PhD thesis proposal (3 years)

(Collaboration: CEA, École Normale Supérieure Paris-Saclay, École Centrale Nantes)

Domains. Computational mechanics, materials and structural mechanics.

Supervision. (i) Prof. **Rodrigue Desmorat**, École Normale Supèrieure Paris-Saclay, Paris-Saclay University (desmorat@lmt.ens-cachan.fr); (ii) Prof. **Nicolas Moës**, École Centrale de Nantes (nicolas.moes@ec-nantes.fr); (iii) **Giuseppe Rastiello**, CEA Paris-Saclay, Paris-Saclay University (giuseppe.rastiello@cea.fr).

Thick Level Set method for the anisotropic damage to cohesive fracture transition in quasi-brittle materials

Context et motivations. Under the effect of mechanical loads, cracking occurs in quasi-brittle materials (e.g., concrete). This leads to a gradual degradation of the mechanical performances of the structure and directly impacts its robustness and reliability. Also, these cracks constitute preferential pathways for the penetration of fluids and aggressive agents and significantly add their contribution to material degradation.

The prediction of material cracking is a major issue in structural mechanics (and not only in the nuclear context). Cracking of quasi-brittle materials is, however, an extremely complex process. It includes an initial phase characterized by the formation of micro-cracks distributed in a material volume finite in size. Then some micro-cracks coalesce gradually until the formation of a fracture (kinematic discontinuity). Models conventionally used in the literature to represent these phenomena can be classified according to two main theories: on the one hand the Continuum Damage Mechanics, for which cracking is represented by means of a stiffness degradation over a finite volume of material (and represented via a damage variable), and on the other hand the Fracture Mechanics, for which a kinematic discontinuity surface is modeled explicitly. It seems however advisable to place oneself in the Damage Mechanics Context (continuous displacement field, volumetric energy dissipation) to describe the micro-cracking phase and in the Fracture Mechanics context (discontinuous displacement field, localized dissipation) when a kinematic discontinuity is formed. Modeling such a "continuous-to-discontinuous" transition remains an open research topic (Moës et al., 2011; Lé et al., 2018; Rastiello et al., 2018) in computational solid mechanics.

State of the art. The Thick Level Set (TLS) method (Moës et al., 2011) allows modeling the "damage-to-fracture" transition in a unitary theoretical/numerical framework by using a "level-sets" formulation. In an isotropic damage context, the basic idea is to replace the scalar damage variable $D \in [0, 1]$ by an auxiliary variable, the distance to the damage front $\phi \in [0, +\infty)$, and to rewrite the damage evolution laws by making figuring ϕ. Damage is thus computed from the distance to the front, via a function $D = D(\phi)$ such that $D = 0$ on the damage front ($\phi = 0$) and progressively tends to unity when ϕ tends to a critical length value $\ell_c > 0$. Such a strategy naturally leads to introducing a characteristic length in the formulation, which consequently becomes "non-local." This makes it possible to regularize the mechanical problem, in particular when material softening occurs. Also, since the energetic equivalence between TLS and cohesive crack models can be demonstrated, it is possible to introduce kinematic discontinuities in the formulation in a quite natural way (Lé et al., 2018). This not only leads to a better representation of the cracking process, but thanks to the "eXtended Finite Element Method" (X-FEM) technology, it also provides fine information about local crack features (cracks paths, opening, . . .).

Finalities and work program. In previous works on the TLS method, simple isotropic damage models were considered. However, more complex constitutive laws are necessary to represent more realistically the asymmetry of the cracking processes under prevailing tension and compression, some stiffness recovery when the crack recloses (unilateral effect, e.g., in non-monotonic loading conditions), etc. The anisotropic Damage Mechanics (Lemaitre and Desmorat, 2005) allows the formulation of constitutive laws naturally taking into account these mechanisms. In these models, material degradation is no longer described by a scalar damage variable, but through a damage tensor representing the anisotropic degradation of the material stiffness due to the presence of different families of micro-cracks. Anisotropic models that are theoretically robust and easy to implement in a numerical context are available (Desmorat, 2015).

The proposed PhD work aims to develop a TLS formulation in the context of the Anisotropic Damage Mechanics. Significant theoretical and numerical efforts will be needed to achieve this goal. First, a bibliographic study concerning the Continuum Damage Mechanics, cohesive crack, and TLS models will be performed. An anisotropic damage model will then be formulated in the context of the TLS theory, and the damage-to-fracture transition will be studied. Ad-hoc solution algorithms (e.g. Moreau et al., 2018; Rastiello et al., 2019) and numerical integration methods will then be developed. Finally, structural test cases will be simulated to qualify the method and analyze the advantages of an anisotropic formulation compared to the isotropic case. An extension to the case of damage to ductile materials will also be explored.

Perspectives. In the long term, this formulation will be used for the simulation of the mechanical response of concrete and reinforced concrete structures under quasi-static and dynamic loadings. The physical consistency of the damage models, combined with the potential provided by the TLS theory to couple these formulations with cohesive crack laws, will allow simulating complex multi-dissipative processes (associated with opening/closing of cracks, degradation of the concrete-concrete bond at the level of cracks, etc.). Finally, thanks to an accurate description of the cracking features, the coupled fluid transfer problem in the cracking structures (e.g., reservoirs, containment structures, etc.) might be studied.

Bibliographic references

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Expected starting date. Fall 2019. Three years contract.

Profile. Master of Science (or equivalent). Disciplines: Mechanics, Civil Engineering, Mechanical Engineering, Computational Mechanics, Applied Mathematics. In case of applicants who have not resided or carried out their main activity in France more than 12 months in the last three years (mobility condition), the Ph.D. thesis is eligible for funding through the NUMERICS project (`http://numerics.cea.fr/`), an international Ph.D. program launched by CEA in the fields of numerical simulation and scientific computing. This project has received funding from the European Union's Horizon 2020 research and innovation programme within the Marie Sklodowska-Curie Actions (MSCA). French or international students who do not meet the above-mentioned mobility condition are also encouraged to apply.

Host laboratory. CEA, DEN, DANS, DM2S, Mechanical and Thermal Studies Service (SEMT), Seismic Mechanics Study (EMSI) Lab. CEA Saclay center (Île de France / Parisian region), France

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University and Doctoral School. Paris-Saclay University, Doctoral School SMEMaG, "Sciences Mécaniques et Énergétiques, Matériaux et Géosciences"

Application procedure. Please submit electronically (in PDF format) a detailed resume and a motivation letter. Applications must be sent to Dr. Giuseppe Rastiello (giuseppe.rastiello@cea.fr). In the object of your application email, please include the reference "[PhDThesis-SL-DEN-19-0226-Application]" followed by your NAME and Surname.