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FIRMAIN/CEAUCOMP: Multiphysics modeling of the hygro-mechanical behavior of composites used in Marine Renewable Energy structures

GeM Institut de Recherche en Génie Civil et Mécanique

A. Clément, A. Uguen, Q. Dézulier, S. Fréour, F. Jacquemin

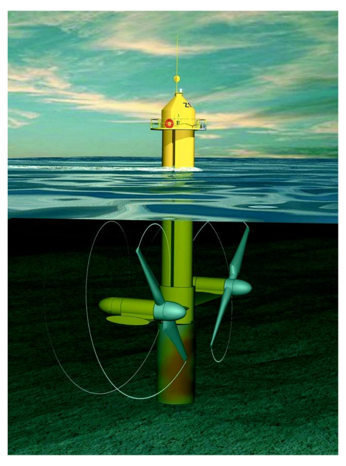
GeM, Research Institute in Civil and Mechanical Engineering, CNRS UMR 6183,
Nantes University, Centrale Nantes, France

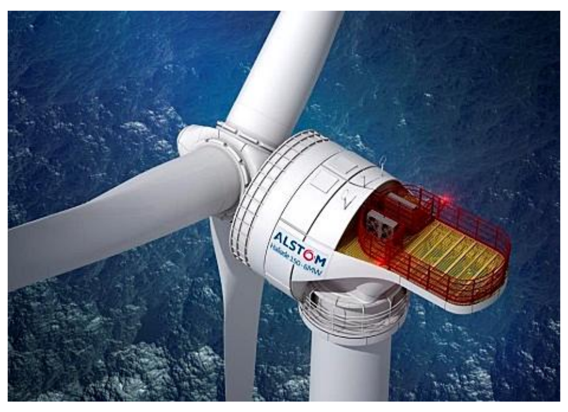
SCIENTIFIC AND INDUSTRIAL MOTIVATIONS

Composite materials used in RME structures are submitted to harsh environments leading to a possible moisture diffusion process. This aging may involve relevant internal mechanical states coupled to a significant drop of the mechanical properties and thus may damage the material and the structure.

General problem

Composite structures submitted to harsh marine environments





Complex coupled loadings:
- Humidity
- Temperature
- Chemical aggressions
- Solar radiations
- Mechanical loadings

Challenges:
- Good understanding of the physical phenomena and their interactions
- Development of efficient/predictive multiphysics and multiscale tools

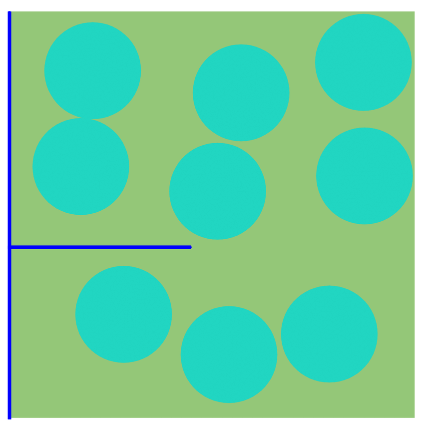
FIRMAIN and CEAUCOMP particular objectives

- The FIRMAIN project aims at studying the impact of hygroscopic aging on crack propagation submitted to uncertainties in composite materials using both X-FEM methodology and spectral stochastic approaches

- The CEAUCOMP project aims at developing predictive models for composites under fully coupled conditions, *i.e.* combined simultaneous exposure of the composite to immersion in water or humid air while being subjected to mechanical loading

FIRMAIN PROJECT (2016-2019)

Heterogeneous Fick diffusion problem



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

$$
\begin{aligned}
\frac{\partial c(\boldsymbol{x},t)}{\partial t} &= \mathbf{D}\Delta c(\boldsymbol{x},t) && \text{in} && \Omega \times \mathbb{R}_*^+ \\
c(\boldsymbol{x},t) &= c^{\infty} && \text{on} && \Gamma_1 \times \mathbb{R}_*^+ \\
(\mathbf{D}\nabla_x c(\boldsymbol{x},t)) \cdot \mathbf{n} &= \mathbf{0} && \text{on} && \Gamma \backslash \Gamma_1 \times \mathbb{R}_*^+ \\
c(\boldsymbol{x},t=0) &= c_0(\boldsymbol{x}) && && \forall \boldsymbol{x} \in \Omega
\end{aligned}
$$

where $\Omega = \Omega_1 \cup \Omega_2$ and $\mathbf{D} = \begin{cases} \mathbf{D_1} \text{ if } \boldsymbol{x} \in \Omega_1 \\ \mathbf{0} \text{ if } \boldsymbol{x} \in \Omega_2 \end{cases}$

eXtended Finite Element methodology

- Implicit description of the geometry with level-sets
- Enriched approximation based on prior physical knowledge [Moës et al. 1999]

Use of a penalty approach for Dirichlet BC along the crack

$$(\mathbf{K} + \gamma \mathbf{K}^p)\mathbf{u} = \gamma \mathbf{f}^p \text{ where } \mathbf{K}^p = \int_{\Gamma_{crack}} N_i N_j d\Gamma \text{ and } \mathbf{f}^p = \int_{\Gamma_{crack}} N_i C_{imp} d\Gamma$$

Enriched approximation to represent irregularities

$$c(\mathbf{x}) = \sum_i N_i(\mathbf{x}) c_i + \sum_i N_i(\mathbf{x}) H(\mathbf{x}) c_i^+$$

where $H(\mathbf{x})$ is the Heaviside function based on the sign of the level set values

Spectral stochastic approach

- Uncertainties propagation with Polynomial Chaos expansion

Decomposition of the solution on a specific basis

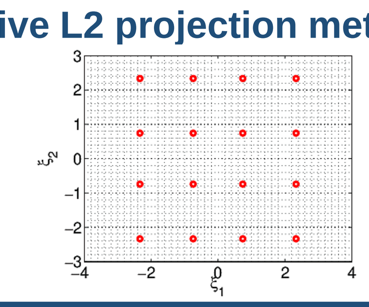
$$c(\mathbf{y}, \xi) \approx \sum_{\alpha=1}^{P} c_\alpha(\mathbf{y}) H_\alpha(\xi)$$

where the $c_\alpha(\mathbf{y})$ 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 with a non-intrusive L2 projection method

$$\mathbf{c}_\alpha = E(\mathbf{c}H_\alpha) = \int_\Theta H_\alpha(\xi)\mathbf{c}(\xi) dP_\xi$$

$$\mathbf{c}_\alpha \approx \sum_{k=1}^{ng} \omega_k H_\alpha(\xi_k)\mathbf{c}(\xi_k)$$

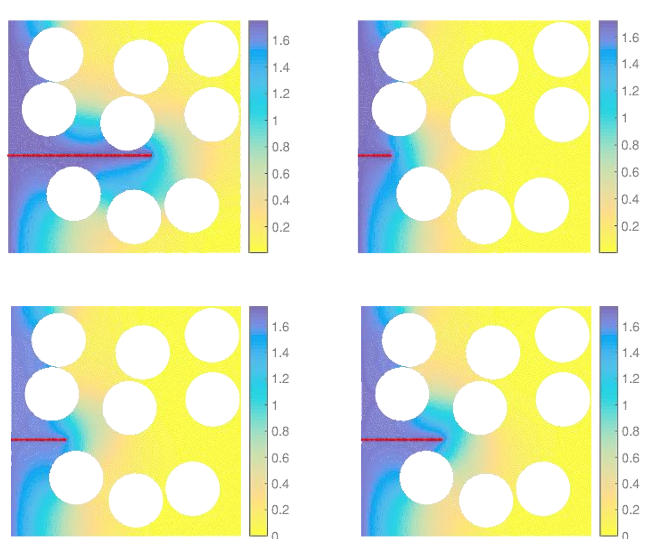


Microscale numerical study

Problem description:
- Random crack length L_{crack} in U(5, 45) µm
- Random imposed C^∞ in U(1.5, 1.9) %H20
- Isotropic moisture coefficient D = 8.2 10^{-2} µm²/s
- Volume fraction v_f = 40% with d_f = 10 µm

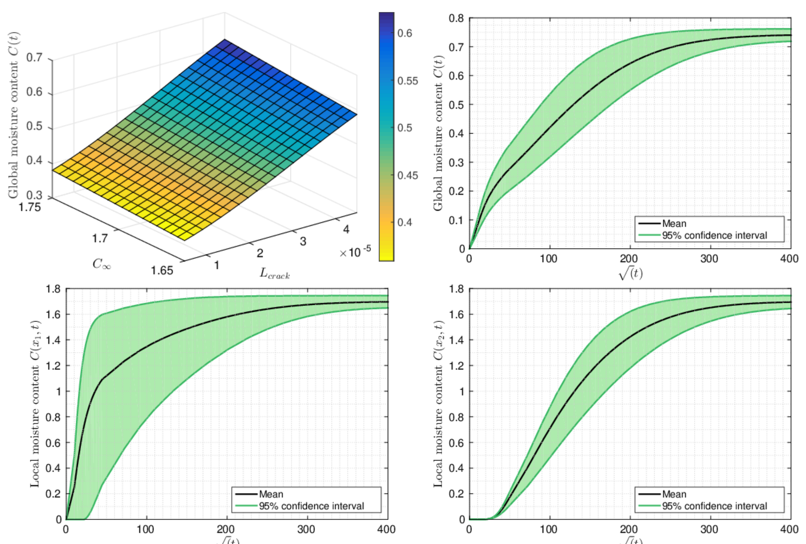
Approximation parameters :
- Mesh with 7200 linear finite elements
- Euler's implicit scheme for T = 45 h with Δt = 100 s
- Penalty parameter γ = 10^6
- Stochastic approximation with p = 3

Random realizations of moisture field



Fast post-processing of the stochastic solution

Results on global and local moisture content



Relevant influence of the crack on both quantities

Ongoing work and perspectives

Ongoing work:
- Implementation of the mechanical problem within the X-FEM framework (crack propagation)
- Determination of effective/apparent properties
- Numerical studies at mesocopic and macroscopic scales
- Experimental campaign on Glass/epoxy composite

Perspectives:
- Introduction of local dependencies for mechanical properties (hygro-mechanical coupled problem)
- Extension to other composite damage processes such as debonding and delamination

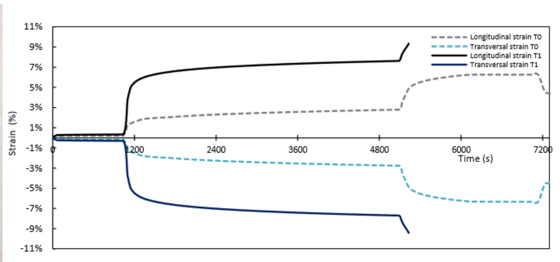
CEAUCOMP PROJECT (2018-2021)

Experimental campaign

Objective: carry out specific coupled creep test in immersion and humid environments

- Development of a specific device
- Use of dedicated obround shaped samples to avoid the use of conventional clamping jaws

Obround shaped samples



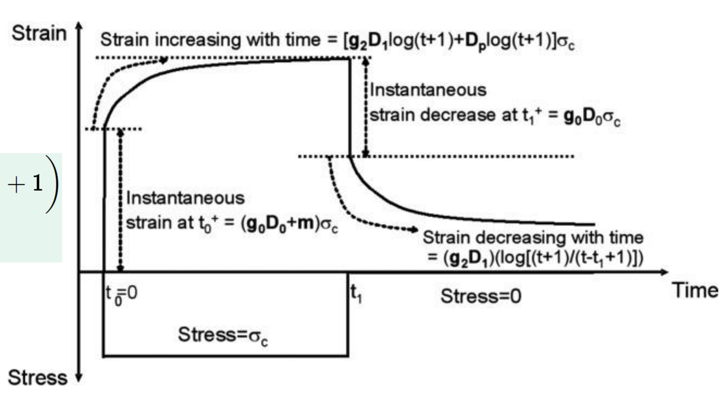
Creep response before and after aging

Coupled hygro-mechanical modeling

Objective: modeling of the visco-elastic behavior during aging

Implementation of dedicated coupled models with moisture diffusion such as [Derombise *et al*., 2011]

$$\varepsilon_c(t) = g_0 D_0 \sigma_c + g_1 g_2 \sigma_c D_1 log_{10}\left(\frac{t}{a_\sigma} + 1\right) + \sigma_c(m + D_p log_{10}(t+1))$$



Perspectives

- Taking into account the various sources of uncertainties
- Adding the possible existence of defects within the material
- Extension of the model to the thermal behavior

References

- Ghanem R. and Spanos P. Stochastic finite elements: a spectral approach, Springer, Berlin, 1991.
- Xiu D. B. and Karniakakis G. E. The Wiener-Askey polynomial chaos for stochastic differential equations, SIAM J. Sci. Comput., 24(2):619-644, 2002.
- Moës N., Dolbow J. and Belytschko T. A finite element method for crack growth without remeshing, IJNME, 46:131-150, 1999.
- Derombise G., Chailleux E., Forest B., Riou L., Lacotte N., Vouyovitch L., Davies P. Long-term mechanical behavior of aramid fibers in seawater, Polymer Engineering and Science, 51(7):1366-1375, 2011.

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