Towards Dynamic Rupture Simulations with High Resolution Fault Zone Inelasticity.

Publications:

Ma, X. and Elbanna, A. E. (2019) Dynamic Rupture Propagation on Fault Planes with Explicit Representation of Short Branches. Earth and Planetary Science Letters (Under Review). DOI: 10.31223/osf.io/xesnz Earth ArXiv URL: https://eartharxiv.org/xesnz/

Ma, X., Hajarolasvadi, S., Albertini, G., Kammer, D., & Elbanna, A. (2018). A hybrid finite element-spectral boundary integral approach: Applications to dynamic rupture modeling in unbounded domains. Int J Numer Anal Methods Geomech. 2018;1-22.

Abstract: Active fault zones are homes for a plethora of complex structural and geometric features that are expected to affect earthquake rupture nucleation, propagation, and arrest, as well as interseismic deformation. Simulation of these complexities have been largely done using continuum plasticity or scalar damage theories. In this paper, we use a highly efficient novel hybrid finite element-spectral boundary integral equation scheme to investigate the dynamics of fault zones with small scale pre-existing branches as a first step towards explicit representation of anisotropic damage features in fault zones. 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 small scale branches while remaining computationally efficient. Our results suggest that the small scale branches may influence the rupture in ways that may not be realizable in homogenized continuum models. Specifically, we show that these short secondary branches significantly affect the post event stress state on the main fault leading to strong heterogeneities in both normal and shear stresses and also contribute to the enhanced generation of high frequency radiation. The secondary branches also affect off-fault plastic strain distribution and suggest that co-seismic inelasticity is sensitive to pre-existing damage features. We discuss our results in the larger context of the need for modeling earthquake ruptures with high resolution fault zone physics.

Main Findings:

The main conclusions may be summarized as follows:

• The secondary faults increases the overall energy dissipation leading to a reduction in the slip, peak slip rate and rupture propagation on the main fault.

• The activation of the secondary faults may lead to backward propagating ripples in the slip rate that increases slip far from the rupture top.

• Rupture activation, propagation, and arrest on the secondary branches lead to a strongly heterogeneous normal and shear stress fields on the main fault. These heterogeneities may potentially be large enough to cause fault opening or shear stress reversal. The complex post-event stress field would not have been generated using continuum plasticity models.

• The interaction of the seismic wave radiated from the main fault and those generated by the secondary branches promotes high frequency generation and generate high frequency fluctuations in computed seismograms.

• The secondary branches lead to evolution of normal undulations in the main fault strike.

Model Setup:

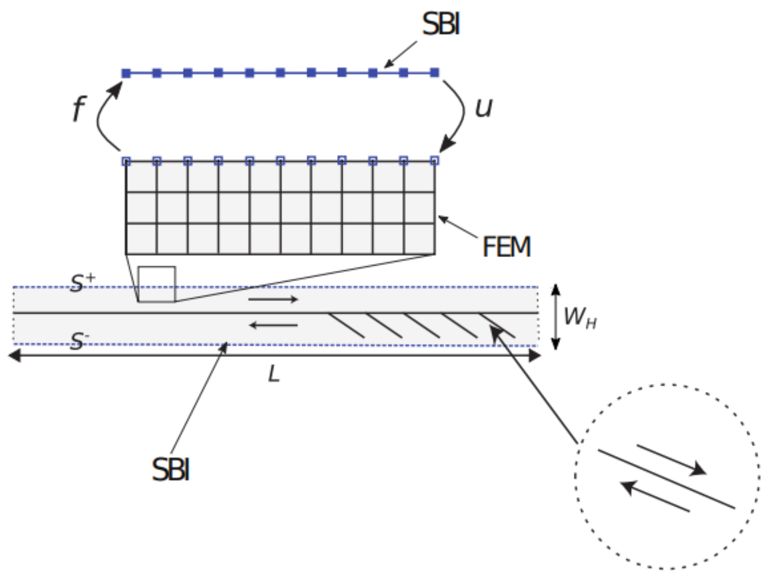

Figure 1: Schematic of the complex fault zone structure considered in this paper. The main fault lies horizontally in the middle of the domain, and the secondary branches are located in a limited region on one side of the fault (tension side). Following Poliakov et al. 2003 we call this setup a fish bone structure. All secondary faults are contained in a narrow virtual strip of dimensions L x W that is discretized using the Finite element method (FEM). On the upper and lower edges S+ and S-, the FEM is coupled with the Spectral Boundary Integral Equation which exactly model the exterior homogeneous elastic half spaces. Tractions and displacements are consistently exchanged between the two methods at the shared nodes.

<u>Example Results:</u>

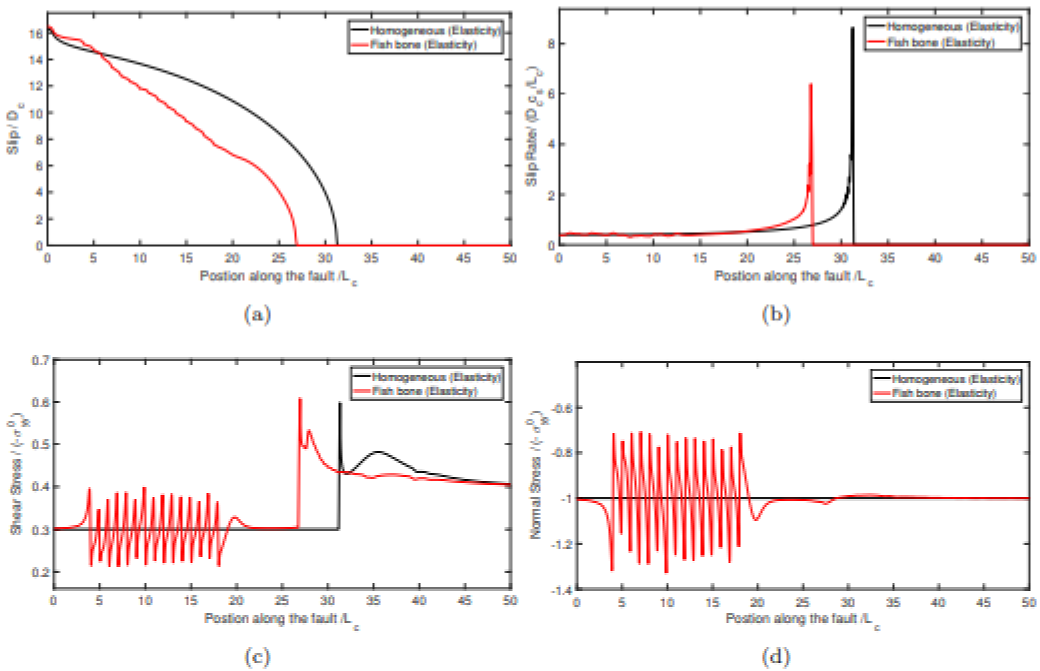

Figure 2: Slip, slip rate and shear stress distributions on the main fault, at the same point in time, with and without secondary branches for the elastic material case. (a) Slip, (b) Slip rate, (c) Shear stress distribution, and (d) Normal stress distribution. Overall, the fish bone case shows significant post-event stress heterogeneities as well as reduced slip, maximum slip rate, and rupture speed.

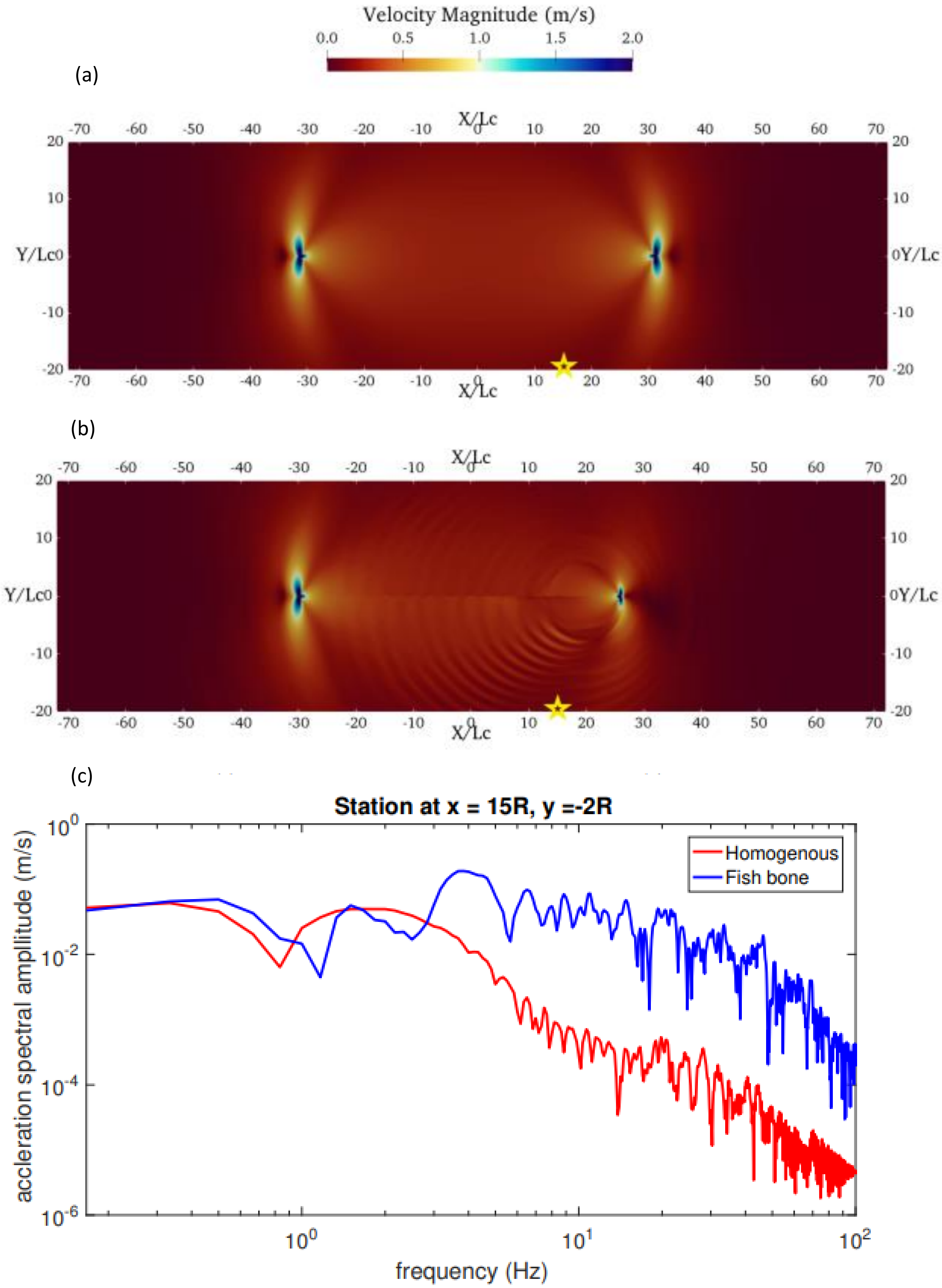
Velocity Magnitude (m/s)
0.0
0.5
1.0
1.5
2.0
(a)
X/Lc
Y/Lc
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
20
10
-10
-20
(b)
X/Lc
Y/Lc
(c)
Station at x = 15R, y =-2R
Homogenous
Fish bone
accleration spectral amplitude (m/s)
frequency (Hz)
10^0
10^-2
10^-4
10^-6
10^1
10^2

Figure 3: Contours of the bulk velocity field and an example acceleration spectrum at a near field station. (a) Bulk velocity field in a Homogeneous medium. (b) Bulk velocity field in a Domain with fish bone structure. Coherent high frequency generation emerge in the case of the fault with secondary branches (fish bone structure) and propagate away from the fault plane as concentric fringes. These high frequency waves are generated as a result of the constructive interference between the waves emitted by the main fault and the secondary branches. In the homogeneous case the high frequency wave field is localized near the rupture fronts. (c) Fault normal acceleration spectral amplitude at station $x* = 15R$ and $y * = -2R$ showing increased high frequency content and a flat frequency spectrum in the range of 1-20 Hz for the fault zone with short branches.

Future work: Future extensions of this work may include systematic investigation of the effect of the length, spacing and orientation of the secondary branches. The investigation may be extended to explore the influence of multiple scales and hierarchies of the secondary branches. The ultimate goal would be to use the hybrid scheme to model earthquake cycles in complex fault zone structures bridging both seismic and aseismic episodes and enabling the interplay between dynamics, stress evolution, and geometry to understand the underpinnings of earthquake complexity.