Study of the hygro-elastic behaviour of composite materials in presence of cracks: application to the durability of renewable marine energy structures

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Context

Problem

Composite structures submitted to harsh environment

Tidal turbines

Offshore windmill

Complex coupled loadings

- Humidity
- Temperature
- Chemical aggressions
- Solar radiations
- Mechanical loadings

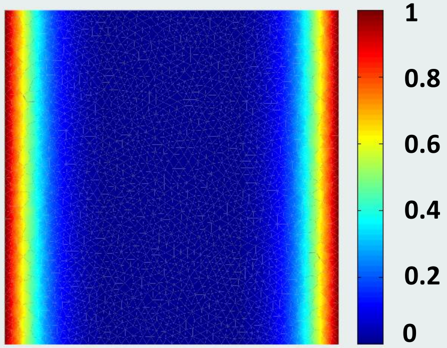
Impact of diffusion and mechanical loadings

- Decrease of the mechanical properties of the material
- Appearance of a hygroscopic differential swelling leading to high stresses
- Consequences: cracks propagation, delamination, fibre/matrix decohesion

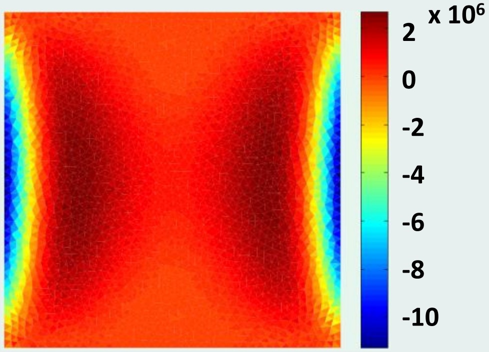
Interaction between moisture diffusion and mechanical behaviour

Hygroscopic swelling

The moisture content leads to a so-called hygroscopic swelling involving relevant internal stresses



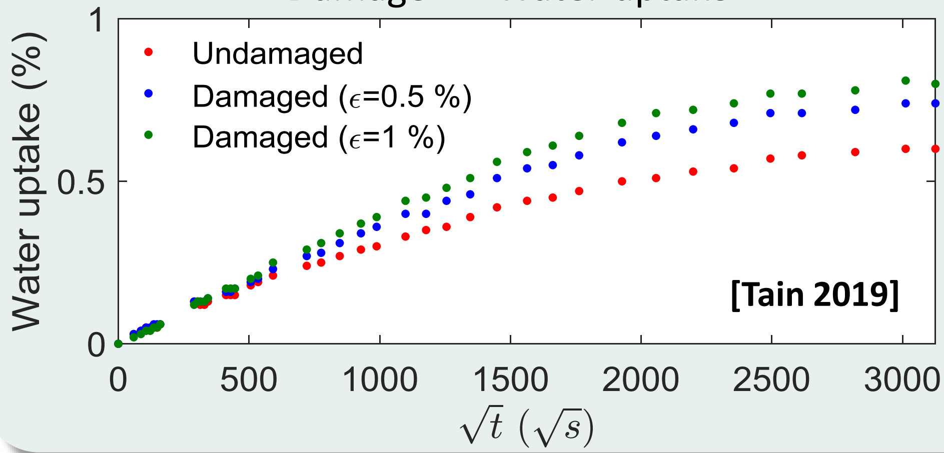
Local moisture content



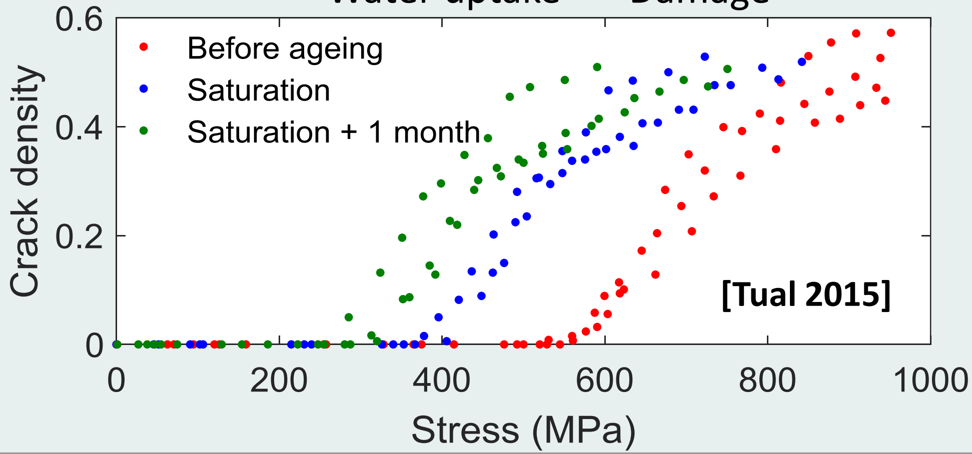
Local stress field σ_{22} (Pa)

Mechanical properties and material damage

Damage ⟶ Water uptake



Water uptake ⟶ Damage



FIRMAIN project

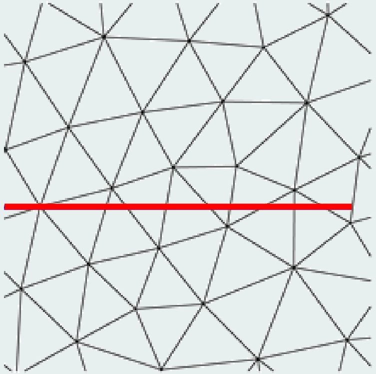
Impact of hygroscopic ageing on the cracking of composite materials in an uncertain context

- Development of relevant physical models
- Implementation of reliable numerical models
- Consideration of the sources of uncertainty

Development of reliable numerical methods combined with multi-physical models for the design of composite structures used as renewable marine energy conversion systems

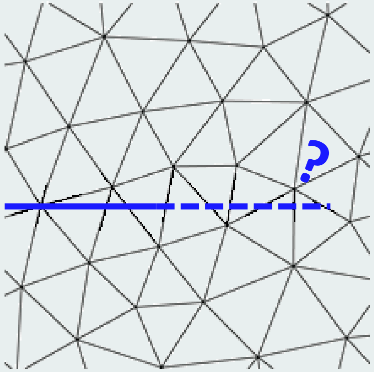
Numerical tools

X-FEM (Extended FEM)



- Does not require a conformed mesh
- Eases the study of crack propagation
- Takes into account the uncertainties
- Allows to study geometric variability

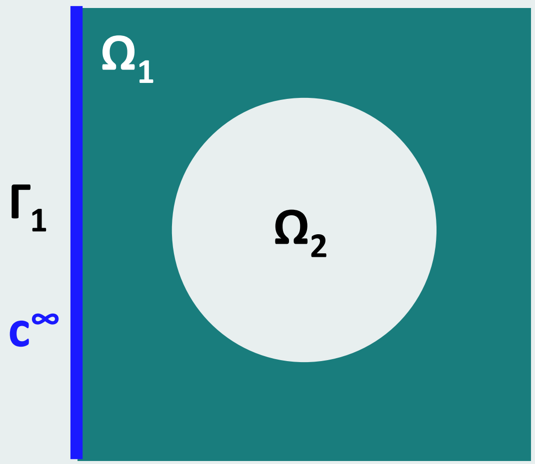
S-FEM (Stochastic FEM)



Outline

Fick diffusion model

Heterogeneous Fick problem : strong form



Find $c(\boldsymbol{x},t) \in \Omega \times \mathbb{R}_*^+$ such that

$$\frac{\partial c(\boldsymbol{x},t)}{\partial t} = \mathbf{D}\Delta c(\boldsymbol{x},t) \quad \text{in} \quad \Omega \times \mathbb{R}_*^+$$

$$c(\boldsymbol{x},t) = c^\infty \quad \text{on} \quad \Gamma_1 \times \mathbb{R}_*^+$$

$$(\mathbf{D}\nabla_x c(\boldsymbol{x},t)) \cdot \mathbf{n} = \mathbf{0} \quad \text{on} \quad \Gamma \backslash \Gamma_1 \times \mathbb{R}_*^+$$

$$c(\boldsymbol{x}, t=0) = c_0(\boldsymbol{x}) \quad \forall \boldsymbol{x} \in \Omega$$

where $\Omega = \Omega_1 \cup \Omega_2$ and $\mathbf{D} = \begin{cases} \mathbf{D}_1 & \text{if } \boldsymbol{x} \in \Omega_1 \\ \mathbf{0} & \text{if } \boldsymbol{x} \in \Omega_2 \end{cases}$

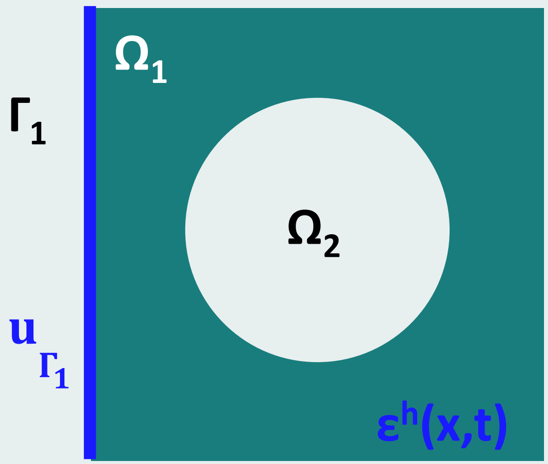
D : diffusion coefficient
c^∞ : saturation content

The spatial average water content $C(t)$ verifies :

$$C(t) = \frac{1}{M_0} \int_\Omega \rho(\boldsymbol{x})\, c(\boldsymbol{x},t)\, d\Omega$$

Mechanical problem model

Heterogeneous uncoupled hygro-elastic problem : strong form



Find $\boldsymbol{u}(\mathbf{x}, t) \in \Omega \times (0, T)$ such that

$$\begin{aligned} \boldsymbol{div}\, \boldsymbol{\sigma} + \boldsymbol{f} = 0 \quad & \text{in} \quad \Omega \backslash \Gamma_{crack} \times (0, T) \\ \boldsymbol{\sigma} = \boldsymbol{C} : (\varepsilon\ (\boldsymbol{u}) - \varepsilon^{h}(\boldsymbol{x}, t)) \quad & \text{in} \quad \Omega \backslash \Gamma_{crack} \times (0, T) \\ \boldsymbol{\sigma} \cdot \boldsymbol{n} = \boldsymbol{0} \quad & \text{on} \quad \Gamma \backslash \Gamma_{crack} \times (0, T) \\ \boldsymbol{u} = \boldsymbol{u}_{imp} \quad & \text{on} \quad \Gamma_{u} \times (0, T) \end{aligned}$$

where $\Omega = \Omega_1 \cup \Omega_2$ and $\boldsymbol{C} = \begin{cases} \boldsymbol{C}_1 \text{ if } \boldsymbol{x} \in \Omega_1 \\ \boldsymbol{C}_2 \text{ if } \boldsymbol{x} \in \Omega_2 \end{cases}$

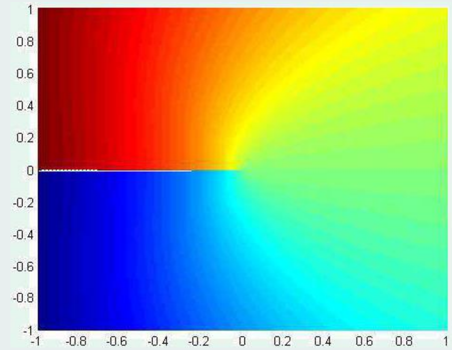
with $\varepsilon^{h}(\boldsymbol{x}, t) = \begin{bmatrix} \beta_x^h c(\boldsymbol{x}, t) & 0 & 0 \\ & \beta_y^h c(\boldsymbol{x}, t) & 0 \\ \text{sym} & & \beta_z^h c(\boldsymbol{x}, t) \end{bmatrix}$

$\longrightarrow$ Field $c(\boldsymbol{x}, t)$ can be obtained from the Fick diffusion model

X-FEM methodology for hygro-mechanical problems

Main ingredients of the X-FEM approach

- Implicit description of the geometry with the level-sets techniques [Sethian 1999]



- Enriched approximation based on the level-set function to capture irregularities in the solution field [Moës et al. 1999]

Specificities implemented for the hygro-mechanical problem

- Penalty approach for imposing Dirichlet boundary conditions on interfaces modeled with level-sets [Fernandez et al. 2004]

- Computation of the hygroscopic strains: find $u \in \mathcal{W}(v)$ such as

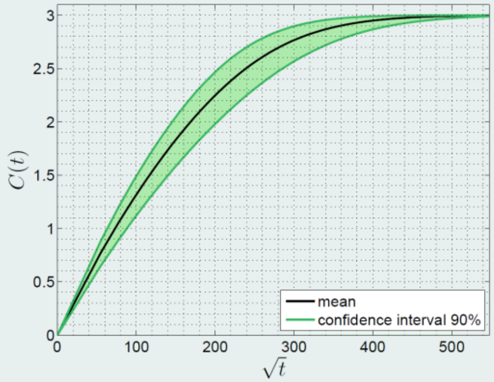
$$\int_{\Omega \backslash \Gamma_{crack}} \varepsilon(v) : \mathbf{C} : \varepsilon(u) d\Omega = \int_{\Omega \backslash \Gamma_{crack}} \varepsilon(v) : \mathbf{C} : \varepsilon^h d\Omega$$

Spectral stochastic approach for uncertainties propagation

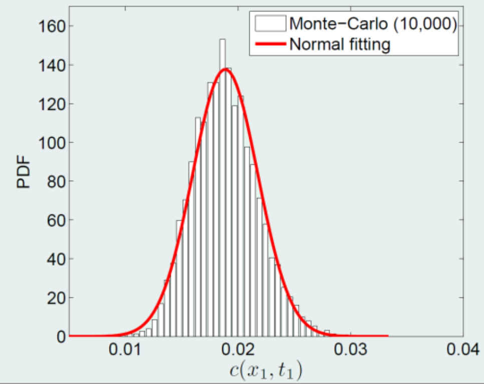
Objectives of the approach

Computation of the output variability with respect to the input uncertainties

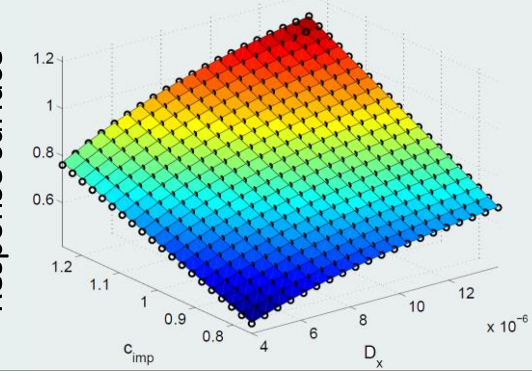
Stochastic process



PDF



Response surface



Decomposition of the solution on a specific basis suited the stochastic problem

The discrete solution $c(\boldsymbol{y}, \boldsymbol{\xi})$ will be searched under the form

$$c(\boldsymbol{y}, \boldsymbol{\xi}) \approx \sum_{\alpha=1}^{P} c_\alpha(\boldsymbol{y}) H_\alpha(\boldsymbol{\xi})$$

where the $c_\alpha(\boldsymbol{y})$ are the unknown of the problem and the $\{H_\alpha\}_{\alpha=1}^{P} \in L^2(\Xi, dP_\xi)$ is a basis of orthonormal polynomials choosing with respect to the density of probability P_Ξ (Polynomial Chaos [Ghanem et al. 1991, Xiu et al. 2002])

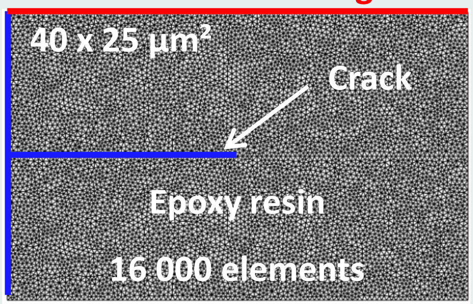
→ computation of the unknown with a non-intrusive L^2 projection method which only requires deterministic computations for particular realizations of $\boldsymbol{\xi}$ [Le Maître et al. 2010]

Outline

X-FEM / FEM comparison

Model

Mechanical loading σ = 1.5 MPa



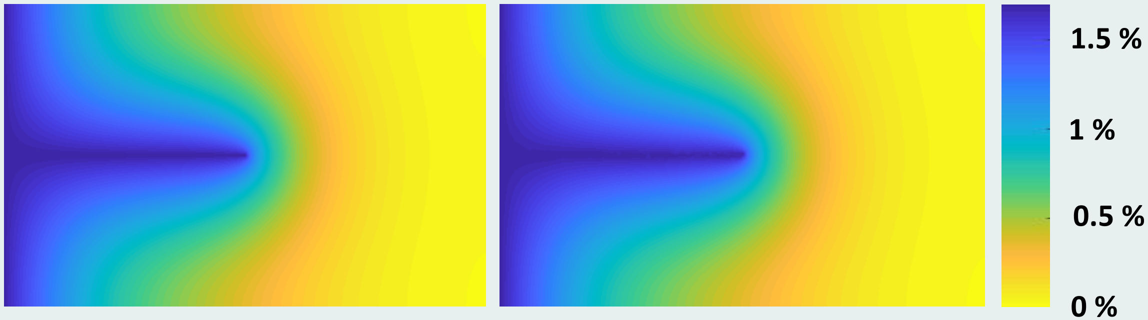
E = 4 GPa
ν = 0.36
ρ = 1310 kg/m³
$\beta = 0.324\ \%$

Hygroscopic loading : c^{∞} = 1.71 %

D = 8.2e-2 µm²/s

Water diffusion

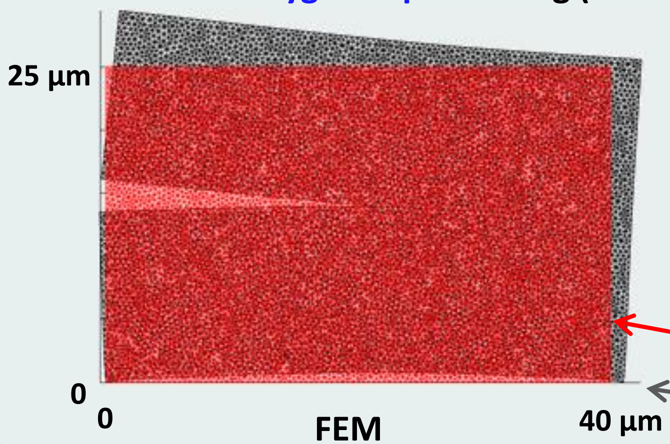
Comparison of water uptake at a specific time (t=500 s)



FEM **X-FEM**

Displacement field

Mechanical + hygroscopic loading (t=500 s)

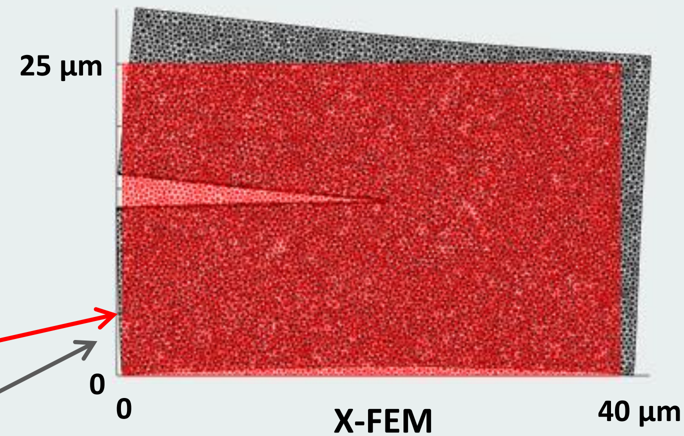


FEM

Initial undeformed shape

Final deformed shape

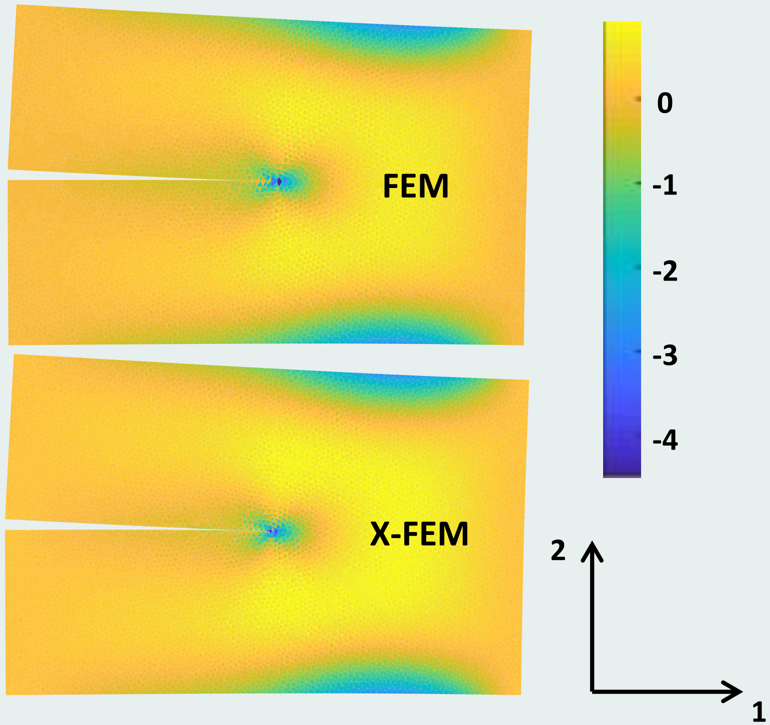
Mechanical + hygroscopic loading (t=500 s)



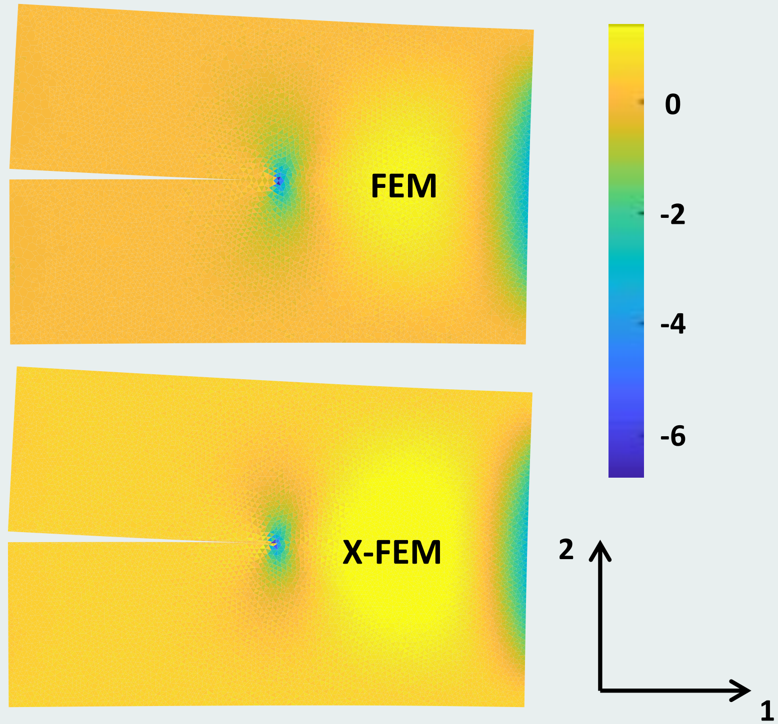
X-FEM

X-FEM / FEM comparison

Stress field σ_1 (MPa)



Stress field σ_2 (MPa)



Conclusion

✓ Validation of X-FEM model ✓

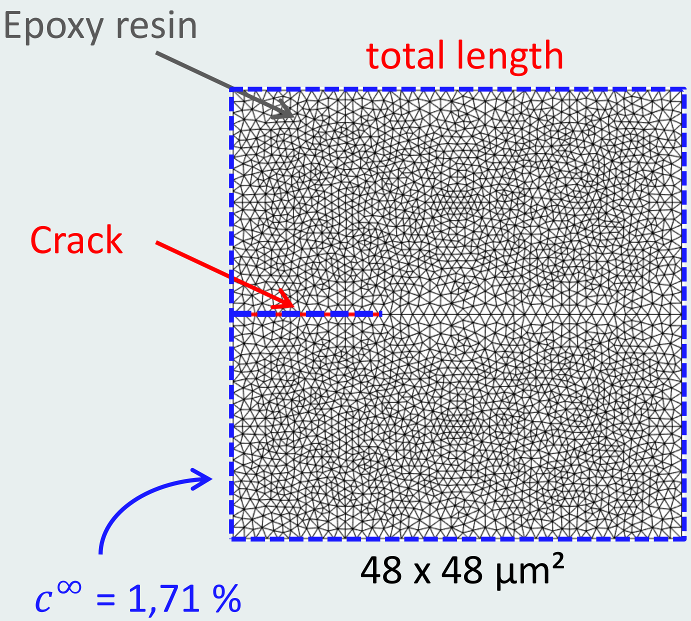
Outline

- Motivations
- Modelling and numerical approach
- X-FEM validation
- Numerical study : homogeneous case
- Numerical study : heterogeneous case
- Conclusions and future works

Effect of cracking on diffusion – homogeneous case

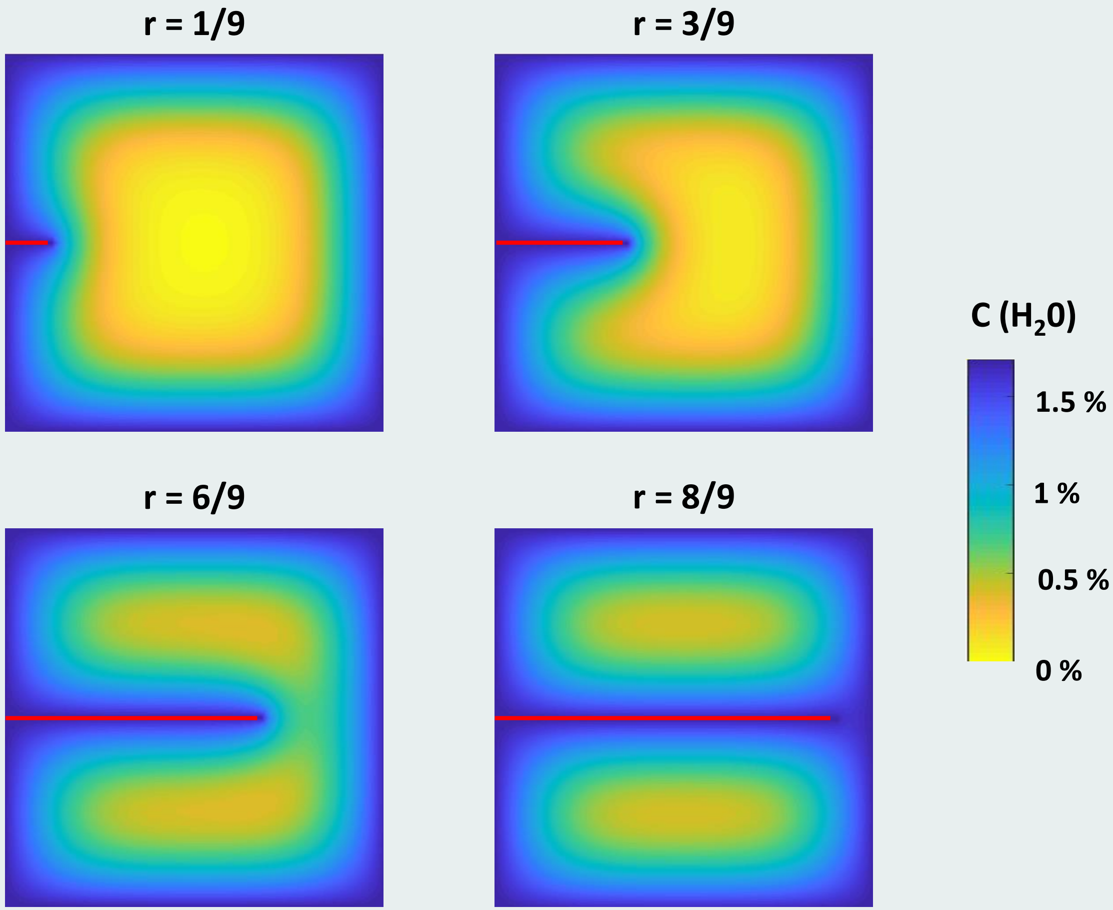
Meshing and boundary conditions

Cracking ratio $r = \frac{\text{crack length}}{\text{total length}}$



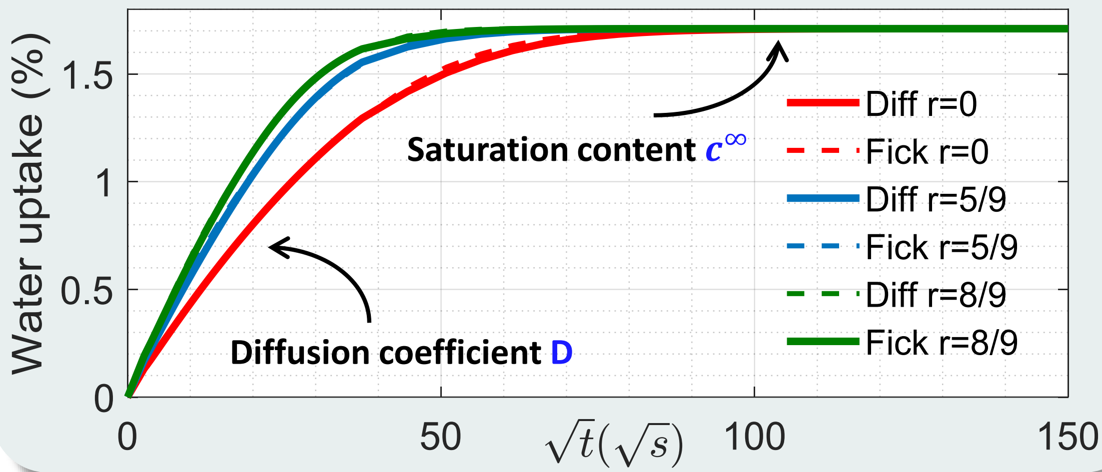
3500 elements

Diffusion versus cracking ratio

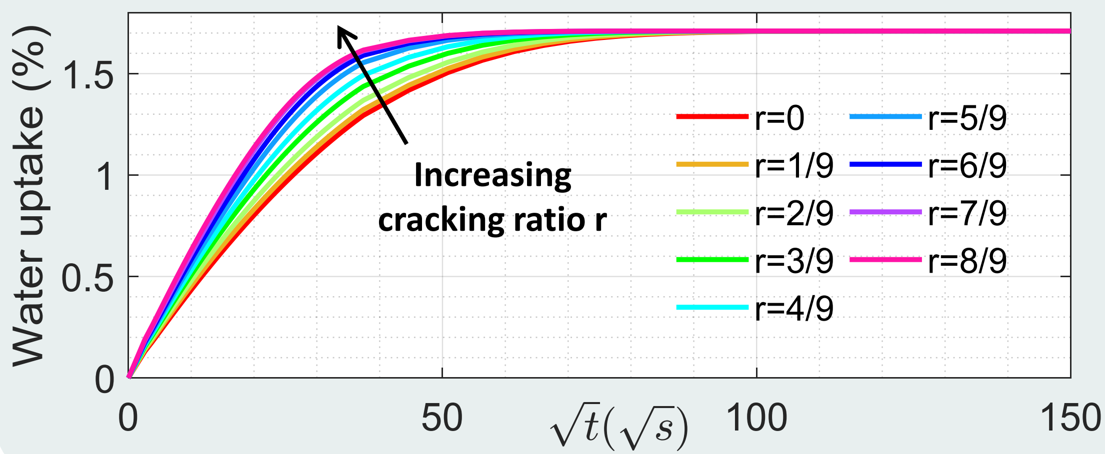


Effect of cracking on diffusion – homogeneous case

Identification of diffusion curves using a Fick model

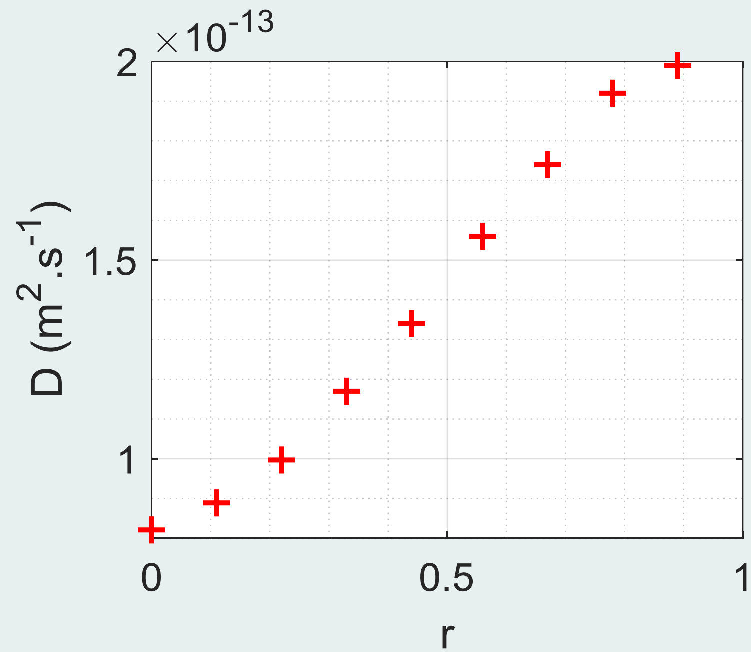


Evolution of diffusion curves as a function of *r*



Conclusions

- Accurate identification of the diffusion curves
- The larger the crack size, the faster the diffusion occurs



- Non-linear evolution of D = f(r)

Outline

- Motivations
- Modelling and numerical approach
- X-FEM validation
- Numerical study : homogeneous case
- Numerical study : heterogeneous case
- Conclusions and future works

Effect of cracking on diffusion – heterogeneous case

Meshing and boundary conditions

Cracking ratio $r = \frac{\text{crack length}}{\text{total length}}$

Epoxy resin

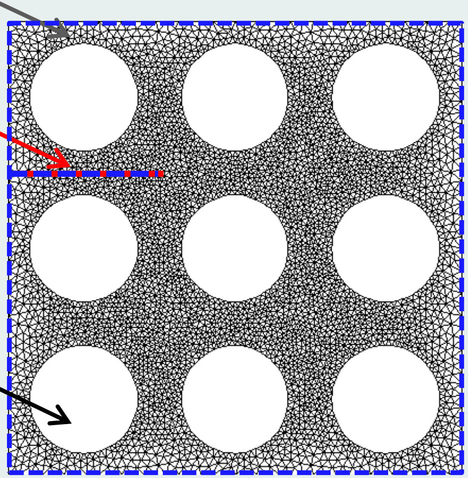
15 300 elements

Crack

Glass fibre

(V_f = 40 %)

(d_f = 17 µm)



β = 0 %

E = 72.5 GPa

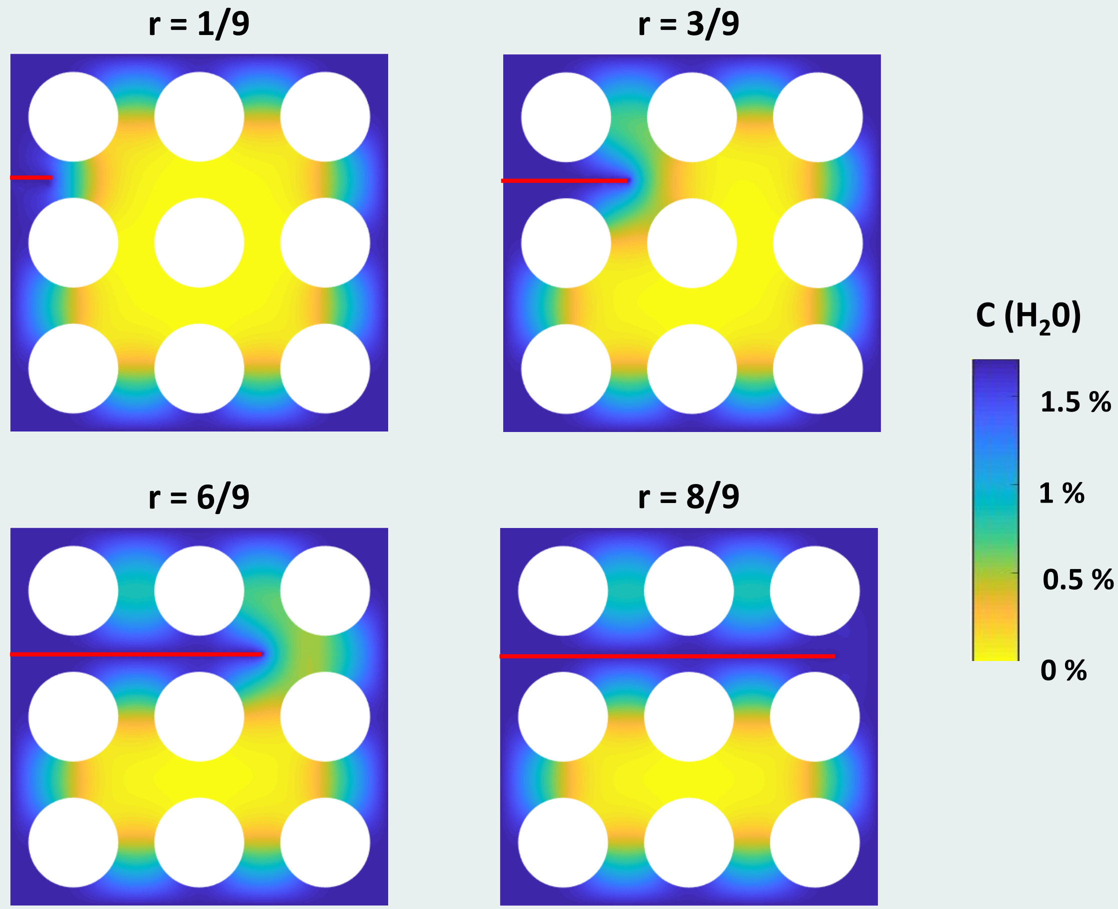
ν = 0.22

ρ = 2540 kg/m³

71 x 71 µm²

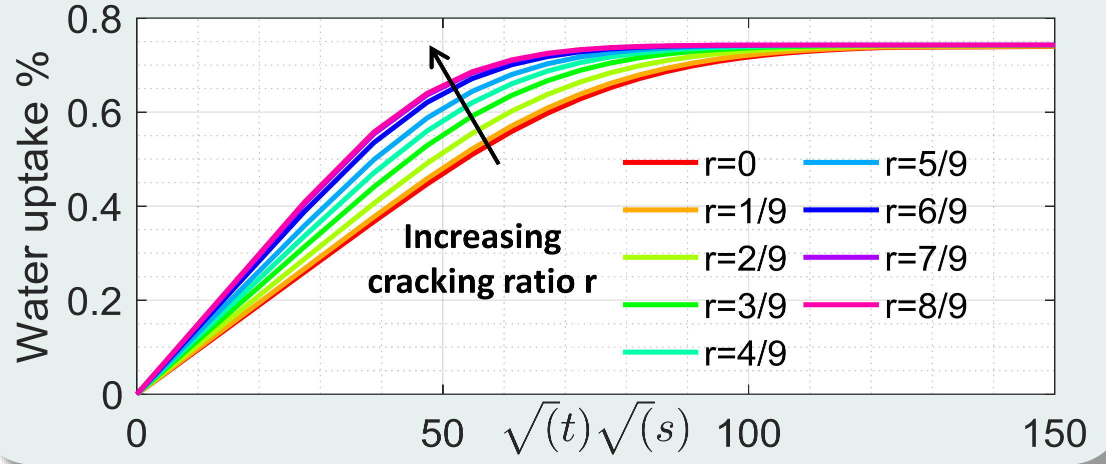
c^{∞} = 1,71 %

Diffusion versus cracking ratio

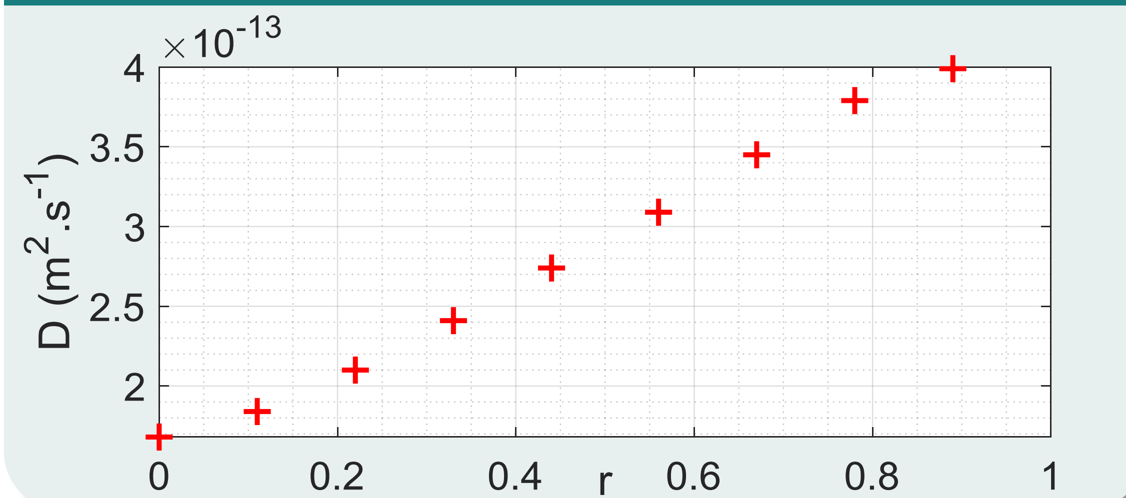


Effect of cracking on diffusion – heterogeneous case

Evolution of diffusion curves as a function of *r*



Evolution of diffusion coefficient as a function of *r*



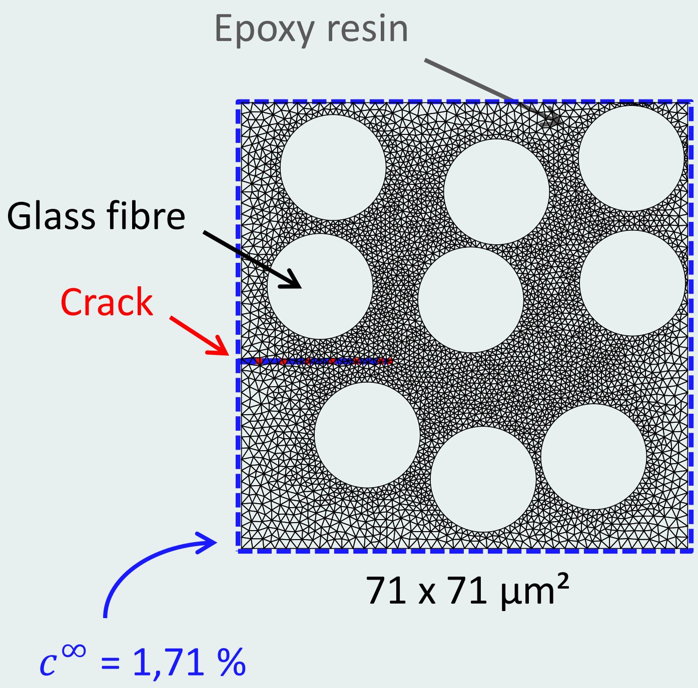
Conclusions

- Accurate identification of the diffusion curves
- The larger the crack size, the faster the diffusion occurs
- Saturation content is only 0.75 % (whereas c_{imp}=1.71 %) because fibers are not subjected to water uptake
- Non-linear evolution of D = f(r)

Effect of cracking on diffusion – heterogeneous random case

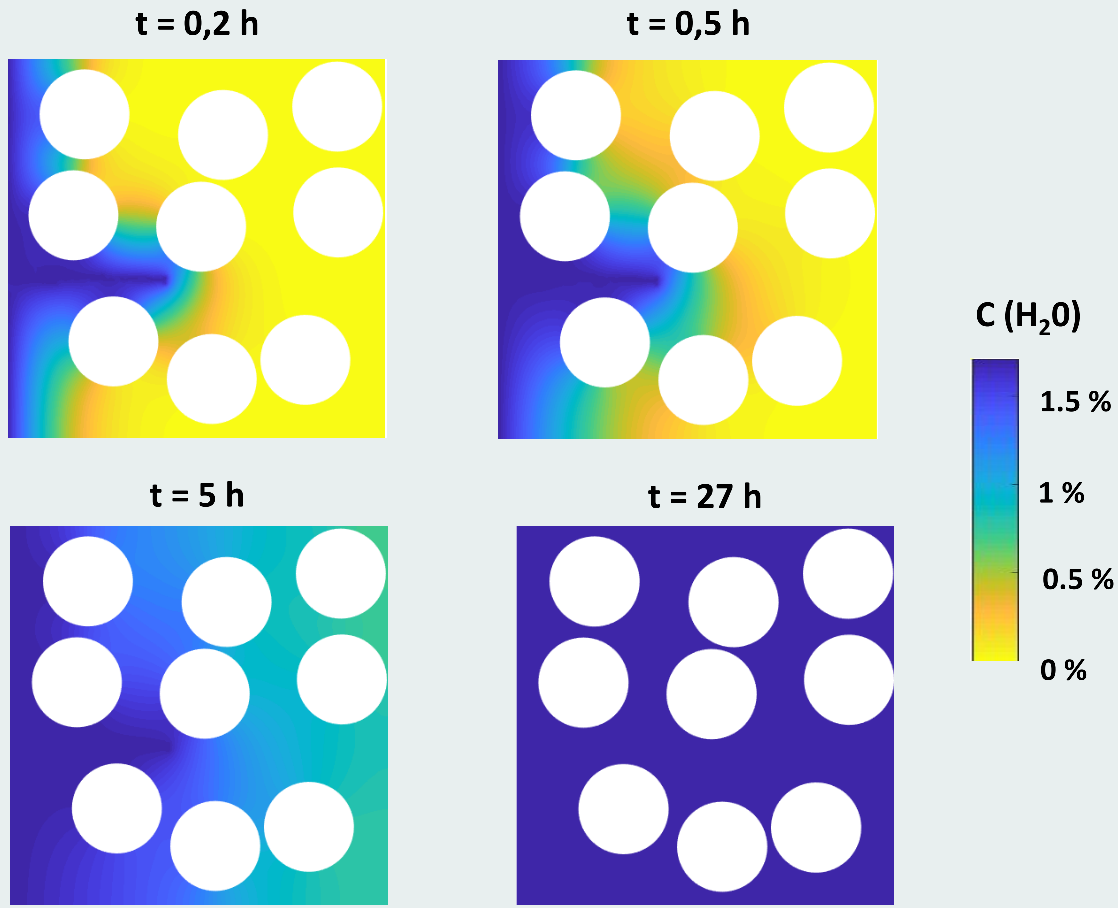
Meshing and boundary conditions

Cracking ratio $r = \frac{\text{crack length}}{\text{total length}}$



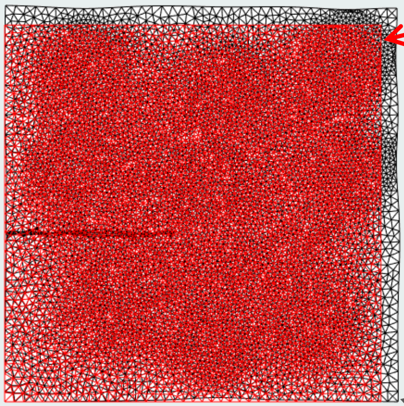
14 900 elements

Diffusion over time (r=0.42)



Effect of cracking on diffusion – heterogeneous random case

Hygroscopic strain fields during diffusion

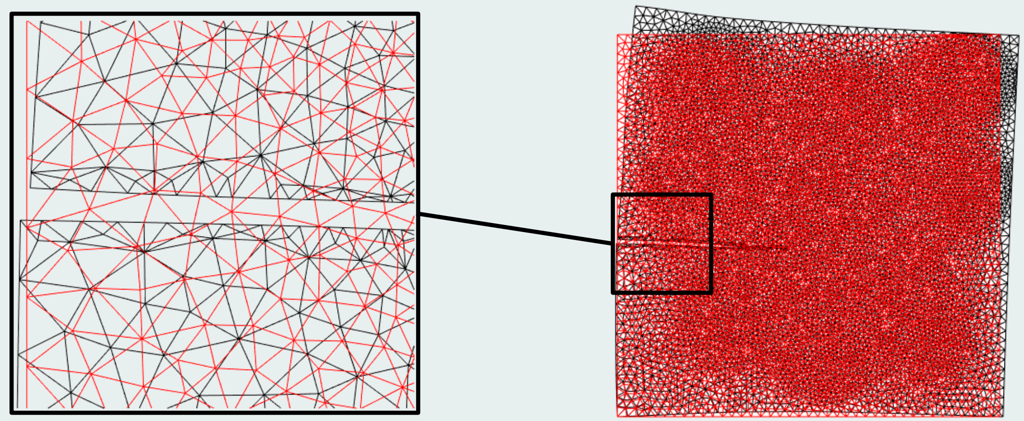


Stationary state

Initial undeformed shape

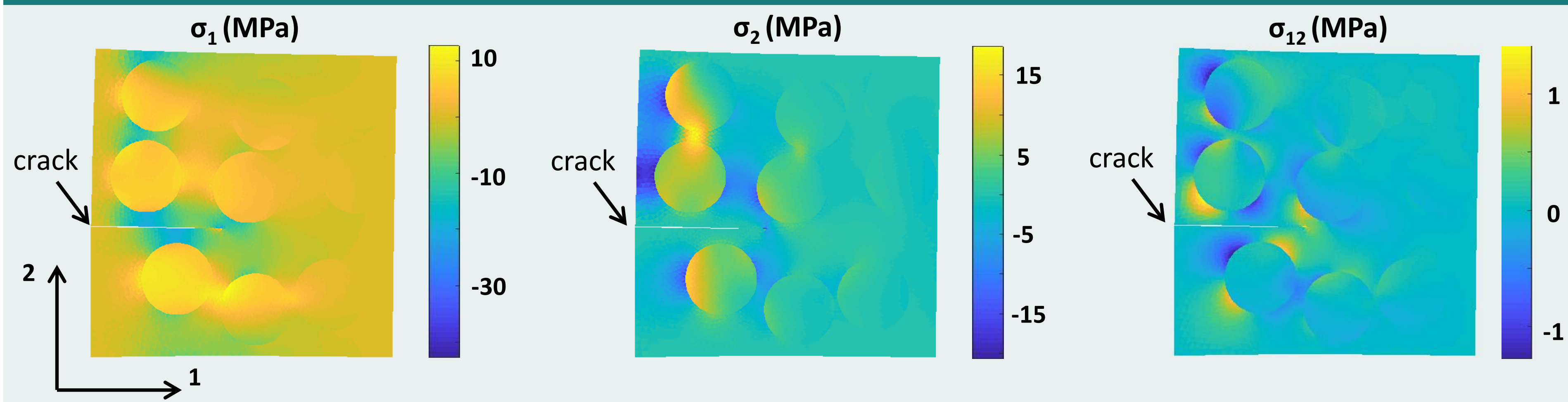
Crack opening occurs during water uptake because of swelling gradient

Final deformed shape



Transient state (5 h)

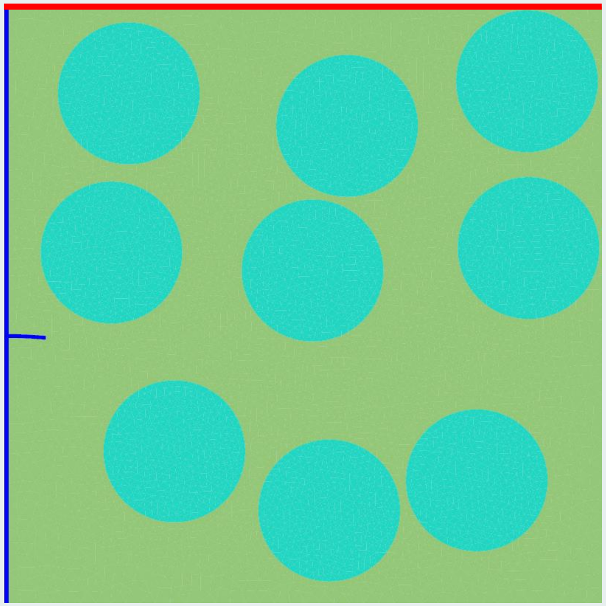
Hygroscopic stress fields during diffusion (transient state - 5 h)



Internal stresses and opening of the crack appear because of the swelling gradient during diffusion

Stochastic numerical study

Problem diffusion



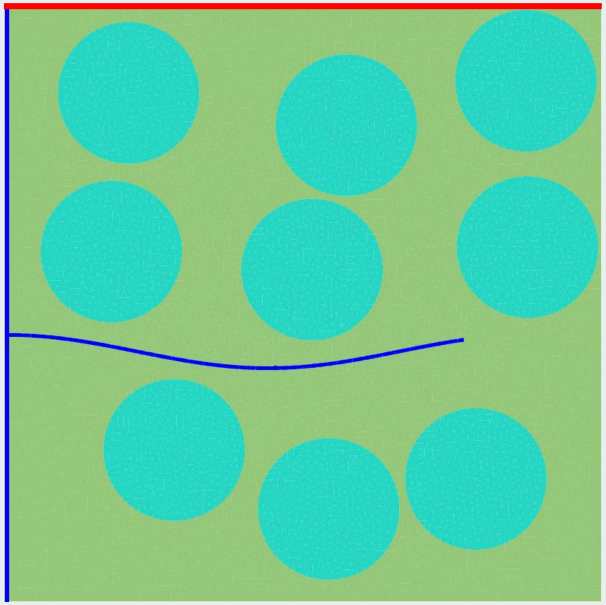
- Random crack length $L_{\text{crack}} \in (5, 55)$ µm (cov = 50 %)
- Random imposed $C_\infty \in (1.6, 1.8)$ % $H_2 0$ (cov = 4 %)
- Mechanical loading σ = 1.5 MPa imposed on the top edge
- Isotropic moisture diffusion tensor with $D = 8.2\ 10^{-2}\ \mu m^2/s$
- Volume fraction $v_f = 40$ % with $d_f = 17\ \mu m$
- Epoxy elastic parameters : $E_m = 4\ GPa, \nu_m = 0.36$ and $\beta = 0.324$ %
- Glass elastic parameters : $E_f = 72.5\ GPa, \nu_f = 0.22$ and $\beta = 0$ %

Approximation parameters

- Spatial approximation with 14000 linear finite elements
- Euler's implicit time scheme for $T = 45\ h$ with $\Delta t = 10\ min$
- Penalty parameter $\gamma = 10^6$
- Stochastic approximation based on polynomial chaos with order $p = 3$

Stochastic numerical study

Problem diffusion



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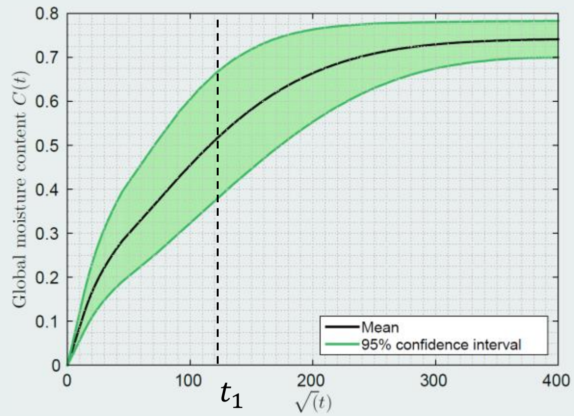
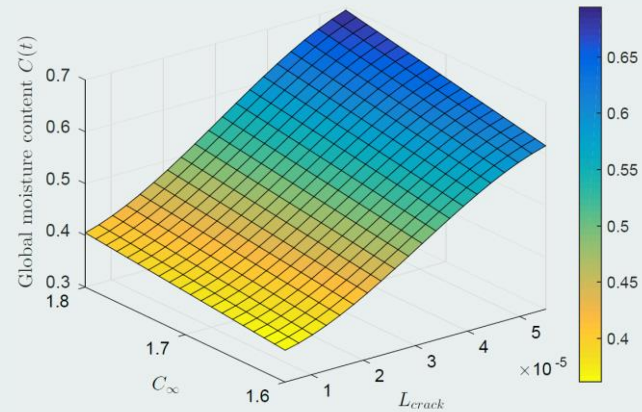
Stochastic numerical study: diffusion results

Results on the global moisture content $C(t)$

Random sorption curve

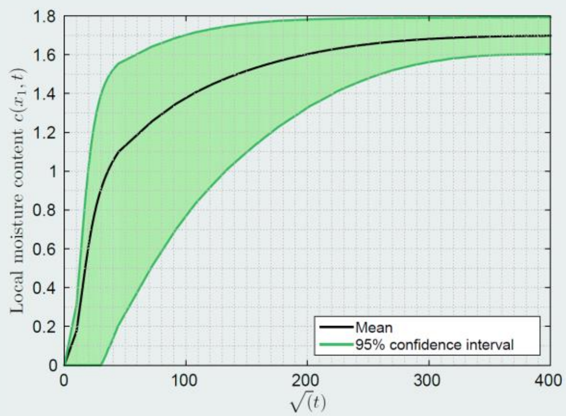


Response surface at $t_1 = 4\ h$

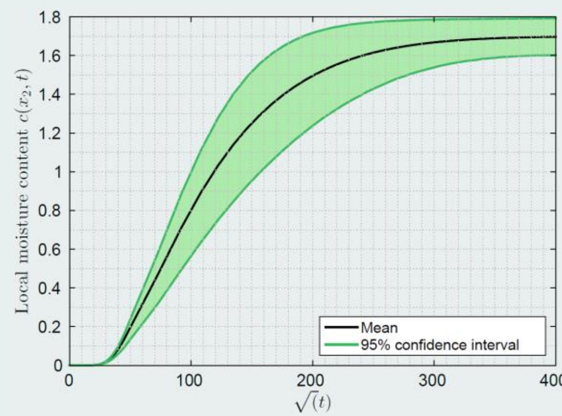


Results on the local moisture content $c(x,t)$

$c(x_1,t)$ with x_1 close to the crack



$c(x_2,t)$ with x_2 further from the crack

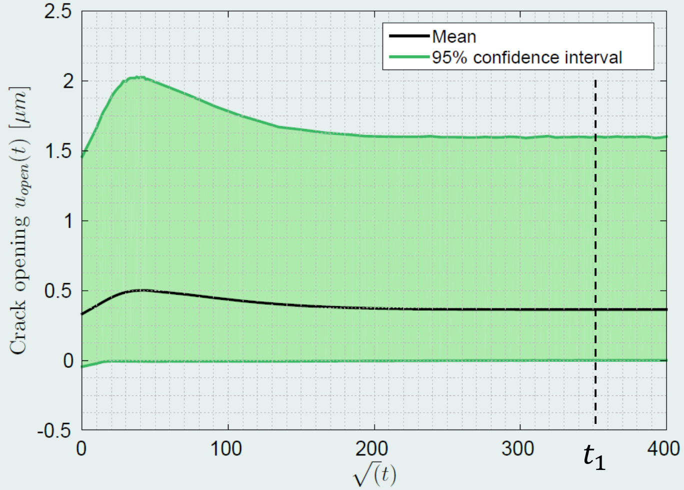


→ relevant influence of the crack length on both global and local moisture contents

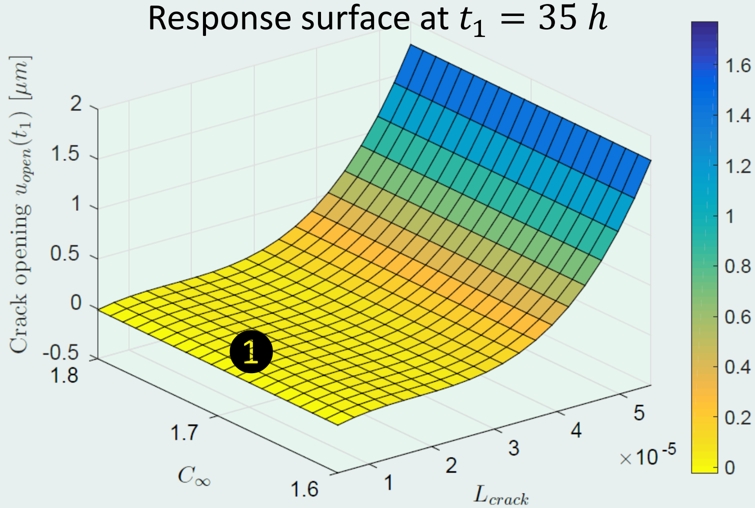
Stochastic numerical study: mechanical results

Results on the vertical crack opening uopen(t)

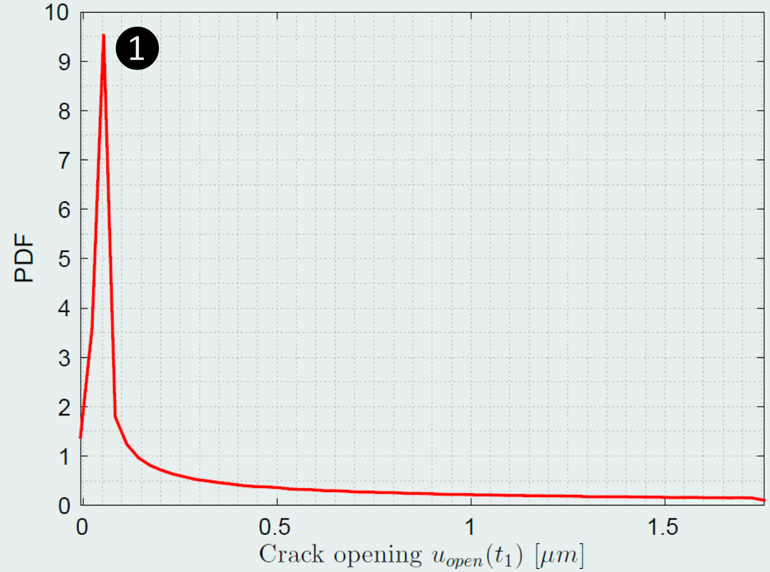
Stochastic process $u_{open}(t)$



Response surface at $t_1 = 35\ h$



PDF at $t_1 = 35\ h$



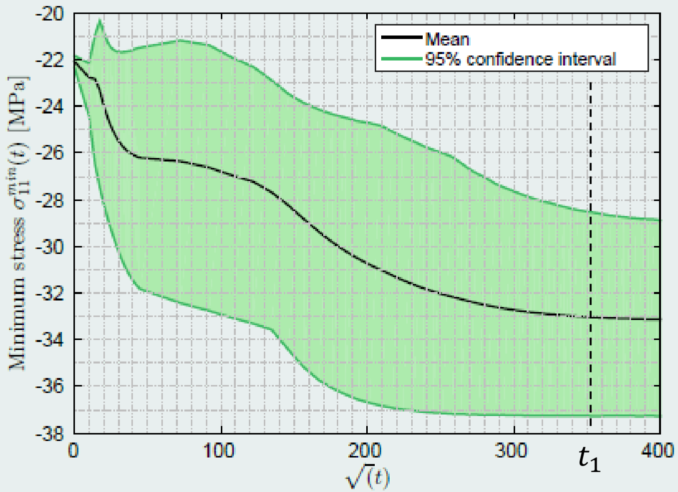
$\text{P}(u_{open}(t_1) > 1.5\ \mu m) = 4\ \%$

Significant variability mainly due to the **crack length randomness**

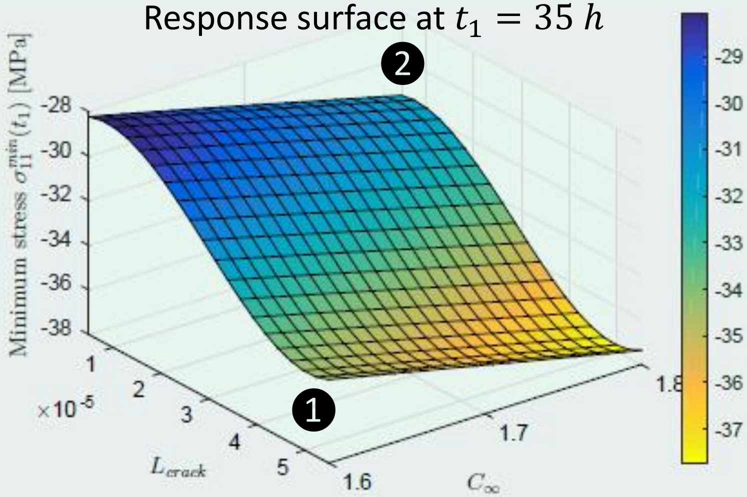
Stochastic numerical study: mechanical results

Results on the minimum local stress $\sigma_{11}^{min}(t)$ – compressive state

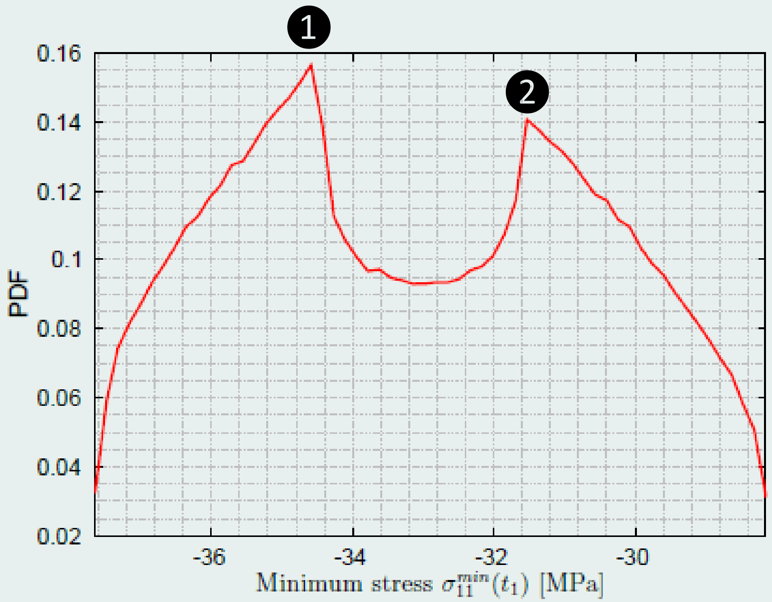
Stochastic process $\sigma_{11}^{min}(t)$



Response surface at $t_1 = 35\ h$



PDF at $t_1 = 35\ h$



$P(\sigma_{11}^{min}(t) \leq -37\ MPa) = 4.7\ \%$

Significant variability mainly due to the **crack length randomness** but also to the **maximum absorption capacity randomness**

Conclusions & future works

Conclusions

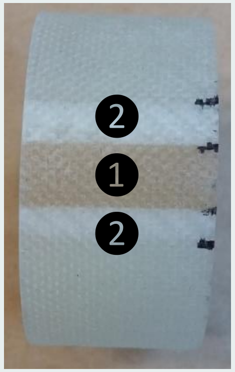
- Study of the impact of hygroscopic ageing on the cracking of composite materials in a deterministic and stochastic context
- Implementation of numerical models based on X-FEM and S-FEM methods
- Consideration of uncertainties to study the influence of the geometric and diffusion parameters

Ongoing and future works

- Dealing with the random crack propagation problem coupled with diffusion phenomenon (computation of stress intensity factors & numerical uptake of the level-set function during crack propagation)
- Gathering experimental data to obtain real input parameters and validate the numerical approach

1 controlled defect

2 defect propagation



Study of the hygro-elastic behaviour of composite materials in presence of cracks: application to the durability of renewable marine energy structures

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Thank you for your attention

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