelling and the hydro-mechanical coupling, both at a meso scale. The section 3 briefly sum up the experimental study of C. Desmettre and J.P. Charron [2] and checks the experimental datas against our numerical results.

2 Sequential multi-scale framework

As said previously, the aim is to compute a flow problem on isotropic as well as anisotropic crack patterns on cement base materials. Firstly, it means that the mechanical model must be able to deal with heterogeneous materials. Actually, reinforced concrete is composed of steel bars and concrete, which itself is a mix of mortar and aggregates. Secondly, the flow is strongly influenced by the crack openning $[\![u]\!]$ as the Poiseuille flow Q_P going through a $[\![u]\!]$ gap between two planes is proportionnal to the cube of the opening ($Q_P \propto [\![u]\!]^3$). Therefore, the crack opening is a crucial value for the mass transfer computation.

Greatfully, the model used [3] has those two specificities :

- it represents multi-phasic materials (cement paste, aggregates and steel have different mechanical and transfer caracteristics),
- it gives the value of the opening $[\![u]\!]$ of each broken element whatever the sollicitation is.

The next part focuses on those two special features of the mechanical model before describing the permeation computation.

2.1 Crack representation : Strong discontinuities

When a concrete specimen (ie: made of cement paste and aggregates) is under a tensile sollicitation, the stress in the cement paste quickly reaches its rupture value ($f_t \approx 3MPa$) resulting in a crack initiation before its propagation. This is a dissipative phenomenon where the so-called "fracture energy" (Gf $[J.m^{-2}]$) represents the energy dissipated by a one square metre crack. Practically, it can be easily deduced from a light experimental device like a three points bending test and is therefore one of the most used caracteristics of concrete as the tensile limit stress (σ_f) or the Young modulus (E). Thence, those three parameters seems judicious to be the basis of a mechanical element able to represents the behaviour of a brittle material like concrete is.

Dealing with brittle and quasi-brittle material in computational mechanic is still a big issue and numerous models exist, each one with its benefits and its drawbacks. On one hand, discrete mesh models [6] are able to represent the crack opening, but they usually need intensive re-meshing in order to compute the crack direction. On the other hand, with a Finite Element basis, several approach exist like the smeared crack models [5]. Their main drawback is their mesh dependency, problem which can be bypasses introducing a length scale wich is mesh objective.

Recently [7], [8], [9], an elegant crack model based on FE theory has been developped. This method is mesh independent and doesn't need re-meshing but introduce a so-called strong discontinuity in the displacement field. The strong discontinuity is activated thanks to a yield function Φ written as :

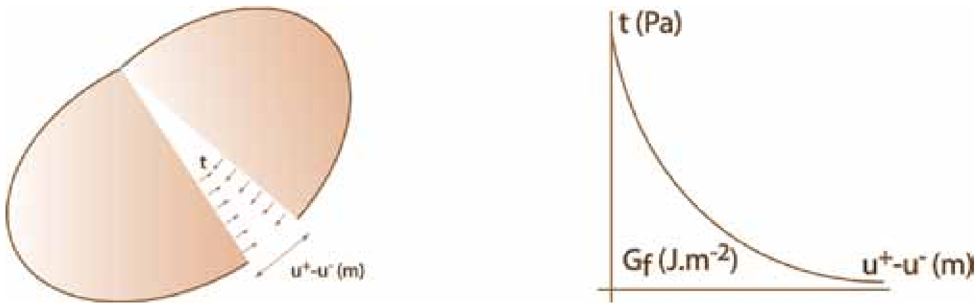

Figure 1: Strong discontinuity crack representation and crack opening process

$$\Phi(t, q) = t - (\sigma_f - q) \tag{1}$$

where t is the traction vector at the discontinuity and σ_f the limit stress. The softening is introduced through the variable $q = k(\llbracket u \rrbracket)$ by considering the exponential form (cf figure 1),

$$k(\llbracket u \rrbracket) = \sigma_f \left(1 - exp\left(-\frac{\sigma_f}{G_f}(\llbracket u \rrbracket)\right)\right) \tag{2}$$

The next part focuses on the permeability part.

2.2 Mesoscopic scale flow: The Poiseuille law

Once the cracks initiates, the second step starts : the aim is to compute a mass transfer problem with the damaged mesh. Here is the key point, the material is composed of a "double porosity". At a micro-scale, the cement paste porosity is isotropic. It represents the undamaged part of the permeability (pore diametre ¡ $10\mu m$). The flow can be computed with the Darcy law (eq 3). This equation links the mass flow density $\underline{q}$ $[kg.s^{-1}.m^{-2}]$ and the pressure p.

$$\underline{q} = \rho\underline{v} = -\frac{1}{\mu}\rho.k.\underline{\underline{1}}\ \underline{grad}(p) \tag{3}$$

The permeability (k) unit is m^2.

As soon as the first crack initiates, a bigger porosity appears and the permeability rises.

If the crack pattern is isotropic, one can analytically links damage to permeability [4]. In case of anisotropy, which represents most of the realistic studies, the problem is therefore more complex to solve. Taking into accounts the anisotropy of the crack pattern is inherent to our model. It is based on a local implementation of the constitutive equation which gives the Poiseuille flow between two planes (cf figure 2 and equation 4).

$$q_{Edge} = \rho\ v_{Edge} = \rho\ \frac{w_{Edge}^3}{12\mu L_{Edge}}\ \frac{\Delta p}{L} \tag{4}$$

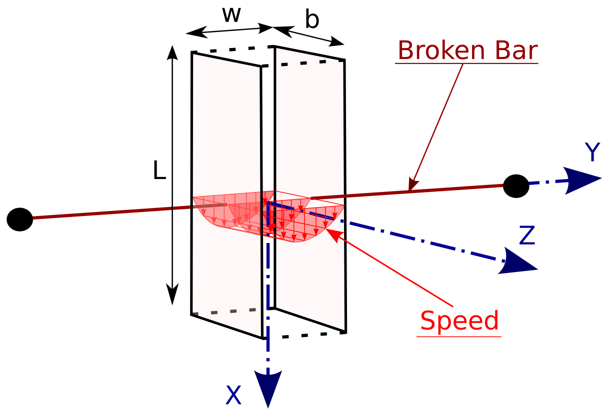

Figure 2: speed between two planes defined by the Poiseuille law

where μ is the viscosity of the studied fluid ($\mu_{water} = 8,90.10^{-4} Pa.s$ at 20 $^\circ$ C) and ρ is a constant as this equation 4 is given for incompressible fluid.

Once the elementary permeability matrices written, the "double porosity" is easy to be written as the sum of the isotropic permeability and the anisotropic permeability due to the possible crack : $\underline{\underline{K}} = \underline{\underline{K}}_{iso} + \underline{\underline{K}}_{ani}$ where $\underline{\underline{K}}_{iso} = \frac{-k}{\mu}\underline{\underline{1}}$ and $\underline{\underline{K}}_{ani} = \frac{w^3}{L\mu}(\underline{\underline{1}} - \underline{n} \otimes \underline{n})$

As the anisotropic permeability matrix shows it, there is no flow in the colinear direction of the bar while in the two perpendicular direction, the permeability is equal to $\frac{w^3}{L\mu}$.

Once the assembly of the elementary matrices done thanks to a classical FE software, the problem can easily be solved and, as a result, the macroscopic flow can be computed. This method is an elegant way to automatically takes into account the tortuosity and the connectivity of the cracks.

2.3 Permeability of RC element under load

The multiscale framework we present here is clearly suitable dealing with mass transfers within concrete structures or their components. To that aim we focus on experimental results from [2] who designed a coupled tensile – permeability test on Reinforced Concrete (RC) specimens ($610 \times 90 \times 90$ mm^3 concrete element including a 11 mm diameter reinforcement bar). Here we aim at comparing their experimental measures to numerical results and focus on the permeability evaluation along the failure process.

The fine scale mechanical analysis of this RC tie is based on a spatial truss representation [3] built with non-adapted meshes. In order to fit to the experimental conditions, displacements are prescribed at both ends of the steel reinforcement bar. Such increasing load leads to progressive cracking of the concrete element and Figure 3 shows a typical crack pattern obtained from a numerical analysis. Three main macroscale cracks are distributed along the tie which is in accordance with experimental observations. Moreover,

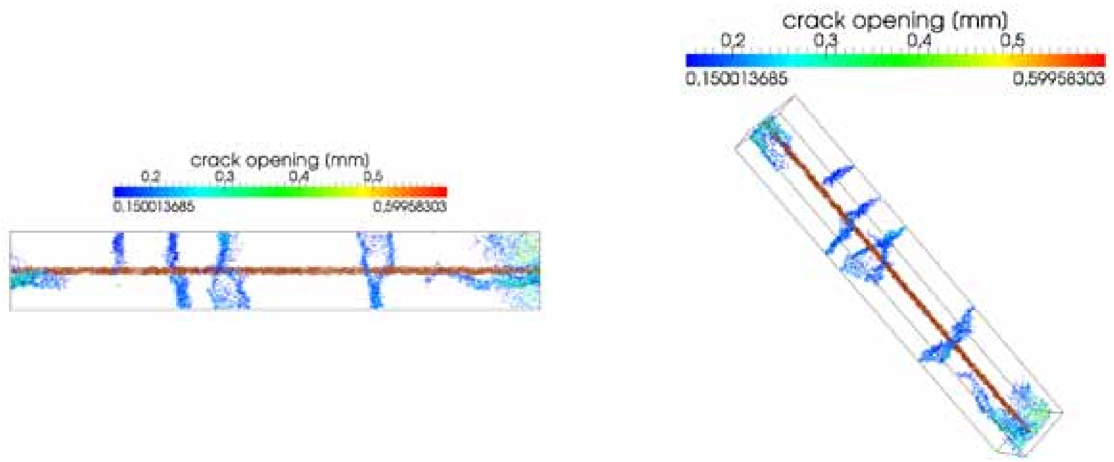

Figure 3: RC tie: numerical crack patterns

we show on Figure 4 that there is a quite good agreement between the measured values of those cracks openings during the loading process and the corresponding numerical values.

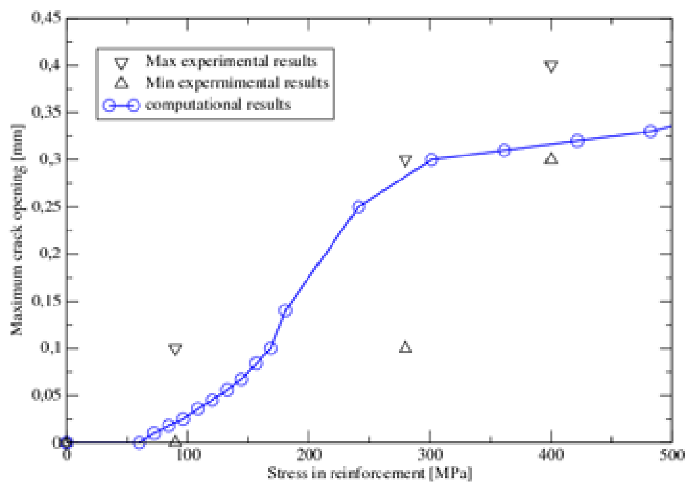

Figure 4: RC tie: maximum crack opening versus stress in reinforcement (experimental [2] vs computational results)

On the permeability assessment point of view (here the test deals with water), Figure 5 shows the norm of the mass flow vector at the end of the failure process. Although the concrete specimen contains a large number of mesoscale cracks, it is clear that the mass transfer takes place within a subset of those cracks, corresponding to several percolated paths. Thus, on the mass transfer point of view, the former may be seen as a set of macroscale cracks. Hence, it is worth noting that, apart from considering the opening value as the pertinent criterion, this mass transfer analysis leads to an other way to determine this set of macroscale cracks. This analysis being linear and so quite simple to drive, it is a very convenient way to characterize macroscale cracks.

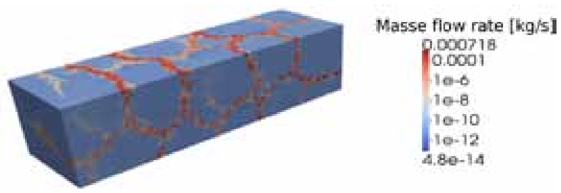

Figure 5: RC tie: numerical values of the mass flow vector norm

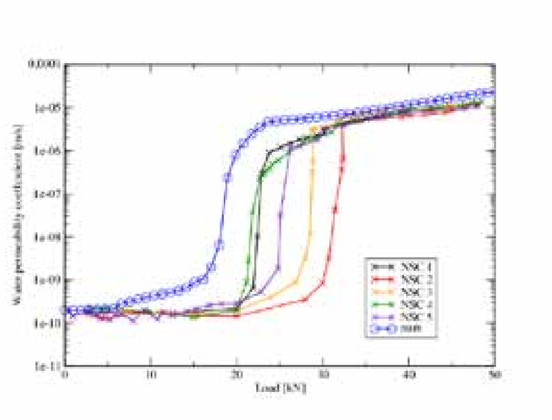

Figure 6: RC tie: numerical crack patterns

Finally, Figure 6 shows the permeability coefficient – here in [m.s^{-1}] – evolution along the load increase. The permeability increases from approximatively $2.10^{-10} m.s^{-1}$ to $1.10^{-5} m.s^{-1}$ both for numerical and experimental studies. It is also worth noting that the increasing rate is also quite well represented. Yet, the permeability rise appears for smaller loading values in the numerical study than in the experimental one. Considering the concrete heterogeneity as well as the experimental discrepancy, those results are quite promising.

3 Concluding Remarks

This paper presents the results given by a mesoscopic model able to compute the flow going through a specimen under load. Three important points have been validated :

- Cracks spacing (3 main cracks on the 610mm long specimen),
- Cracks opening (0,35mm maximum opening when the yielding stress is reach in the reinforced bar),
- Permeability values during loading (rise of 5 orders of magnitude from the original permeability for this study).

The numerical results are therefore quite promising, especially knowing that more attention can be paid on the boundary conditions and loading to fit to the experimental study.

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