Bridging Scales and Methods in Heterogeneity and Fracture Mechanics: from Higher-Order Continua and Adaptive FEM-SPIM to Machine Learning Surrogates

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Room	**2R, DICAM Mesiano**

The computational modeling of crack nucleation and propagation in heterogeneous, quasi-brittle materials (such as concrete or rock formations) represents a major frontier in structural and geological engineering. Traditional single-scale models often fail to capture micro-structural complexities, while classical multiscale configurations (such as standard FE2 schemes) introduce prohibitive computational costs and a high dependence on elusive microstructural parameters. To overcome these dual challenges of physical expressiveness and computational efficiency, this presentation explores a comprehensive system of recent advancements that couple variational phase-field fracture formulations with higher-order continua, adaptive multi-method solvers, and physics-informed machine learning (ML) surrogates. The presentation is structured into three main interconnected pillars: First, we address microstructural representation and kinematics. To capture micro-scale energy dissipation and rotational incompatibilities that classical Cauchy continua neglect, a micropolar (Cosserat) phase-field framework is introduced. Implemented within the object-oriented INSANE platform using a staggered solver, this model incorporates independent micro-rotational degrees of freedom and a wryness tensor. Parametric analyses using single-edge notched shear tests reveal that the micro-rotational stiffness parameter (Gc2) acts as an energetic penalty against rotation gradients, effectively regulating crack bifurcation and gov-

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erning the rectilinearity of the fracture path. Second, we explore computational efficiency in explicit multiscale mechanics (FE2) for complex scenarios like hydraulic (pressurized) fracturing. On a single-scale level, a novel adaptive and automated coupling between the Finite Element Method (FEM) and the meshfree Smoothed Point Interpolation Method (SPIM) is presented, where SPIM is dynamically restricted to active fracture regions guided by phase-field indicators. Moving to the FE2 multiscale framework, efficiency is further optimized by restricting the phase-field calculation strictly to the micro-scale Representative Volume Element (RVE). Furthermore, we discuss advanced homogenization strategies—specifically a fracture-region averaging technique—which isolates the homogenized constitutive properties more accurately by mitigating the artificial boundary effects of localized damage within the RVE. Third, to completely bypass the explicit RVE execution at every macroscopic integration point, we present a thermodynamics-based machine learning surrogate paradigm. Synthetic training data is generated from 2D phase-field RVE simulations capturing concrete variations (aggregate fractions, gradations, and interfacial transition zone properties) under multiple biaxial loading states. By incorporating physical regularization terms directly into the neural network loss functions, thermodynamic consistency and high generalization capabilities are successfully enforced. Conclusively, this integrated overview demonstrates that the combination of localized meshfree-finite element adaptivity, refined microstructural kinematics, and physics-informed machine learning offers a robust, accurate, and practical framework for solving multi-scale fracture problems in real-world engineering applications.

Keywords: Phase-field fracture, Multiscale analysis (FE2), Micropolar continuum, FEM-SPIM adaptive coupling, Machine learning surrogates, Homogenization techniques, INSANE platform

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