SCEC 2009 Progress Report
Shear Strain Localization in Dynamic Earthquake Rupture: Shear Heating, Dynamic Weakening, and Slip Below the Seismogenic Zone

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Overview and Accomplishments

We continued our work investigating the physics of plastic deformation and strain localization in dynamic earthquake problems. We utilized Shear Transformation Zone (STZ) Theory to study aspects of earthquake physics at multiple scales, from microscopic deformation and localization to fault scale rupture propagation. Our work addressed several SCEC priority science objectives in Fault and Rupture Mechanics, including testing hypotheses for dynamic weakening (A8), examining heterogeneities in rupture models (A10), and examining the interaction between the brittle upper crust and the ductile lower crust (A11).

We accomplished the following:

- We developed a quantitative partition of dissipated energy in sheared disordered solids.
- We found that strain localization decreases the total energy dissipated during slip. Changes in local configurational disorder dissipate a fraction of the total energy, reducing the amount of energy dissipated as heat.
- Our models showed that systems that exhibit strain localization dissipate heat more rapidly than homogeneous systems due to the rapid stabilization that follows shear band formation.
- We showed that STZ Theory predicts that for rate strengthening materials, interseismic deformation should be accumulated broadly, while a transient instability leads to spontaneous localization during coseismic rupture.
- We performed dynamic rupture simulations with strain localization at depth that show that nearly all coseismic strain at depth occurs in a localized manner

This work builds upon our accomplishments on previous SCEC projects looking at the small scale physics of strain localization (Manning *et al.*, 2009; Daub and Carlson, 2009) and the impact of strain localization on fault scale dynamic ruptures (Daub *et al.*, 2008; Daub *et al.*, in press). We build upon the small scale physics results by examining how energy is dissipated during localized sliding, and expand our fault scale work to include depth-dependent frictional properties and to examine the dynamics of strain localization in rate strengthening materials at depth.

Energetics of Strain Localization

The discrepancy between laboratory-based predictions and field measurements of surface heat flow (Brune *et al.*, 1967; Lachenbruch and Sass, 1980) motivate a quantitative approach to partitioning released strain energy during slip. Many models approximate the rate of heat dissipation to be constant as a function slip and attribute the remaining dissipated energy to rock fracture (*e.g*. Kanamori and Heaton, 2000). In an effort to better understand the role of microscopic, physical processes on energy dissipation, we developed a quantitative approach to partitioning dissipated energy in sheared granular materials that accounts for contributions due to non-affine, configurational rearrangements.

To quantify dissipation, we modeled a sheared layer of granular fault gouge driven at the boundaries at a constant velocity. STZ Theory governs the material dynamics, and the STZ effective temperature provides a quantitative measure of local configurational disorder within the gouge material. As the material is sheared, changes in effective temperature dissipate energy that is traditionally attributed to thermal heating and fracture. Assuming that all additional energy is dissipated as heat, we quantified the partition of dissipated energy between heat and local disorder as a function of slip for both homogeneous and strain-localized deformation.

We found that changes in local disorder play a significant role in energy dissipation. First, they provide a mechanism for strain localization, which leads to a rapid decrease in shear stress following the formation of a shear band and results in a lower dynamic sliding stress than in the homogeneous case. These two effects decrease the total energy dissipated during slip. Second, changes in local disorder dissipate a fraction of the total energy, thereby decreasing the energy dissipated as thermal heat. This fraction is large for small values of slip when both the shear stress and the effective temperature are rapidly changing. Once the stress and effective temperature stabilize, no additional energy is dissipated to increasing the effective temperature, and all energy is dissipated as heat (Figure 1). As a result, the total heat dissipated depends largely on the total slip (Figure 2). While we assume that local disorder and thermal heat are the only contributing factors to energy dissipation, this description already predicts a reduction in heat flow from that predicted by the traditional heuristic energy partition (Figure 1(a)). We expect that additional mechanisms, such as fracture and thermal weakening due to variability in material properties, will further contribute to a decrease in heat flow.

We explored the implications of this description on the rate of heat dissipation, which we found to increase as a function of slip and approach a constant, steady state value in both the homogeneous and strain-localized systems (Figure 2). While the homogeneous system showed a gradual increase in the rate of heat dissipation, the strain-localized system showed a more rapid increase that approached a lower steady-state value than observed in the homogeneous system. This is due to the rapid stabilization and lower dynamic value of shear stress attained by the strain-localized system. These results imply that the change in temperature of a sheared inhomogeneous material should grow more rapidly than that of a homogeneous one, a prediction that agrees with recent laboratory measurements taken on a halite slider in the presence and absence of granular gouge material (Mair *et al*., 2006).

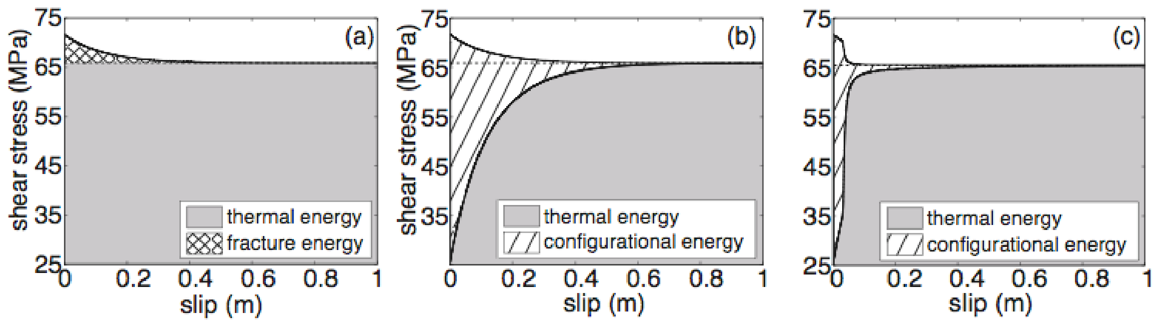

Figure 1: STZ partition of dissipated energy for (b) homogeneous (H) deformation, and (c) strain-localized (SL) deformation. The total energy dissipated, indicated by the total filled region, is less in the (SL) system than in the (H) system. Dissipated energy is partitioned between thermal energy (heat) and configurational energy (local disorder). During the initial stress drop, a large fraction of energy is dissipated to increasing local disorder. As the stress stabilizes, the local disorder approaches its steady-state value, and all energy is dissipated as heat. (a) For comparison, dissipated energy is traditionally partitioned between a coarse estimate of the thermal energy and the fracture energy.

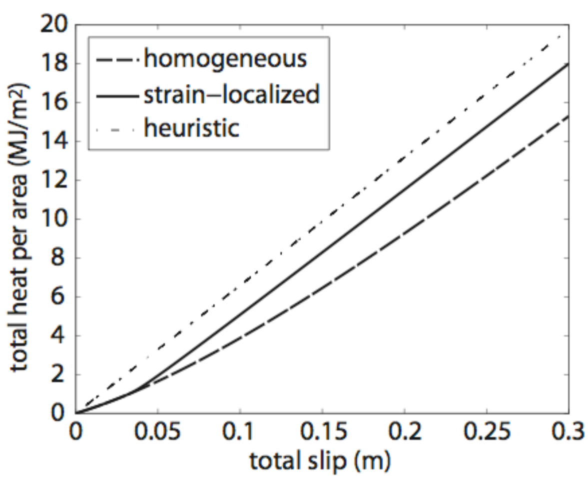

Figure 2: Total heat dissipated per unit area as a function of total slip for homogeneous and strain-localized deformation compared to the traditional heuristic estimate. The rate of heat dissipation, proportional to the slope of each curve, increases more gradually in the homogeneous system than in the strain-localized system. Both systems dissipate heat at a lower rate than predicted by the heuristic partition, indicated by the dot-dash curve.

Strain Localization Below the Seismogenic Zone

At the fault scale, we studied the dynamics of strain localization below the seismogenic zone. Field observations show that rocks that were deformed at depths below the seismogenic zone can exhibit both broad and localized shear (Simpson, 1984). These structures, known as S-C mylonites, are usually interpreted as evidence of broad, ductile deformation on interseismic time scales, and localized strain on coseismic time scales, as ruptures propagate downdip from the seismogenic zone. However, models do not capture the dynamics of this process, and seismologists cannot implement such localization into earthquake rupture models. Because large crustal earthquakes rupture the full extent of the seismogenic zone, understanding the consequences of strain localization at depth is particularly important for determining the rupture process, and therefore subsequent ground motions, of large, damaging earthquakes.

Localization at depth is puzzling due to laboratory observations that rock friction at large temperatures and pressures is rate strengthening at steady state. Results from our research with STZ Theory (Manning *et al*., 2009) show that both rate weakening and rate strengthening form shear bands. For rate strengthening materials, deformation with a homogeneous initial effective temperature is linearly stable. This implies that during the interseismic period, when long periods of steady deformation occur, shear strain is accommodated broadly across the fault zone. This leads to the broad strain observed in sheared rocks at depth. However, rate strengthening materials form shear bands due to a transient instability – when a material is driven far from steady state, heterogeneities in the fault zone are amplified and deformation occurs through a narrow shear band. Therefore, when a fault at depth is driven from the long term plate rate (~10^{-9} m/s) to a coseismic slip rate (~1 m/s), an instability occurs and deformation localizes to a shear band. The combination of broad interseismic strain and localized coseismic slip produces the observed superposition of broad and narrow shear over many seismic cycles. Although the shear band forms due to a transient instability, it persists for time scales much longer than the duration of coseismic slip in an earthquake.

We showed that coseismic rupture can lead to strain localization at depth through a dynamic rupture model. We assign depth-dependent frictional properties on the fault; with a transition from rate weakening to rate strengthening at the bottom of the seismogenic zone at 15 km. Rupture is nucleated in the seismogenic zone and propagates downdip into the rate strengthening region. Figure 3 illustrates the dynamics of localization at 16 km depth. Figure 3(a) shows the evolution of shear stress as a function of slip, and Figure 3(b) shows the plastic strain rate profile across the width of the fault zone. Early stages of slip occur broadly across the width of the fault zone, after which strain localizes to a narrow shear band that persists for the duration of coseismic slip. The model dynamics show that STZ Theory captures both the broad and localized observed in the field.

We also examined fault scale rupture propagation in our model. Figure 4 shows several snapshots of the slip rate as a function of depth for the dynamic rupture model. For comparison, the slip rate for a rupture that does not form a shear band at depth is also shown in the plots. The figures illustrate that in both models, slip propagates several kilometers below the transition from rate weakening to rate strengthening. Interestingly, there are only small differences between the model that forms a shear band and the model where strain occurs homogeneously throughout the fault zone. The slip rate behind the rupture front is larger, as the shear stress weakens more rapidly with slip in the model that forms a shear band. However, other effects such as heating and weakening could be activated by localized slip at depth but not in the model that deforms the fault zone homogeneously. Further research is needed to examine these effects.

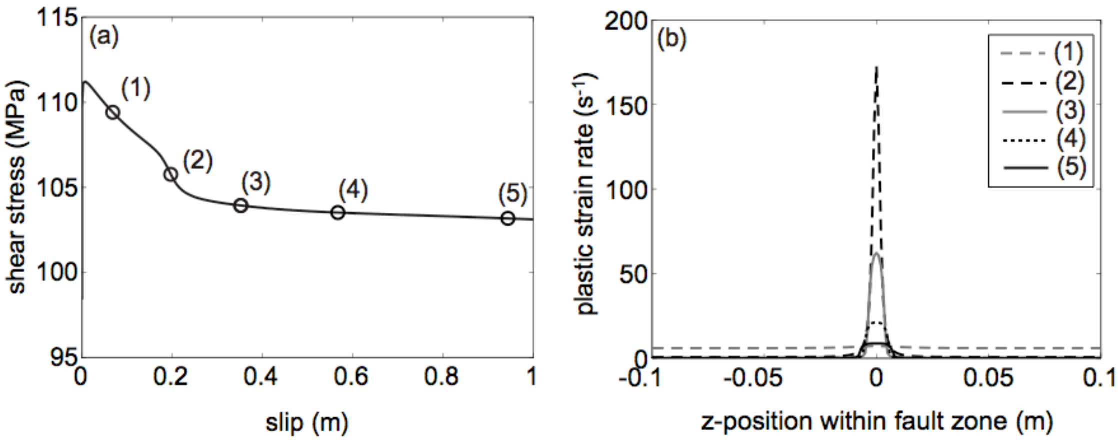

Figure 3: (a) Shear stress as a function of slip below the seismogenic zone for a dynamic rupture simulation with depth-dependent frictional properties. Fault friction is governed by STZ Theory, which allows for dynamic localization of strain below the seismogenic zone. Shear stress weakens gradually at first, then more quickly when strain localizes at depth. Plot is at 16 km depth, and the frictional rate dependence transitionfs from rate weakening to rate strengthening at 15 km depth. (b) Plastic strain rate as a function of position across the fault zone width. Curves correspond to the five points along the shear stress versus slip plot. After a brief period of homogeneous deformation, strain localizes to a narrow shear band that persists for the duration of coseismic slip.

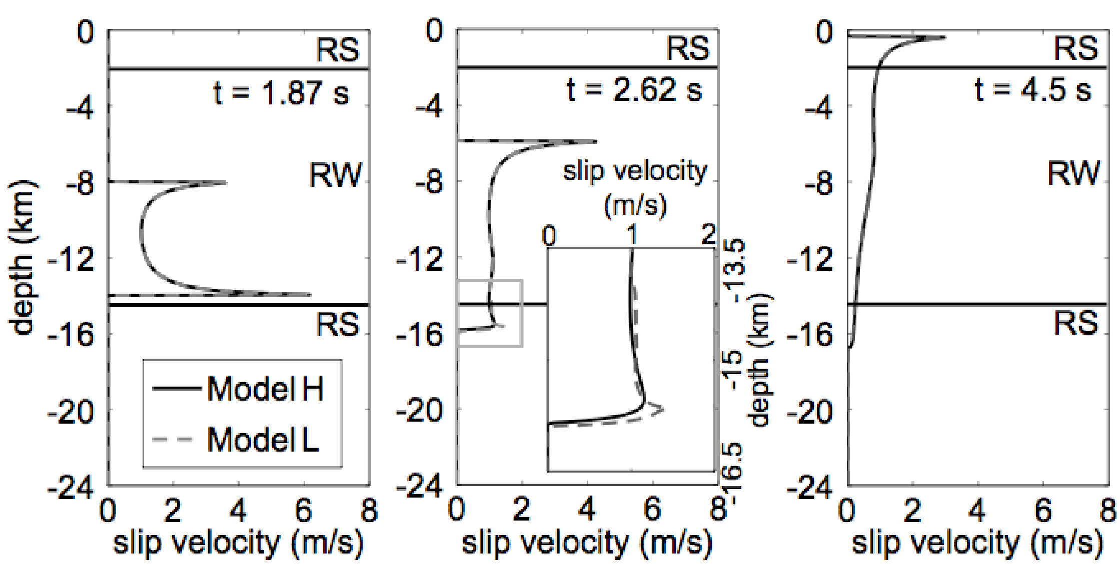

Figure 4: Snapshots of slip rate as a function of depth in dynamic rupture models with depth dependent friction. Lines indicate where the frictional properties transition from rate weakening to rate strengthening. A plot of a rupture model where strain can dynamically localize (Model L) is compared to a model where the fault zone is deformed homogeneously across its width (Model H). (a) Rupture propagates unstably through the seismogenic zone in both models. (b) Rupture is able to propagate into the rate

strengthening region in both models. Strain localization results in a small change in the slip rate. (c) Rupture arrests after propagating ~2 km into the rate strengthening region in both models.

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Publications

Daub, E. G., and J. M. Carlson (2009), Stick-slip instabilities and shear strain localization in amorphous materials, *Phys. Rev. E*, 80, 066113. (SCEC paper number 1319)

Daub, E. G., M. L. Manning, and J. M. Carlson, Pulse-like, crack-like, and supershear earthquake ruptures with shear strain localization, *J. Geophys. Res.*, in press. (SCEC paper number 1303)

Daub, E. G., and J. M. Carlson, Friction, Fracture and Earthquakes, *Ann. Rev. Condens. Matt. Phys.*, in press.

A. M. Hermundstad, E. G. Daub, and J. M. Carlson, Energetics of strain localization in a model of seismic slip, *J. Geophys. Res.*, in press. (SCEC contribution number 1328)

Presentations

Daub, E. G., "Stick-slip instabilities and shear strain localization in granular materials," poster presentation, AGU Fall Meeting, San Francisco, CA, December 2009.

Hermundstad, A. M., “Energetics of strain localization in a model of seismic slip,” poster presentation, SCEC Annual Meeting, Palm Springs, September 2009.

Daub, E. G., “Strain Localization in a Model of Coseismic Slip Below the Seismogenic Zone,” poster presentation, SCEC Annual Meeting, Palm Springs, CA, September 2009.

Daub, E. G., “Shear Strain Localization in a Model of Coseismic Slip Below the Seismogenic Zone,” SSA Annual Meeting, Monterey, CA, April 2009.

Daub, E. G., “Shear Strain Localization in Amorphous Materials and Dynamic Earthquake Rupture,” Earth and Environmental Sciences Seminar, Los Alamos National Laboratory, March 2009.