SCEC 2009 Progress Report

"Inelastic Off-Fault Deformation During Repeated Earthquake Ruptures and Plastic Zone Scaling",

Award 09090 (A7, A8, A9 FARM)
PI: J. R. Rice, Co-PI: R. Dmowska, $25,000 for 1 Feb 2009 to 31 Jan 2010

James R. Rice and Renata Dmowska
Harvard University, 25 February 2012

a. Summary:

We addressed how inelastic deformation in off-fault damage zones interacts with earthquake rupture. A major focus was on the way that plasticity interacts with other features in determining a possibly preferred directivity of propagation along faults separating seismically dissimilar materials. Also, we examined residual stress fields left as a result of plastic deformation in a single rupture, and showed in a simple case how those residual stresses would make the next rupture propagate with different speed, and leave a generally lesser increment of plastic strain in its wake. Finally, we showed that while a band of plastically deformed material was left along the border of a propagating rupture, only a very thin sliver of that plastic region, located near the rupture front and having a geometrically complex relation to the slip-weakening zone, was deforming plastically at any given moment in time.

b. Technical Report:

b.1. Rupture directivity issues for failure along bimaterial interfaces:

Material juxtapositions across mature faults are a common occurrence. Previous work has found that this elastic mismatch results in a rupture that will preferentially propagate in the direction of slip displacement on the more compliant side of the fault, with more off-fault damage in the stiffer material. Fig. 1 illustrates that result, but shows also the complications when, at low seismic *S* ratios, the slower propagation in the "non-preferred" direction undergoes a transition to super-shear propagation. Such results have implications for inferring preferred rupture directions based on observations of damage zone asymmetry.

Allowing for the possibility of off-fault plastic yielding, we performed a complete numerical investigation of the role of the stress state on the distribution of plastic deformation and the direction of preferred rupture propagation. We show that there are important factors, in addition to the elastic mismatch, which control the preferred direction of propagation as well as the side of the fault in which damage predominately accumulates. The orientation of the most compressive principal stress is the controlling factor in determining the location of plastic deformation. For different orientations, plastic deformation can accumulate in either the stiffer or the more compliant material. For high angles of most compressive stress, the aforementioned preferred rupture direction prediction holds true. However, the off-fault plastic response can reverse that direction (Fig. 2) for low angles of most compressive stress so that rupture will preferentially propagate in the direction of slip displacement in the stiffer material.

b.2 Residual stress states left in plastically deforming damage zones by a single rupture and effect on the next rupture.

We addressed the question of what are the effects of prior ruptures on plastic off-fault response during repeated events. For that, we investigated effects of residual fault-parallel stress, left in the damage zone by previous ruptures, on the next rupture. That includes possible effects on generating a preferred propagation direction, as well as effects on the extent and shape of the plastic zone.

In zones of plastic deformation on the compressional side of the fault, σ_{xx} becomes *less* compressive, while in zones of plastic deformation on the extensional side, it becomes *more* compressive. The changes in σ_{xx} on the extensional side of the fault make the angle Ψ of the most compressive principal stress, relative to the fault, shallower in that zone, while changes in σ_{xx} on the compressional side increase Ψ in that zone. Fig. 3 shows the residual change in the fault-parallel stress across the plastic zone, at a place along the fault where the plastic zone width is $\sim 1.3R_0$ (R_0 is the nominal slip-weakening zone size in the low propagation speed and high S ratio limit) for an initial stress state with $\Psi = 56^\circ$. For the case shown, all plastic strain occurs on the extensional side of the fault. Very near the fault, the residual change in fault-parallel stress causes a decrease in Ψ to 18°. To investigate how the stress change could alter the next rupture, we conducted analyses taking as an initial fault-parallel stress for the next rupture (denoted here by $\sigma_{xx}^{(1)}$) the residual stress from the first event:

$$\sigma_{xx}^{(1)} = \sigma_{xx}^{R}(y) \text{ for } -1.3R_0 \le y \le 0 \text{ ; } \sigma_{xx}^{(1)} = \sigma_{xx}^{(0)} \text{ for } y \le -1.3R_0 \text{ and } y \ge 0 \quad \mathbf{(4)}$$

Along the entire fault length, within a zone of width $1.3R_0$, we applied the residual fault-parallel stress from the first event as the initial stress for the next event. Fig. 4 compares the plastic strain during the second event to plastic strain during the first event for the same slip-weakening friction parameters and off-fault material strength. We found that the rupture propagation speed is different in the two directions of rupture propagation. For rupture in the direction (to the right in the figure) which tends to again activate plastically the extensional side of the fault, i.e., the side having the altered residual stress, the amount of plastic strain is now smaller, there is a slower onset of a noticeable plastic zone, and the rupture propagates at a faster velocity ($v_r = 0.94c_R$) than during the first event ($v_r = 0.89c_R$). There is no noticeable change in the rupture velocity or plastic zone for rupture in the reverse direction (to the left), in which plasticity takes place on the side with no imposed change in fault-parallel stress.

Under the constraints of time and funding, we did not advance on this topic beyond the initial studies shown in Figs. 3 and 4.

b.3 The zone which is momentarily undergoing plastic straining during dynamic rupture.

While much attention has been given in our own earlier work (Templeton and Rice, JGR, 2008; Viesca et al., JGR, 2008), and in many other elastic-plastic studies, to the shapes of plastically deformed zones generated by propagating ruptures (like in Figs. 2 to 5), it seems that the precise shape of the zone that is momentarily deforming plastically has not been reported. To resolve that we carried out extremely fine-grid finite element calculations, Fig. 6. The results show that only a very thin sliver of that plastic region, located near the rupture front and having a geometrically complex relation to the slip-weakening zone, was deforming plastically at any moment in time. Nevertheless, while the zone is thin, it seems to span too many elements to support a possible contention that such a zone could be a finite-element smearing-out of a propagating surface of discontinuity in particle velocity in some as yet unknown continuum solution. Also notable is the nearly complete detachment of the lenticular plastically straining zone from another plastically straining zone bordering the rear part of the slip-weakening zone.

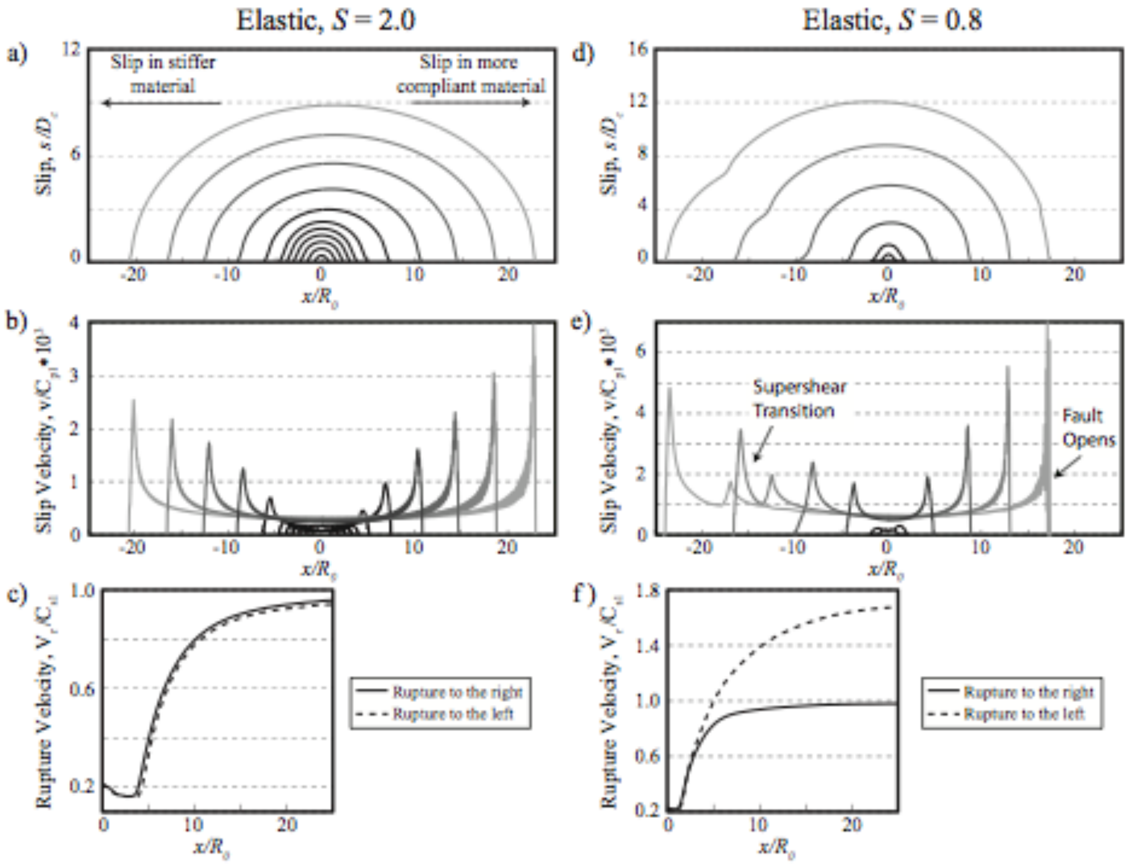


Fig. 1. For an elastic off-fault material, the S ratio affects the rupture propagation. (a) and (d) Slip distribution. Lines are plotted for equal time steps. (b) and (e) Slip velocity. For both S ratios, there is a higher peak slip velocity for rupture traveling towards the right. (c) and (f) Rupture velocity in both directions. For an S ratio of 2.0, (a) - (c), rupture preferentially travels towards the right, with slip in the more compliant material, while for an S ratio of 0.8, the propagation is more complex, and the leftward rupture transitions to supershear.

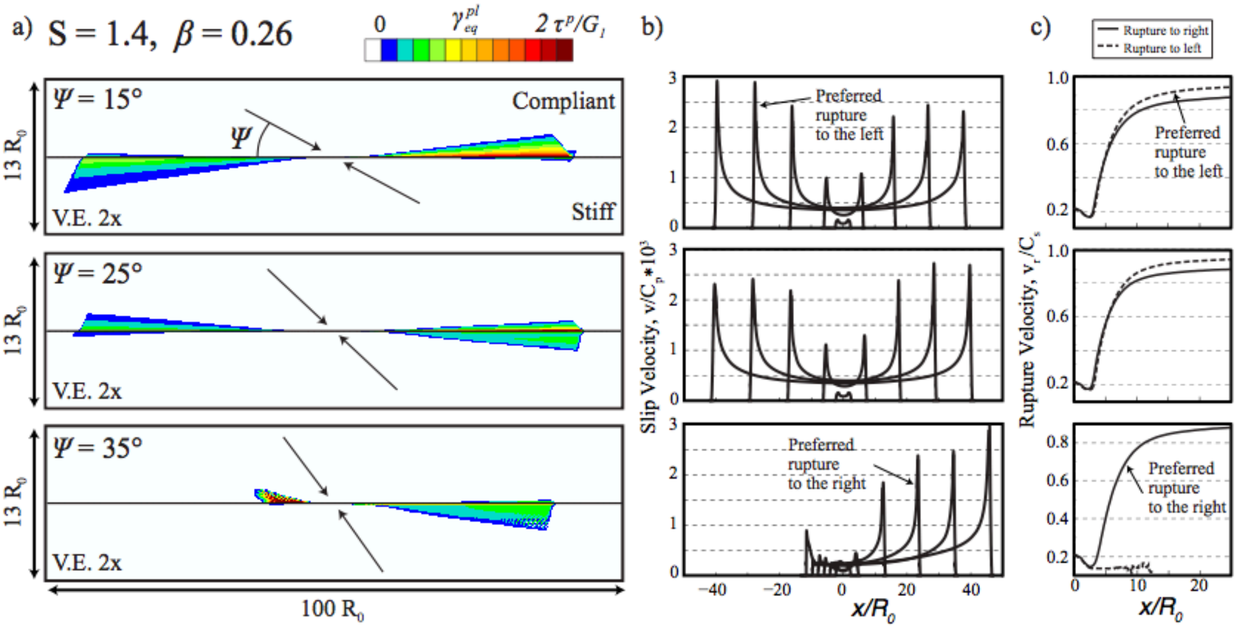


Fig. 2. Changes in rupture propagation and plastic deformation result from changing Ψ. (a) Contours of plastic deformation. (*Note: there is a 2x vertical exaggeration for easier viewing of the plastic zone, but which makes the* Ψ *angle appear larger than actual.*) (b) Slip velocity at different times during rupture (c) Rupture velocity to the right and left of the nucleation. This shows how the presence of plastic yielding together with low angles Ψ of the principal compression direction relative to the fault can reverse the elastically predicted preferred direction of propagation

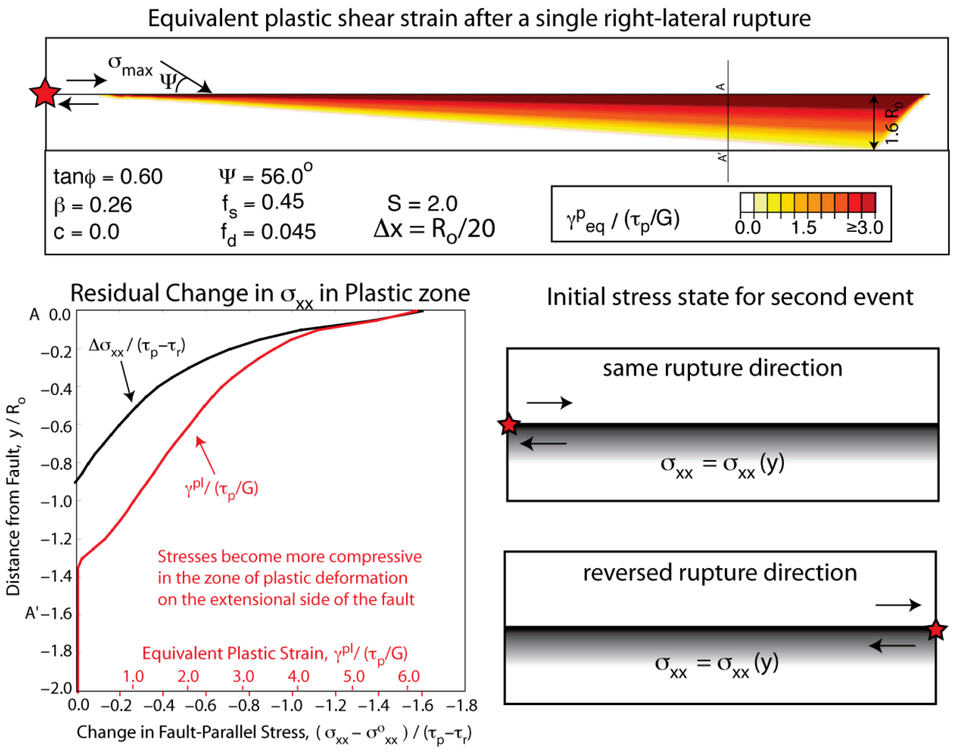


Fig. 3. Accumulated plastic strain and residual stress within plastic zone as a function of distance from rupture plane.

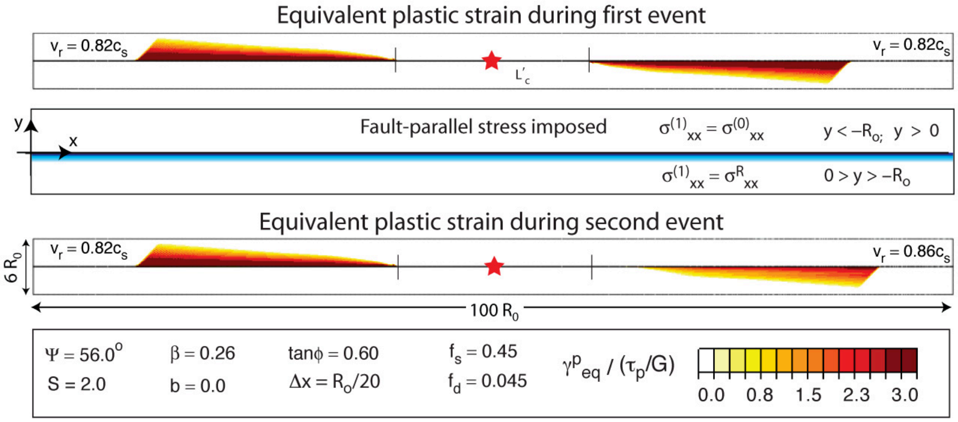


Fig. 4. Plastic strain during repeated rupture with initial stress state for the second rupture based on the residual fault-parallel strain, σ^{R}_{xx} , left in the zone of plastic deformation after the first event. This is based on a simple representation of that that residual stress as being uniform within the blue strip marked.

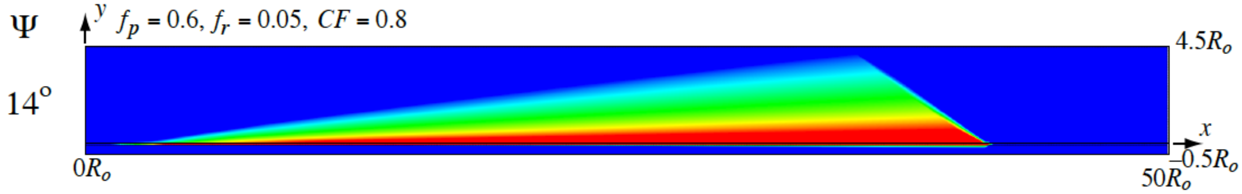
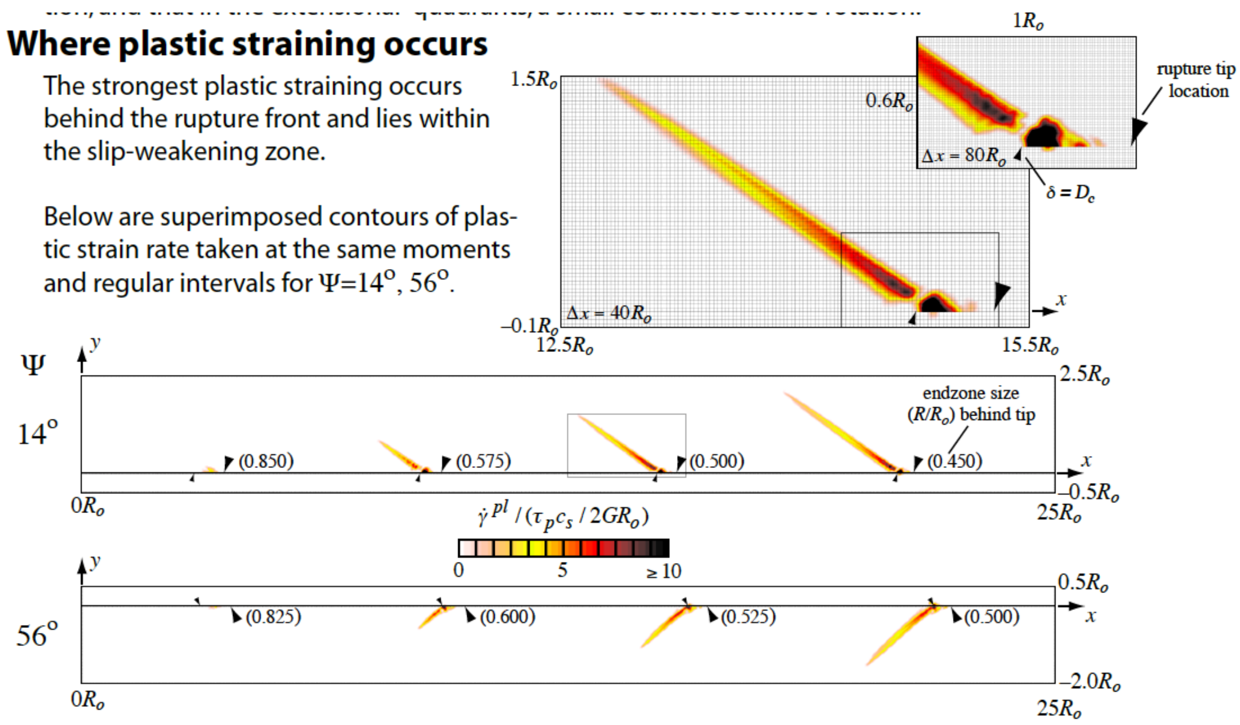


Fig. 5. Where plastic stain has occurred during a slip-weakening rupture, from Viesca et al, SCEC Ann. Mtg., 2009. These results, and those of the next figure, were obtained through solving a numerical finite element model for Drucker-Prager elastic-plastic off-fault response under the assumption of full saturation of the medium with pore fluid, and of effectively undrained response (i.e., negligible Darcy transport of fluid on the short time-scale involved; Viesca et al., JGR 2008).



Where plastic straining occurs

The strongest plastic straining occurs behind the rupture front and lies within the slip-weakening zone.

Below are superimposed contours of plastic strain rate taken at the same moments and regular intervals for Ψ=14°, 56°.

Fig. 6 Where plastic straining is momentarily occurring (Viesca et al, SCEC Ann. Mtg., 2009). (The figure was mislabeled and should show, at upper center $\Delta x = R_0 / 40$ and at upper right $\Delta x = R_0 / 80$, signaling 40 elements within a nominal slip-weakening zone length in the outer region, and 80 elements within the rectangular refined mesh zone. That is more than an order of magnitude more refined than for typical finite-element studies of slip-weakening rupture.) The extremities of the slip weakening zone are marked at the upper right as "rupture tip location", where the first increment of fault slip is occurring and "$\delta = D_c$" where the slip weakening process is complete (the calculation assumed a linear slip weakening, from peak to residual friction).

c. Intellectual merit and broader impacts

The activity on this project has been a major part of the Ph.D. thesis research of Elizabeth Templeton, and has contributed to that of Nora DeDontney and Robert Viesca.

Apart from the educational contribution, it has provided a more rigorous formulation, for ruptures along faults separating seismically dissimilar materials, of the relations among preferred rupture directivity, orientation of the regional stress field relative to the fault, and presence of damage zones preferentially on one or the other side of the fault. Also, it poses a problem of explaining the special geometric features of the momentarily active zones of plastic straining.

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

Paper published:

DeDontney, N., E. L. Templeton-Barrett, J. R. Rice, and R. Dmowska, "Influence of plastic deformation on bimaterial fault rupture directivity", *Journal of Geophysical Research - Solid Earth*, vol. 116, B10312, doi:10.1029/2011JB008417, 12 pages, 2011.

Thesis:

Templeton, E. L., "Effects of Inelastic Off-Fault Deformation on the Dynamics of Earthquake Rupture and Branch Fault Activation", Ph.D. Thesis, Harvard University, June 2009.

Other reports, abstracts, talks:

Rice, J. R., "Elastic-plastic and pore fluid effects on fault rupture dynamics", American Society of Mechanical Engineers (ASME) Annual International Conference and Exhibit, Drucker Medalist Symposium in honor of medalist, Professor John W. Rudnicki, 14-15 November 2011.

Templeton-Barrett, E. L., N. DeDontney, J. R. Rice and R. Dmowska, "Influence of plastic deformation on bimaterial fault rupture directivity", Abstract S54C-04 (oral) presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec., 2011.

Viesca, R. C., E. L. Templeton, E. M. Dunham and J. R. Rice, "Plasticity in rupture dynamics: what role does pore fluid play?", invited talk at Computational Infrastructure for Geodynamics Workshop on Numerical Modeling of Crustal Deformation and Earthquake Faulting, Golden, CO, 22-26 June 2009.

Viesca, R. C., J. R. Rice, and E. M. Dunham, "Plastic deformation at a propagating rupture front: Its coupling to fault pore pressure and influence on the seismic moment tensor" (poster), SCEC Annual Mtg., 13-16 Sept 2009.