Sequences of Fast and Slow Ruptures on a Frictional Interface in an Elasto-plastic Solid: Application to Earthquake Modeling

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Earthquakes are among the most damaging natural hazards. Our current understanding of earthquakes suggest that they nucleate as instabilities under slow tectonic loading and propagate as shear fractures, mostly at sub-Rayleigh speeds but occasionally as supershear cracks. During an earthquake, the change in the strain energy from the bulk is transformed in fracture energy to facilitate the breakdown processes, heat due to frictional dissipation, radiated energy in the far-field, and inelastic dissipation in the near-field.

While significant progress has been made in understanding earthquake source processes in linear elastic domains, the effect of more realistic inelastic rheologies including plasticity is poorly understood. Here, we simulate the co-evolution of shear fractures on pre-existing fault surfaces and bulk inelastic deformation through modeling a sequence of (fast) earthquakes and (slow) aseismic slip of a 2D rate-and-state frictional interface embedded in a full-space elastic-plastic bulk. We use a computationally efficient hybrid finite element spectral boundary integral scheme that relies on domain decomposition in space and extreme adaptive stepping in time. The hybrid computational scheme enables exact near-field truncation of the elastodynamic field allowing us to use high resolution finite element discretization in a narrow region surrounding the fault zone that encompasses the potential plastic deformation. Wave propagation and long range static stress transfer in the exterior half spaces are handled using the spectral boundary integral equation. The adaptive time stepping is based on the maximum velocity jump across the fault surface. The resulting time step varies from milliseconds to days enabling the simulation of both slow deformation and fast dynamic ruptures over multiple earthquake cycles.

We show that off-fault plasticity may lead to partial ruptures as well as temporal clustering of seismic events. Furthermore, the interaction of fault slip and off-fault plasticity results in pockets of slip deficit signaling that part of the permanent deformation is accommodated in the bulk as inelastic strain. This is different from purely elastic case where all the inelastic deformation is localized as slip on the fault surface. While the energy dissipated through plastic deformation remains a small fraction of the total energy budget, if the yield stress is high enough compared to the fault reference frictional strength, its impact on the source characteristics is disproportionately large through the redistribution of stresses and viscous relaxation. However, if the yield stress of the bulk approaches the frictional strength of the fault, new family of rupture patterns emerge characterized by significant energy dissipation in the bulk and localized slow or creeping ruptures on the fault with no inertia effects Our results emphasize the critical role of bulk strength in controlling multi scale earthquake dynamics and suggest a new mechanism of dynamic heterogeneity in earthquake physics that may have important implications on earthquake size distribution and energy budget. Our findings may also shed light on the dynamics of other systems with similar co-evolutionary processes such as grain boundaries in crystalline structures.