SCEC 2011 Progress Report

"Dynamics of Branched Rupture, with Bimaterial and Elastic-Plastic Effects"
Award 11012
PI: J. R. Rice, Co-PI: R. Dmowska, $40,000 for 1 Feb 2011 to 31 Jan 2012

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Harvard University, 25 February 2012

a. Summary:

Factors governing rupture path selection at a branch junction are characterized by theoretical/numerical modeling, separately for the cases of elastic-plastic off-fault response and for rupture along a bi-material interface. Plasticity is shown to suppress local opening at the tip, as sometimes predicted in purely elastic analyses. For dissimilar media, side-branches are more likely to rupture when the branch is in a more compliant ("slower") material.

b. Technical Report:

b.1. Removing ambiguities of finite element modeling of rupture through branched triple junctions, and plasticity effects on fracture path selection at a junction and on possible fracture opening at a junction:

Fault intersections are a type of geometric complexity that frequently occurs in nature, and here we focus on earthquake rupture behavior when a continuous, planar main fault, has a second fault branching off of it. We use the finite element method to examine which faults are activated and discuss the complexities of fault interactions that arise due to the presence of a triple junction. Physically, if there is no fault opening, slip must go to zero on the branch as the junction is approached; otherwise slip on the branch fault would result in opening on the main fault. If there is no opening, then there is no relative displacement of the nodes of a FE or FD mesh at the junction, and numerical routines as they regularly programmed within contact algorithms or split-node procedures are adequate to describe the response.

However, we have found that for simulations of branched rupture in elastic media, opening does frequently occur, especially for branches on the compressional side of the fault.

We find, nevertheless, that a mitigating factor is that the high stresses that are present around the propagating rupture tip and at the branching junction will typically bring the surrounding material to "failure" (i.e., to onset of plastic yielding), especially when that material is within the damaged border zones of a maturely sheared fault. With an incohesive elastic-plastic model having $c = 0$ (the term c denotes cohesive strength in a Drucker-Prager or Mohr-Coulomb description), which is appropriate for extensively damaged -- and not partially re-cemented -- rock, fault opening is inhibited for a wide range of realistic material parameters. For very large cohesive strengths c for re-cemented rocks, and for those on the high end for pristine rock, opening can occur, but for cohesive strengths thought to be more representative of damaged rock around a mature fault, opening does not occur in our simulations.

For all other parameters of the geometry, material description, and ratios of remote stress components to one another held constant, there will be a critical ratio c / σ_n (where σ_n is the initial fault-normal compression stress), given for some cases in our related publication in press in BSSA, such that opening will not occur when c / σ_n is less than that critical value. For a broad range of cases, that critical ratio is evidently infinite -- those being the cases for which a purely elastic model would not predict opening.

Also, the real physical description for re-cemented, and thus initially cohesive, rock is that the cohesive strength will degrade in shear. That means that the plastic strain hardening modulus h of a Drucker-Prager or Mohr-Coulomb plasticity formulation is negative, i.e., it corresponds to strain softening. Analyses of such media are fraught with uncertainty because of strain localization and loss of ellipticity issues. Nevertheless, our results do suggest that realistic softening is able to mitigate the effects of large initial cohesion and lead, in simulations, to an absence of fault opening at the branch junction even when c / σ_n is larger than the critical ratio just discussed.

When opening does not occur, the behavior at the triple junction is simplified and the algorithmic difficulties mentioned above do not arise.

Most importantly, our results show that the inclusion of off-fault plasticity can also change the rupture behavior at the branching junction. Compared to an elastic model, an incohesive elastic-plastic off-fault material will inhibit rupture on compressional side branches and promote rupture of extensional side branches. In future work we hope to investigate the role of pore-fluid saturation in such response, and suspect that it may partially redress those changes.

b.2. Branching issues for failure along bimaterial interfaces:

Again, material contrasts across faults are a common occurrence, and it is important to understand if these material contrasts can influence the path of rupture propagation. Here we examine models, solved numerically, of rupture propagation through one type of geometric complexity, that of a fault branch stemming from a planar main fault on which rupture initiates. This geometry, with a material contrast across the main fault, could be representative of either a mature strike-slip fault or a subduction zone interface. We consider branches in both the compressional and extensional quadrants of the fault, and material configurations in which the branch fault is in either the stiffer or the more compliant material and configurations with no material contrast. We find that there are regimes in which this elastic contrast can influence the rupture behavior at a branching junction, but there are also stress states for which the branch activation will not depend on the orientation of the mismatch. For the scenarios presented here, both compressional and extensional side branches are more likely to rupture if the branch is on the side of the fault with the more compliant material versus the stiffer material. The stresses induced on the branch fault, by rupture traveling on the main fault, are different for the two orientations of material contrast. We show how the interactions between rupture on the two faults determine which faults are activated.

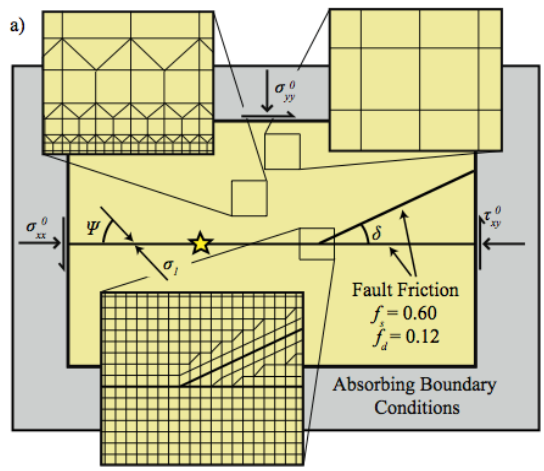

Fig. 1. (a) Basic Finite Element Model setup with absorbing boundary conditions and a uniform stress state with plane strain elements. New mesh geometry in which larger elements are utilized far away from the faults for computational efficiency. The few corner elements which are much smaller than the fine resolution section are artificially denser so as to not dictate the model time step. (b) Definition of compressional and extensional side branches.

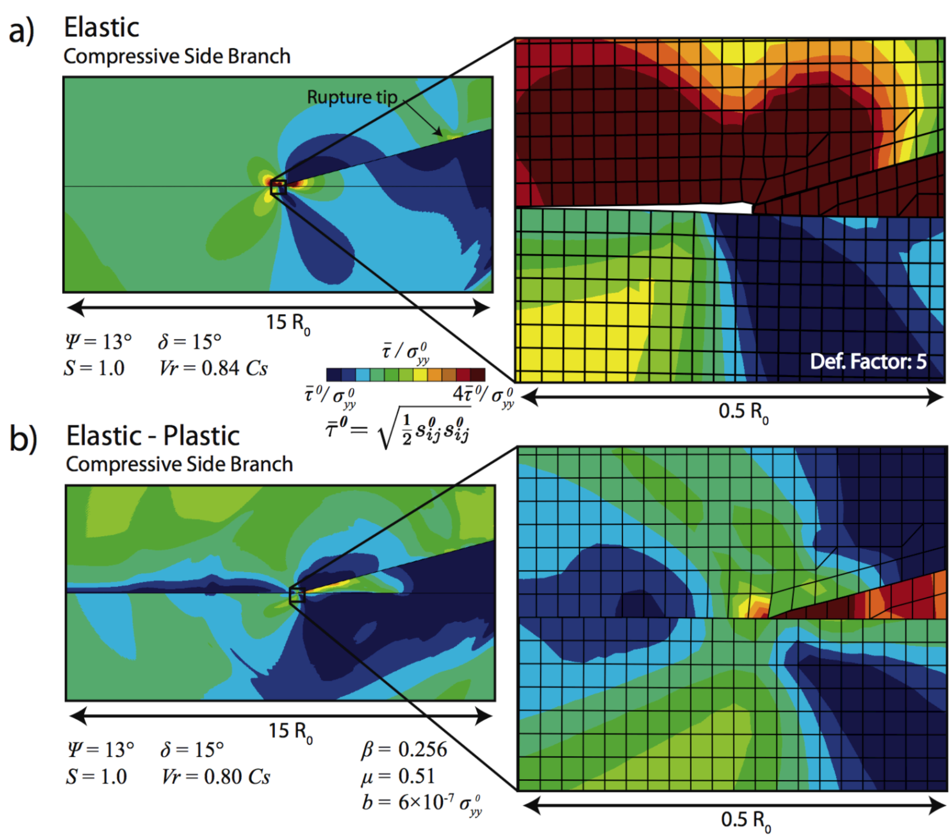

Fig. 2. Image of the branching junction some time after the rupture has propagated onto the compressive side branch and a small distance along the main fault. Contours show the shear stress level. (a) Opening occurs at the junction for an elastic off-fault material. (b) Opening does not occur for an incohesive elastic-plastic material.

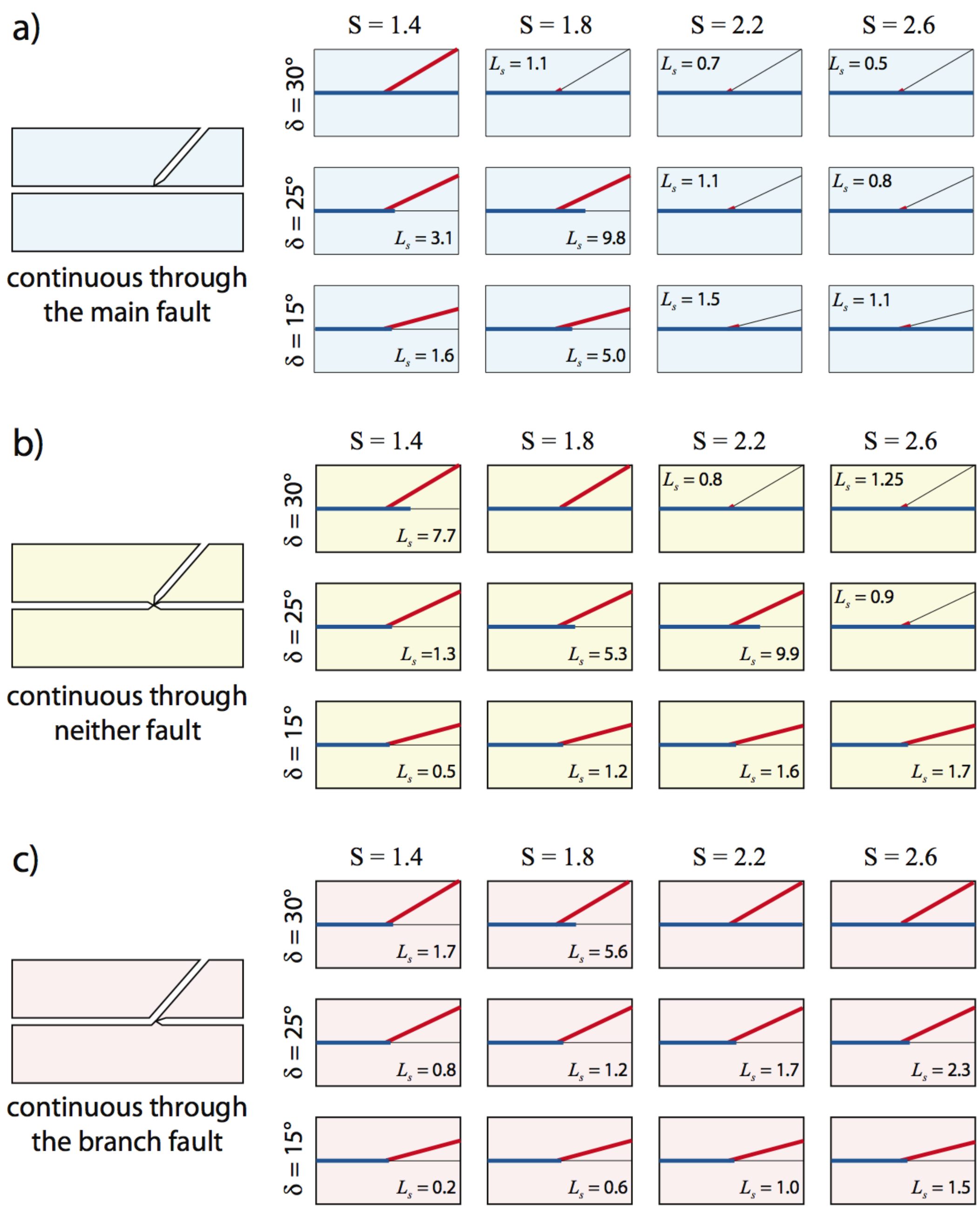

Fig. 3. Algorithmic issue: Effect of the definition at the branching junction on the rupture path selection. The rupture prefers to propagate on the continuous surface. All cases shown for Ψ = 13º and Vr = 0.86 Cs at the junction. As the S ratio changes, so does the rupture path selection.

Ls indicates the length, in units of *Ro*, of the terminated rupture propagation away from the junction.

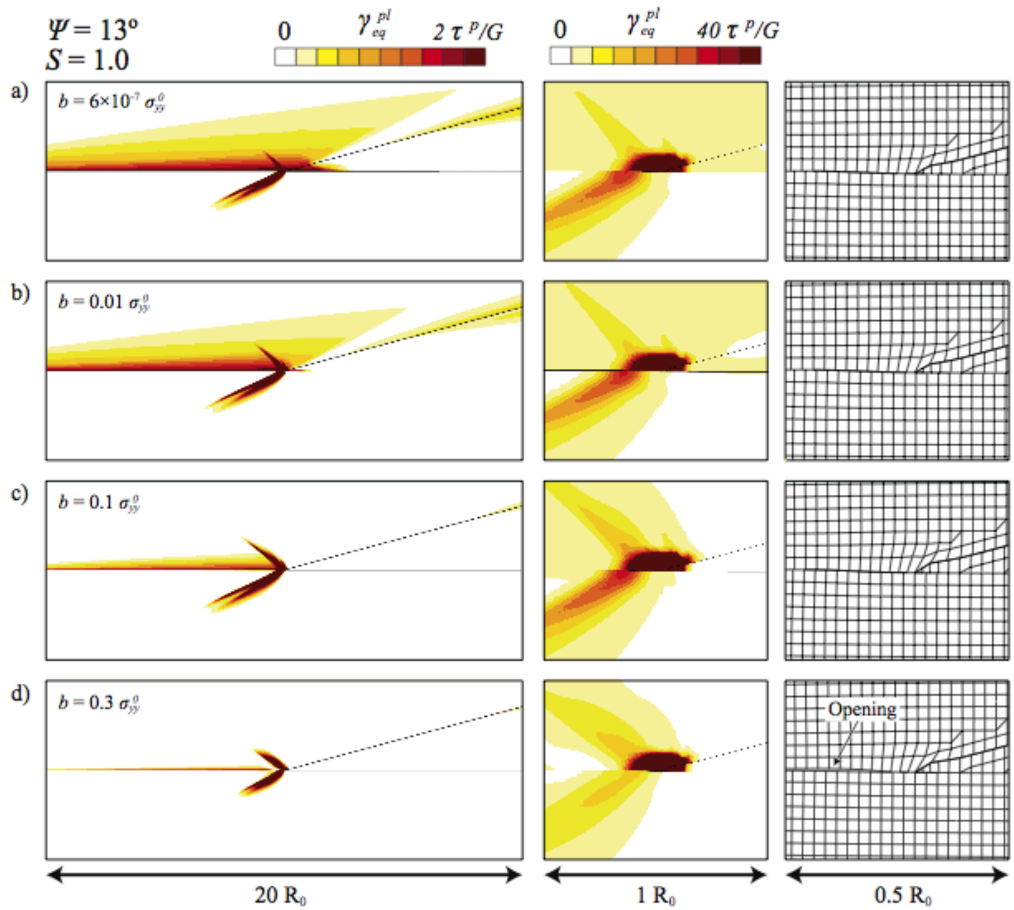

Fig. 4. Plastic deformation for models with varying amounts of cohesion *b*, increasing from (a) to (d) and shown as a fraction of the initial compressive stress. Column two is the same case as shown in column 1, but shows a close up of the branching junction and uses a different color scale since deformation is very high near the junction. Column 3 shows the mesh deformation for a further close up of the junction. The only case which shows opening on the main fault is (d). However, the last figure on the previous page shows that when we realistically recognize that the cohesion (if from recementing of previously, and cyclically, damaged gouge) will be lost in a few percent of strain, i.e., when we include strain softening, the opening no longer result.

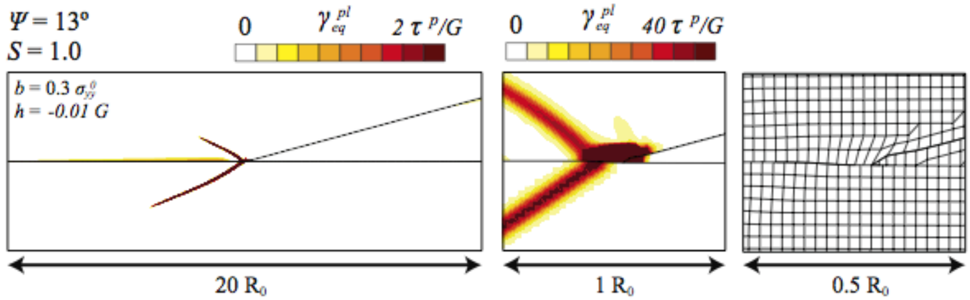

Fig. 5. The addition of material softening to the strongest cohesion case, shown above as case (d), causes opening to no longer occur at the branch junction.

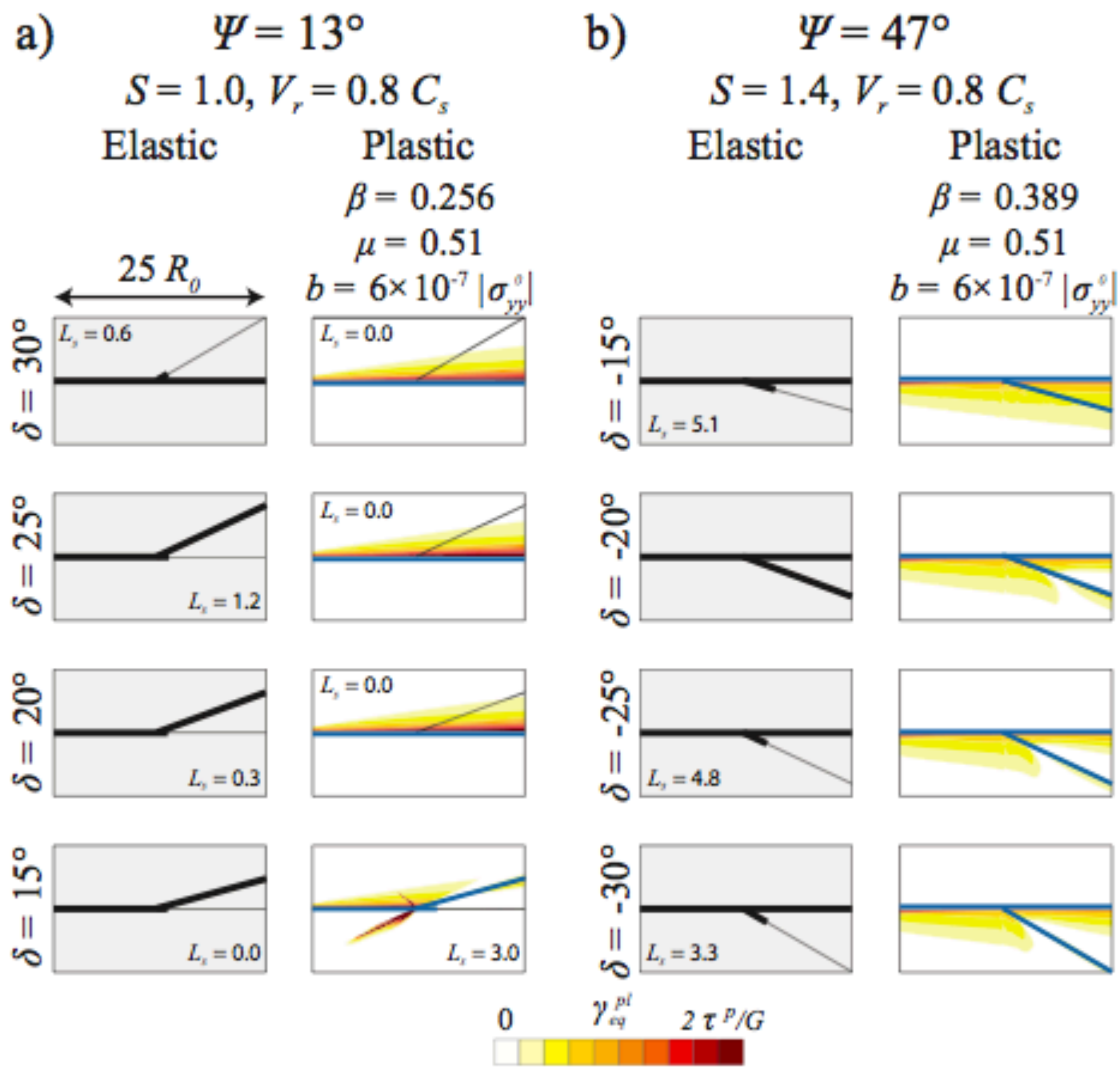

Fig. 6. Influence of off-fault plastic deformation on branch activation: (a) Compressional side branch. (b) Extensional side branch.

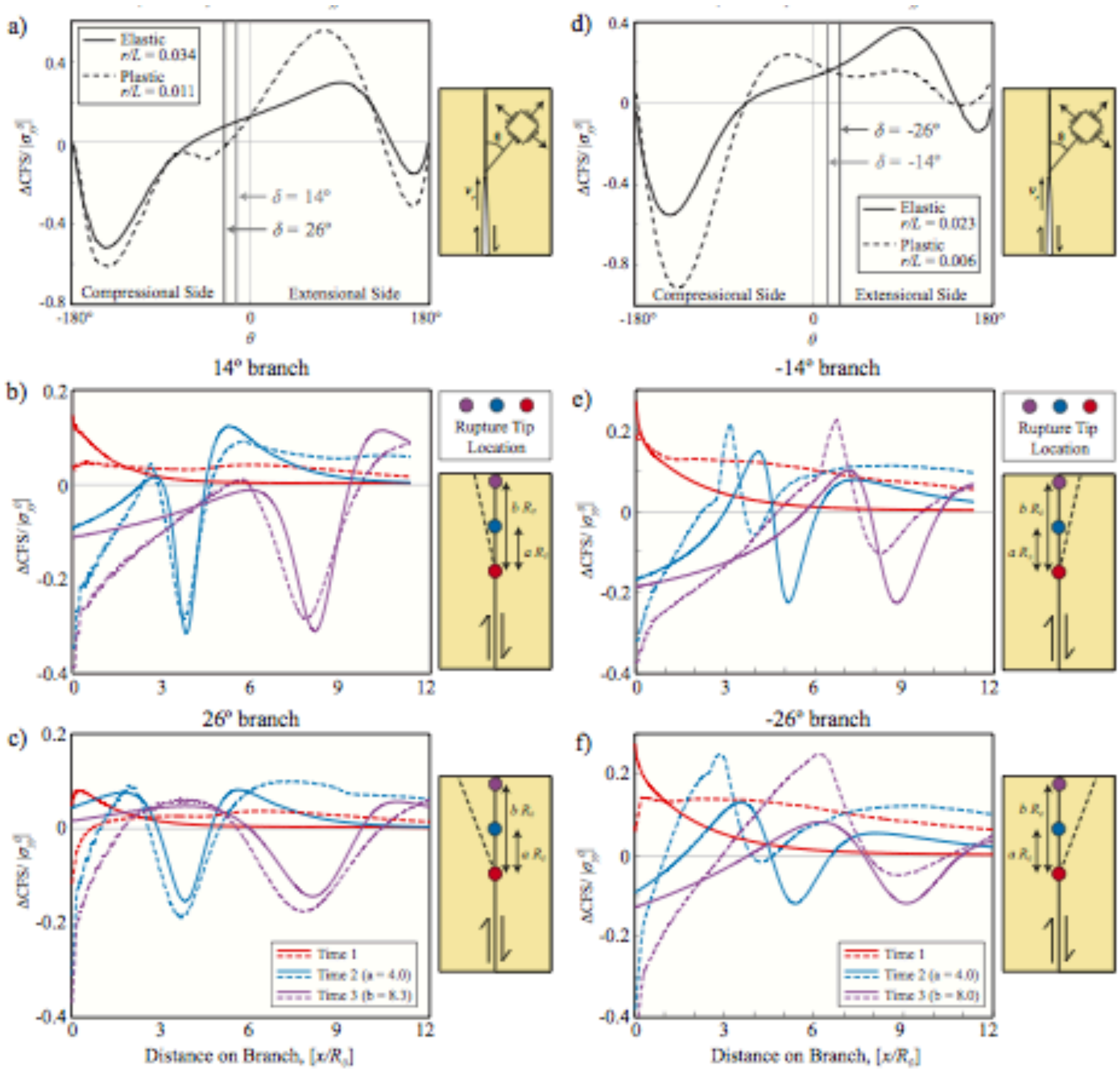

Fig. 7. Change in CFS due to rupture propagation for elastic and elastic-plastic materials $\Delta(\mathrm{CFS}) = \Delta\tau - 0.6\Delta\sigma_n$. (a) - (c) Compressional side branch. (d) - (f) Extensional side branch. (a) & (d) Stress distribution on all planes radiating from the rupture tip, at a distance $r = L$ from the tip. (b), (c), (e) and (f) Change in CFS on a fictional branch due to rupture propagating past the junction on the main fault ("fictional" in that here the branch path is not allowed to be activated, and we just show stressing along it due to rupture on the main fault.

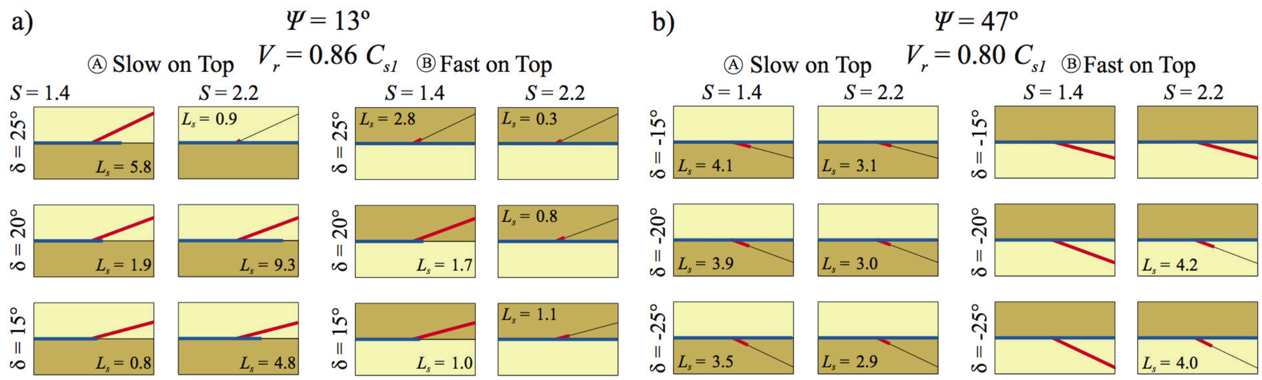

Fig. 8. Branch activation results. (For this and the next figure, the materials joining along the fault are elastic, but have dissimilar seismic properties.) Both compressional side branches, as shown in (a), and extensional side branches as shown in (b), are more likely to rupture when the branch is in a more compliant ("slower") material.

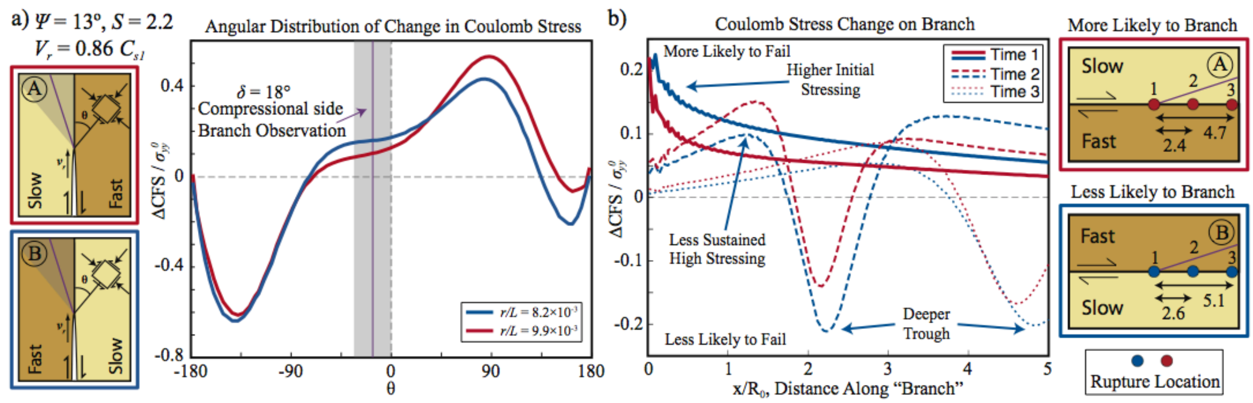

Fig. 9. (a) Elastically predicted change in coulomb stress distribution around a propagating rupture tip, for the parameters in the above figure. Results shows higher initial branch stressing for configuration B (faster material on top). Location of compressional side branch observation line also shown. (b) Change in coulomb stress on noted observation branch due to rupture propagation on the main fault. Stress distribution is very different for the two configurations and results in little branch activation for configuration B.

c. Intellectual merit and broader impacts

Rupture branching is important to the issues of whether a multi-segment rupture can develop. The main issues addressed are (or were when we started) untouched issues on rupture branching in the literature. Our work shows that some commonly adopted numerical schemes in rupture modeling are unable to deal properly with path selection at a branch when local opening occurs.

The activity has been a major part of the Ph.D. thesis research of Nora DeDontney.

Apart from the educational contribution, it does contribute to the problem of understanding how ruptures select their path through geometrically complex fault zones.

d. Recent presentations and publications related to theme of this project:

Paper published:

DeDontney, N., J. R. Rice, and R. Dmowska, "Influence of material contrast on fault branching behavior", *Geophysical Research Letters*, vol. 38, L14305, doi:10.1029/2011GL047849, 5 pages, 2011.

Paper accepted and in press for publication:

DeDontney, N., and J. R. Rice, and R. Dmowska, "Finite element model of branched ruptures including off-fault plasticity", *Bulletin of the Seismological Society of America*, in press, 2012.

Other reports, abstracts, talks:

DeDontney, N., J. R. Rice and R. Dmowska, "Influence of material contrast on fault branching behavior", Abstract S53D-07 (oral) presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec., 2011.

Rice, J. R., "Dynamic slip-rupture along a bimaterial interface", talk presented at Society of Engineering Sciences (SES) Annual Meeting, Symposium in honor of Professor Ares J. Rosakis as the SES Eringen Medal recipient, Northwestern University, 13 October 2011.