Supershear mode I and mode II fracturing in dry and saturated porous media

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Classical fracture mechanics predicts an upper bound on crack propagation speed, typically the Rayleigh wave speed for mode I fractures and the shear wave speed for mode II ruptures. Beyond these limits, tensile and shear fracture are traditionally considered energetically forbidden. However, experimental observations, field evidence from large earthquakes, and recent numerical studies increasingly demonstrate the existence of sub-, inter-, and supershear rupture regimes. In this study, we investigate the dynamic propagation of mode I and mode II fractures in dry and fluid-saturated media using multiple numerical frameworks, including the Extended FEM (XFEM), peridynamics (PD), and hybrid FEM/PD formulations.

For mode I fracture, simulations reveal a systematic transition in fracture behavior with increasing mechanical or hydraulic loading. Crack propagation evolves from smooth steady growth to stepwise regime, and ultimately to previously undocumented forerunning characterized by the nucleation of cracks ahead of the main tip. This progression is observed in both dry and saturated porous media, under mechanical loading and fluid injection. Notably, forerunning is shown to occur not only at supershear speeds but also under subsonic crack advance, as demonstrated in a beam on an elastic foundation subjected to sinusoidal loading. In saturated media, increased injection rates strongly promote the transition to stepwise and forerunning behavior, enabling crack speeds that exceed both shear and dilatational wave velocities.

For mode II fracture, we employ a newly developed 2-D hybrid FEM/PD model to study the transition from sub-Rayleigh to supershear rupture in dry and fluid-saturated media. The model reproduces laboratory observations of direct and indirect (mother-daughter crack or Burridge-Andrews) transitions and captures the formation of shear Mach cones. In fluid-saturated media, poroelastic coupling near the rupture front favors direct transitions to supershear fracturing, even in the absence of daughter cracks.

The consistency of these results across distinct numerical methods and constitutive descriptions supports the robustness of supersonic fracture and rupture in both tensile and shear modes. The findings have direct implications for earthquake dynamics, fluid-rich fault zones, and geophysical processes involving rapid fracture acceleration (slab tearing, volcanic systems).