SCEC report, project #07146

Study of the bimaterial effect and potential preferred rupture direction through simulations of earthquake sequences

Principal Investigator: Nadia Lapusta

California Institute of Technology

Category: Integration and Theory

Priority objectives addressed by the proposed research:

A9. Assess predictability of rupture extent and direction on major faults

A8. Test hypothesis for dynamic fault weakening

A7. Determine the origin, evolution and implications of on- and off-fault damage

Interdisciplinary Focus Area: Fault and Rock Mechanics (FARM)

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1. Summary of the project goals

Large crustal faults usually juxtapose rocks with different mechanical properties. One example is the San Andreas Fault near Parkfield in Southern California, which separates mainly Franciscan assemblage on the Northwest side and Salinian granitic rocks on the Southwest side (Boatwright, 1982**;** Somerville et al. 1997). Geological observations along the San Andres, Punchbowl, and San Jacinto faults show that the damage pattern of the fault zone rocks is asymmetric, which may be caused by a preferred rupture propagation direction along these faults (Dor et al, 2005, 2006). For seismic hazard assessment, it is important to understand whether there is a preferred rupture propagation direction on faults with material contrast (which are typically called bimaterial faults).

The goal of this project has been to develop numerical methodology suitable for simulating the dynamics of bimaterial faults, e.g., faults between two dissimilar elastic media. The emphasis has been on considering the long-term history of the fault, including earthquake sequences.

2. Relevance of the project goals to the objectives of SCEC

This project addresses the following SCEC3 Science Priority Objectives:

A9. Assess predictability of rupture extent and direction on major faults.
A8. Test hypothesis for dynamic fault weakening.
A7. Determine the origin, evolution and implications of on- and off-fault damage.

A9 and A8 are specifically addressed in our goals. A7 is relevant by implication, as the preferred rupture direction is proposed as an explanation for the origin of asymmetry on off-fault damage. Our project is also well-aligned with the primary mission of Fault and Rupture Mechanics Interdisciplinary Focus Area “to develop physics-based models of the nucleation, propagation and arrest of dynamic earthquake ruptures” and its goal to “contribute to our understanding of earthquakes in the Southern California fault system.” As mentioned, the bimaterial effect may be important for the SAF. The studies proposed in this project would contribute to a number of aims of FARM, with the most relevant ones being: “Characterize the probability [...] of preferred earthquake rupture direction”, “Investigate the relative importance of different dynamic weakening and fault healing mechanisms [...]”, and “Understand the influence of small-scale processes on larger-scale fault dynamics.” (p. 14 of 2008 Program Announcement). Whether the preferred rupture direction exists or not is important for probabilistic seismic hazard assessments for faults in Southern California.

3. Previous studies and observations related to the bimaterial effect and preferred rupture direction

With significant simplifications, theoretical developments and simulations of in-plane sliding (e.g. Weertman 1980, Adams 1995, Andrews and Ben-Zion, 1997) suggest that there is a preferred rupture propagation direction on a bimaterial fault. Some geological observations seem to support the theory, such as damage pattern asymmetry (Dor et al. 2005, 2006) and aftershock asymmetry (Rubin and Ampuero 2006) on faults with material contrast. However, other evidence seems to contradict the theory. For example, Harris and Day (2005) pointed out that among 8 M4-6 well-studied earthquakes in Parkfield, only 3 earthquakes have propagated in the direction predicted by the theory, although Ben-Zion (2006b) provides an explanation for that. Numerical simulations also lead to diverse conclusions (Andrews and Harris 2005; Harris and Day 2005, 2006, Ben-Zion 2006a,b, Shi and Ben-Zion 2006, Rubin and Ampuero 2006; Ampuero and Ben-Zion, 2007; Dalguer and Day, 2007), since material contrast is not the only parameter controlling dynamic rupture. Simulations show that when the bimaterial effect is combined with linear slip-weakening friction, rupture on a bi-material fault is often bilateral, although the rupture tip that propagates in the theoretically preferred direction is often stronger, with higher slip rates and larger dynamic variations in stresses. However, rupture can also be unilateral and propagate in the preferred direction if the prestress level is sufficiently low, friction is rate-dependent, and/or certain nucleation procedures are used in single-event simulations, such as an imposed, relatively fast, variations in pore fluid pressure.

4. Why it is important to study bimaterial effect with simulations of earthquake sequences

As established in prior simulations of single dynamic ruptures, a number of factors can combine with the bimaterial effect to either suppress or enhance the preferred rupture direction. In particular, the stress level before large events and nucleation mechanisms were shown to be important. In a simulation of a single dynamic rupture, prestress before dynamic rupture and the nucleation location can be imposed as initial conditions. It is not clear whether those initial conditions are compatible with other model ingredients (such as the assumed friction law) and hence whether they would ever repeat if a longer slip history were simulated.

Hence it is important to understand how the entire earthquake cycle operates on bimaterial faults, what level of prestress before large earthquakes develops on such faults and how that level depends on assumptions about fault friction, and how nucleation locations, slip in prior events, and aseismic slip might influence directionality of subsequent ruptures.

Such study can only be done in the context of simulations of earthquake sequences in which prestress before seismic events, nucleation locations, and nucleation processes are determined by prior seismic and aseismic slip history and are consistent with model ingredients such as the assumed friction law and frictional properties of the interface. By incorporating slow tectonic loading and laboratory-based rate-and-state friction laws, our models can simulate aseismic slip and accelerating earthquake nucleation. We can also include strongly rate-dependent dynamic resistance motivated by flash heating and/or pore pressure evolution induced by shear heating. By including creeping regions, we can study the interaction of bimaterial effect with stress concentration created by aseismic creep. Therefore, in the context of earthquake sequence simulations, we can study a number of plausible scenarios of long-term fault behavior and evaluate the propensity for a preferred rupture propagation direction on bimaterial faults in a statistical sense.

5. Summary of progress this year

In the current year, we have extended our 2D and 3D boundary integral (BIM) codes to incorporate the bimaterial effect and used them to study single instances of dynamic ruptures on bimaterial interfaces. In part, we have participated in the SCEC code validation exercise based on the proposal "A Collaborative Project: 3D Rupture Dynamics, Validation of the Numerical Simulation Method" (PI Ruth Harris).

We have also worked on extending to the bimaterial case our BIM methodology that is capable of simulating thousands of years of slow loading and associated seismic and aseismic slip while incorporating all inertial effects of seismic events. Unfortunately, variable time stepping that worked very well for the case of the same material on both sides of the fault (Lapusta et al., 2000; Liu and Lapusta, 2007) does not lead to stable simulations in the bimaterial case.   To remedy the problem, we need to switch from semi-implicit to fully implicit updating scheme. That would significantly increase our computational time, while still leaving us with a relatively restricted approach in terms of fault geometries and bulk properties.

Hence we have concentrated our efforts on developing a spectral element methodology (SEM) for simulating long-term slip histories (Kaneko et al., 2007). By combining implicit quasi-static SEM with fully dynamic SEM, we were able to simulate a long-term slip history that included aseismic slip punctuated by a sequence of dynamic ruptures in a simple 2D earthquake model of a fault that separates identical elastic media (Figure 1). The results are in excellent agreement with the boundary-integral simulations of the same problem (Figure 2).   Since SEM readily allows variations in bulk properties, and since the quasi-static part of the simulation is already fully implicit, extending the code to the bimaterial problem should not pose any conceptual difficulty. Moreover, the developed methodology will allow us to study long-term history of the fault – including earthquake sequences – not only in fault models with the bimaterial effect, but also in models with other important features of the elastic medium surrounding the fault, including scenarios with layered properties and near-fault damage zones.

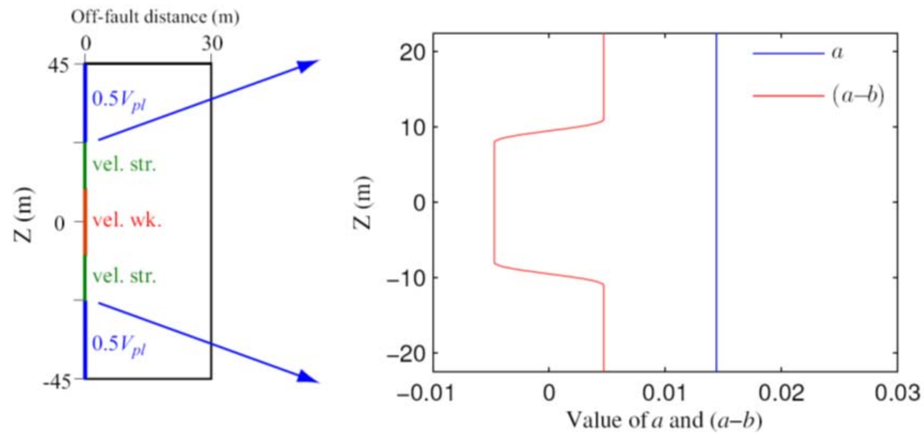

Figure 1. A simple 2D model of a small rate and state fault for testing the developed SEM methodology for long-term simulations. A steady-state velocity-weakening patch, potentially seismogenic, is surrounded by steady-state velocity-strengthening regions that creep under the imposed loading. Outside of the velocity-strengthening regions, slip with the plate rate is prescribed. Periodic boundary conditions are imposed in the along-fault direction, and absorbing boundary conditions are imposed on the boundary parallel to the fault. The elastic material on both sides of the fault is the same in this simple problem.

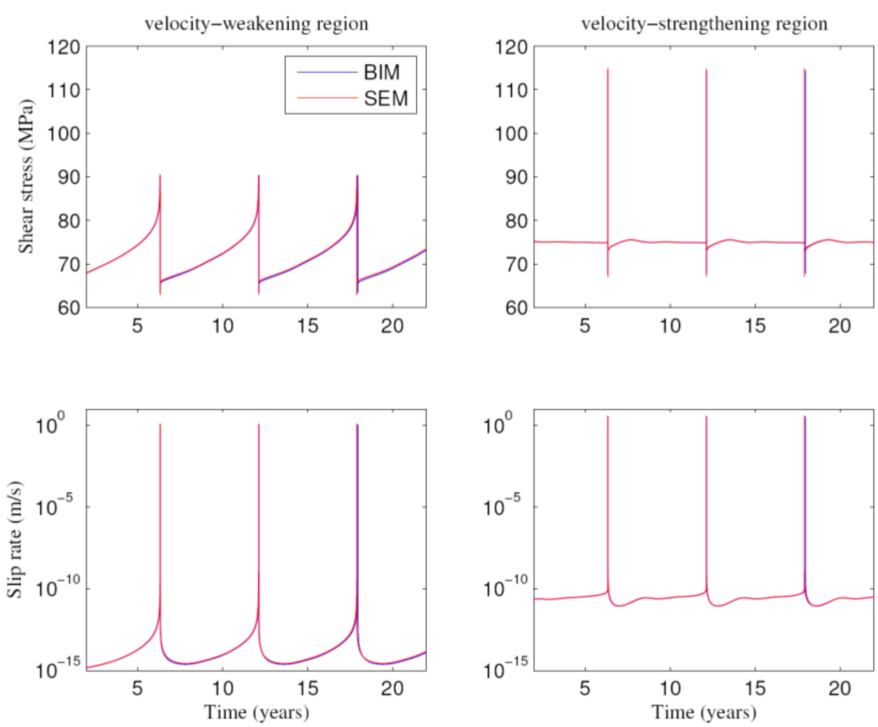

Figure 2. Comparison of simulation results for SEM and BIM methods. Several years have been simulated, and the fault produced a sequence of small repeating events. The agreement between the two methods is excellent. We propose to use the SEM methodology for simulating long-term histories of seismic and aseismic slip to study the bimaterial problem.

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