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A unified first order hyperbolic model for nonlinear dynamic rupture processes in diffuse fracture zones

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Earthquake fault zones are more complex, both geometrically and rheologically, than an idealised infinitely thin plane embedded in linear elastic material. Field and laboratory measurements reveal complex fault zone structure involving tensile and shear fractures spanning a wide spectrum of length scales (e.g., Mitchell & Faulkner, 2009), dense seismic and geodetic recording of small and large earthquakes show hierarchical volumetric faulting patterns (e.g., Cheng et al., 2018, Ross et al., 2019) and 2D numerical models explicitly accounting for off-fault fractures demonstrate important feedback with rupture dynamics and ground motions (e.g., Thomas & Bhat 2018, Okubo et al., 2019).

Here (Gabriel et al., 2021) we adopt a diffuse crack representation to incorporate finite strain nonlinear material behaviour, natural complexities and multi-physics coupling within and outside of fault zones into dynamic earthquake rupture modeling. We use a first-order hyperbolic and thermodynamically compatible mathematical model, namely the GPR model (Godunov & Romenski, 1972; Romenski, 1988), to describe a continuum in a gravitational field which provides a unified description of nonlinear elasto-plasticity, material damage and of viscous Newtonian flows with phase transition between solid and liquid phases.

The model shares common features with phase-field approaches but substantially extends them. Pre-damaged faults as well as dynamically induced secondary cracks are therein described via a scalar function indicating the local level of material damage (Tavelli et al., 2020); arbitrarily complex geometries are represented via a diffuse interface approach based on a solid volume fraction function (Tavelli et al., 2019). Neither of the two scalar fields needs to be mesh-aligned, allowing thus faults and cracks with complex topology and the use of adaptive Cartesian meshes (AMR). High-order accuracy and adaptive Cartesian meshes are enabled in 2D and 3D by using the extreme scale hyperbolic PDE solver ExaHyPE (Reinarz et al., 2019).

We show a wide range of numerical applications that are relevant for dynamic earthquake rupture in fault zones, including the co-seismic generation of secondary off-fault shear cracks, tensile rock

fracture in the Brazilian disc test, as well as a natural convection problem in molten rock-like material. We compare diffuse interface fault models of kinematic cracks, spontaneous dynamic rupture and dynamically generated off-fault shear cracks to sharp interface reference models. To this end, we calibrate the GPR model to resemble empirical tensile and shear crack formation and friction laws. We find that the continuum model can resemble and extend classical solutions, while introducing dynamic differences (i) on the scale of pre-damaged/low-rigidity fault zone, such as out-of- plane rupture rotation; and (ii) on the scale of the intact host rock, such as conjugate shear cracking in tensile lobes.

Our approach is part of the TEAR ERC project (www.tear-erc.eu) and will potentially allow to fully model volumetric fault zone shearing during earthquake rupture, which includes spontaneous partition of fault slip into intensely localized shear deformation within weaker (possibly cohesionless/ultracataclastic) fault-core gouge and more distributed damage within fault rocks and foliated gouges.