2008 SCEC Final Report

Dynamic Fault Weakening due to Shear Strain Localization: Constitutive Laws, Rupture Dynamics, and Ground Motion

PI: Jean M. Carlson
Physics Department
University of California, Santa Barbara

We investigated the effects of strain localization on the frictional properties of earthquake faults and the propagation of elastodynamic ruptures using a microscopic physical model based on Shear Transformation Zone Theory. This addressed many SCEC research goals, especially pertaining to testing hypotheses for dynamic fault weakening (A8), and determining how small scale heterogeneities in fault zones impact the propagation of dynamic earthquake ruptures at the fault scale (A10). Our accomplishments include the following:

- We developed a microscopic physical model for plastic deformation in amorphous solids such as granular fault gouge.
- In the model, shear bands spontaneously form as amorphous materials are sheared. Strain localization occurs due to instabilities in both rate strengthening and rate weakening materials.
- Stick-slip instabilities occur for a wider range of spring stiffnesses when deformation is accommodated in a narrow shear band.
- Dynamic earthquake simulations with STZ Theory reveal that localization is a mechanism for dynamic weakening. Localized slip produces larger peak slip rates and larger stress drops, and allows for pulse-like ruptures to propagate at low shear stress.

We summarize our results in the following sections. The first section focuses on the STZ model and the implications of localization for the physics of frictional interfaces. The second section covers our dynamic rupture models and the fault scale consequences of shear bands in granular fault gouge.

Physics of Strain Localization in Fault Gouge

Experiments and simulations show that strain localization occurs in fault gouge and other amorphous solids (*Morgan and Boettcher* 1999, *Lu et al*., 2003). Although this localization affects the constitutive law on the fault, most continuum models for the friction law do not account for shear banding. We developed a physics-based model for deformation in disordered solids that robustly predicts shear band formation in these materials. This model also describes how the degree of localization changes as a function of strain rate, strain, and material properties.

Our models are based on Shear Transformation Zone (STZ) Theory, a well-studied physical model for non-affine deformation in fault gouge (*Falk and Langer,* 1998; *Pechenik and Langer*, 2003; *Langer*, 2008). Plastic strain occurs in small, localized regions called STZs that are more susceptible to deformation under shear stress. Regions with an increased number of STZs have larger strain rates, and are designated by an elevated effective temperature. The effective temperature can be measured by comparing fluctuations and dissipation in simulations, and specifies the configurational disorder in the gouge.

While the effective temperature is distinct from the thermal temperature, it exhibits similar dynamics such as shear heating and diffusion. STZ Theory accounts for strain localization by adding a finite gouge width into the fault core, and dynamically solving for the effective temperature within the gouge. This approach is distinct from the common practice of implementing a slip weakening or rate and state friction law on a planar fault. In our model for localization, the dynamic response of the effective temperature determines how strain is distributed in the fault core.

We showed that effective temperature STZ theory quantitatively matches simulations for disordered solids (*Shi et al*., 2006, *Manning et al*., 2007). Using new simulation data (*Haxton and Liu*, 2007, *Langer and Manning*, 2007), we extended the theory to explain the degree of localization changes as a function of imposed strain rate. We show that the shear banding behavior is very different for materials which are rate strengthening (steady-state shear stress increases with increasing strain rate) compared to those which are rate weakening. Rate weakening materials are linearly unstable with respect to strain localization and develop very thin shear bands, while rate strengthening materials exhibit an interesting strain-dependent instability and exhibit shear bands with different thicknesses.

The STZ model predicts three major types of deformation: a) homogeneous, b) wide "disorder-limited" shear bands, and c) thin "diffusion-limited" shear bands. Strain rate profiles for each of these types of bands is shown in Figure 1 (a)-(c). Wide shear bands occur at lower strain rates and the length scale depends on the density of STZs, while at larger (co-seismic) strain rates the system develops thin shear bands where the length scale is determined by the diffusion of effective temperature. Importantly, we find that the stress-strain response is sensitive to the degree of localization. Therefore we developed a deformation map (Figure 1 (d)) which predicts the type of localization as a function of the initial conditions and the applied strain rate.

We also explored how localization affects stick-slip instabilities in sheared amorphous materials. Stick-slip instabilities occur in spring slider systems when the friction law weakens faster with slip than the spring can respond, and the block moves with successive stick-slip cycles rather than sliding steadily. Stick-slip motion is observed in many rock friction experiments and provides a test of the friction dynamics incorporated into constitutive laws.

We performed a linear stability analysis to predict the critical spring stiffness as a function of driving velocity. If the spring stiffness is below the critical stiffness, motion occurs as repeated stick-slip cycles, and above the critical stiffness, steady sliding is stable. The laboratory derived Dieterich-Ruina friction laws predict that the critical stiffness is independent of the driving rate, while STZ Theory predicts that the critical stiffness decreases as the interface is sheared at a faster rate. When a shear band forms in an amorphous material, the critical stiffness is increased due to a larger strain rate in the shear band, and for narrower shear bands, the critical stiffness is larger. We verified the stability analysis predictions through numerical integration of the STZ equations, and found that the analytical predictions were in excellent agreement for homogeneous deformation and that for localized deformation the predictions were within a factor of 1.33 of the numerical results (Figure 2).

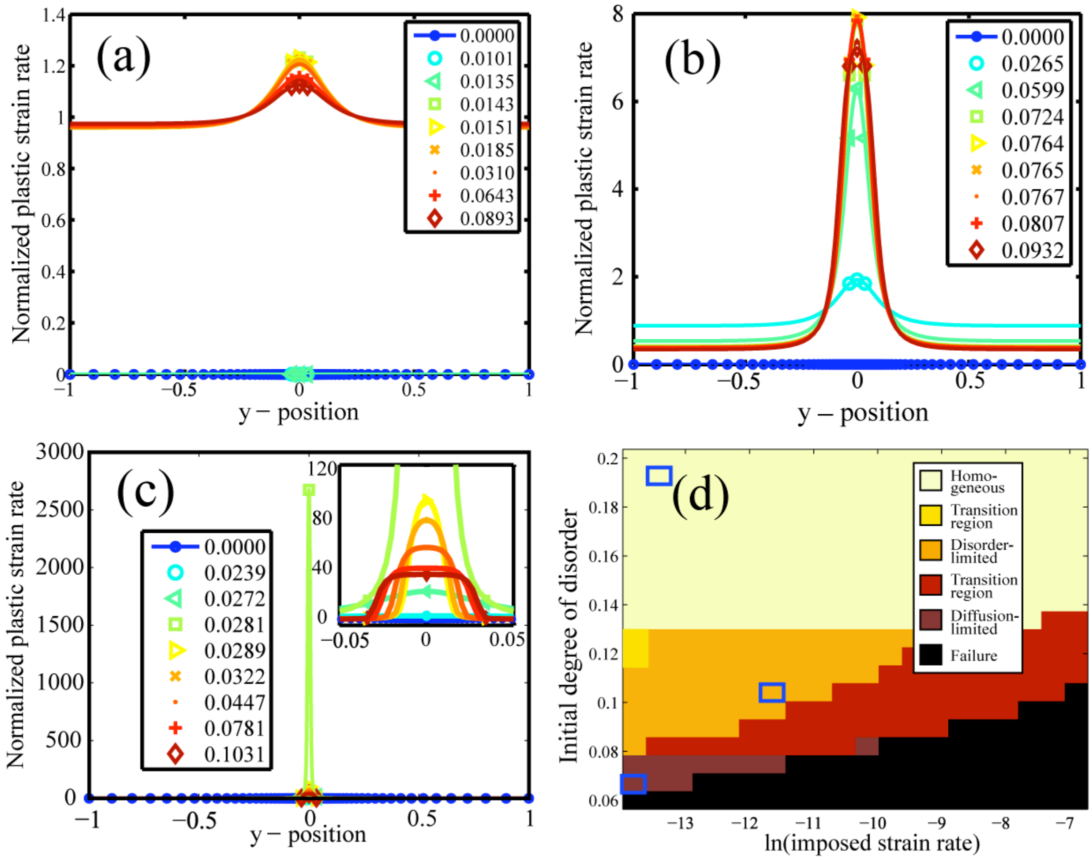

Figure 1. (a)-(c) Each line represents the plastic strain rate as a function of position within the disordered material at a particular value for the total imposed strain. Different colors correspond to different amounts of strain. Each panel (a)-(c) corresponds to a different initial condition as illustrated by the blue boxes in panel (d). Panel (a) illustrates homogeneous deformation with an initial disorder temperature of 0.07 and strain rate of 2×10^{-6}. Panel (b) illustrates a wide shear band with an initial disorder temperature of 0.10 and a strain rate of 9×10^{-6}. Panel (c) illustrates a thin diffusion-limited shear band with an initial disorder temperature of 0.19 and a strain rate of 1×10^{-6}. Panel (d) is a deformation map presented as a function of the imposed external strain rate and the initial degree of disorder in the gouge. The initial disorder depends on the sample preparation – materials which have been at rest longer have lower amounts of disorder.

Strain Localization in Dynamic Rupture Simulations

We conducted numerical simulations of dynamic ruptures governed by STZ Theory to investigate the fault scale consequences of shear bands and strain localization. We model the spontaneous propagation of elastodynamic ruptures, with the fault friction governed by STZ Theory. As in our studies of deformation with the STZ model, the dynamic evolution of the effective temperature determines the strain rate in the granular fault core. The STZ model resolves the spontaneous formation and growth of shear bands in the fault zone, and we examine how localization affects earthquake slip at the fault scale.

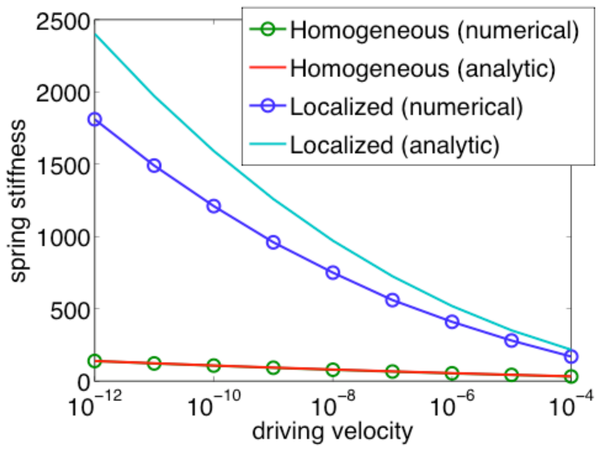

Figure 2: Critical spring stiffness as a function of driving velocity for the STZ friction law. For driving rates and spring stiffnesses below the critical stiffness, steady sliding is unstable and slider motion occurs by successive stick-slip cycles. Our analytical predictions based on a linear stability analysis are in excellent agreement with the numerical results for homogeneous deformation, and our predictions are within a factor of 1.33 of the values obtained by numerical integration.

First, we focused on comparing ruptures that form shear bands to ruptures where the strain rate is uniform with position across the thickness of the gouge. When the initial conditions for the effective temperature are uniform across the gouge thickness, then by symmetry the strain rate is also uniform as the material deforms. If a small perturbation is added to the homogeneous initial conditions, then this perturbation grows unstably, and deformation localizes to a shear band. In our model, "homogeneous" and "localized" only refer to the effective temperature profile across the gouge thickness – in both cases, the effective temperature varies along strike due to the spatial propagation of ruptures, and the effective temperature is also time-dependent. An example of the evolution of the effective temperature during a "localized" dynamic rupture simulation is shown in Figure 3. As the fault slips, initial heterogeneity in the gouge is amplified, and the effective temperature spontaneously grows to form a shear band.

In our model, strain localization is a mechanism for dynamic weakening, and the shear stress during a localized rupture is less than the shear stress for a homogeneous rupture. Localization also increases the peak slip rate during rupture, and decreases frictional dissipation. These comparisons are illustrated in Figure 4. The peak slip rate, frictional dissipation, and stress drop are all important physical quantities that determine the ground motion in an earthquake. This indicates that small scale physical processes such as localization can have large scale effects on earthquake rupture.

We also explored the role that localization plays in determining how ruptures propagate along faults in space and time. The friction law and the initial shear stress control if the earthquake propagates as an expanding crack or a self-healing pulse, and if the rupture speed is sub-Rayleigh or supershear. We performed numerical simulations to determine the rupture type as a function of the initial shear stress and the effective temperature diffusion length scale. The diffusion length scale is a key frictional parameter for determining the shear band thickness in the fault gouge. This is illustrated in Figure 5, which plots shear stress as a function of slip for a variety of values of the diffusion length scale. As the length scale decreases, the shear band thickness decreases, and the fault slips with a lower shear stress.

In our simulations, the dynamic weakening provided by localization allows for pulse-like ruptures to propagate on the fault at low shear stress (Figure 6). Pulse-like rupture does not occur for homogeneous ruptures. This is because the friction law does not weaken enough to permit pulse-like rupture at low initial shear stresses in the absence of strain localization. We also find that localization lowers the initial shear stress where supershear rupture can nucleate. These results indicate that the grain scale physics on the fault can impact the fault scale ground motion and rupture propagation in earthquakes.

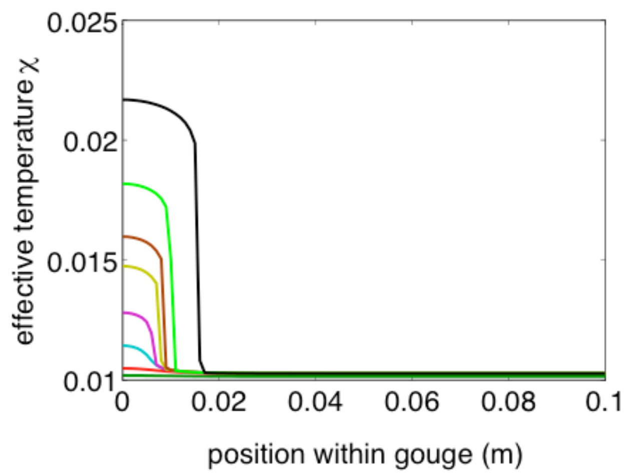

Figure 3: Effective temperature as a function of position in the gouge at several different times during a dynamic rupture simulation. The shear band spontaneously forms and grows in response to the dynamic fault slip.

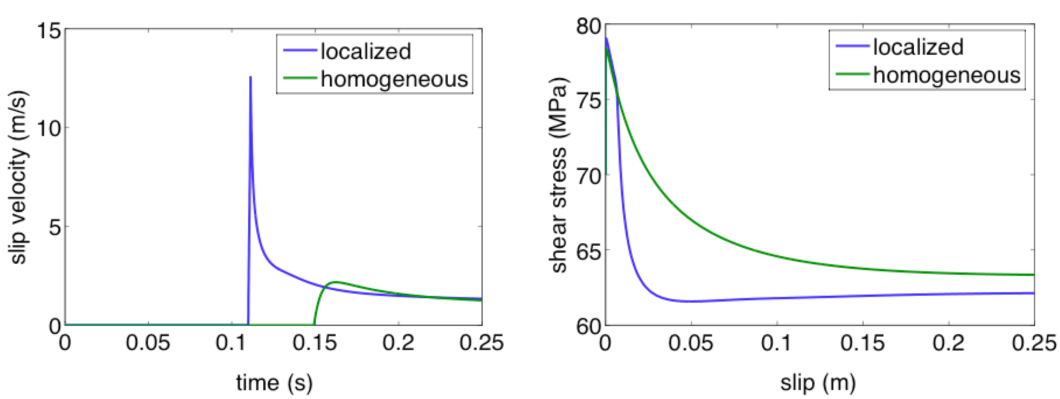

Figure 4: (Left) Slip velocity as a function of time for localized and homogeneous ruptures with STZ Theory. Forming a shear band dramatically increases the peak slip rate. (Right) Shear stress as a function of slip for localized and homogeneous ruptures. Strain localization reduces the shear stress and the frictional dissipation during dynamic earthquake slip.

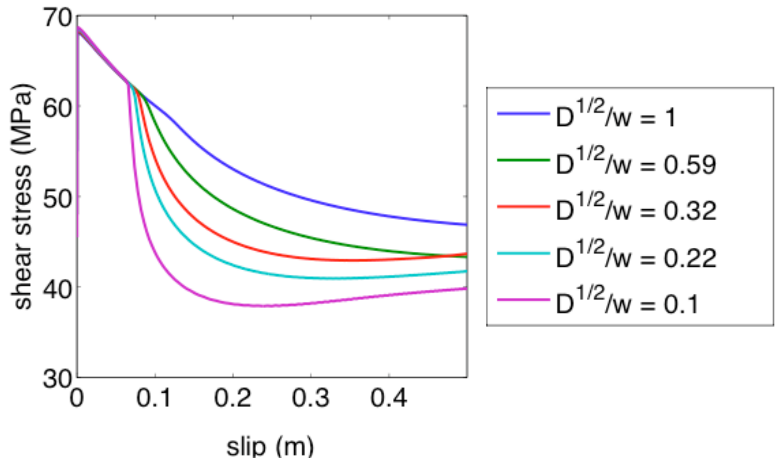

Figure 5: Shear stress as a function of slip for several values of the diffusion length scale. As the diffusion length scale decreases, the shear band becomes narrower, and the fault slips at a lower shear stress. The frictional dissipation also decreases as the diffusion length scale decreases.

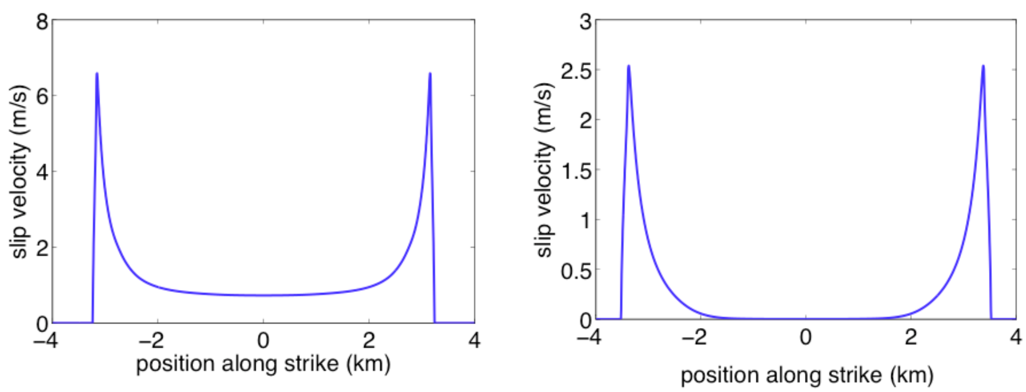

Figure 6: Snapshot of slip rate as a function of position for crack-like and pulse-like ruptures governed by STZ Theory. (Left) Crack-like ruptures occur in the absence of strain localization. (Right) When strain dynamically localizes, the additional weakening provided by localization allows for pulse-like ruptures to propagate for low initial shear stress.

Publications:

E. G. Daub, M. L. Manning, and J. M. Carlson, Pulse-like, crack-like, and supershear earthquake ruptures with shear strain localization, submitted to *J. Geophys. Res.*

M. L. Manning, E. G. Daub, J. S. Langer and J. M. Carlson (2009), Rate-dependent shear bands in a shear-transformation-zone model of amorphous solids, *Phys. Rev. E* **79**, DOI: 10.1103/PhysRevE.79.016110 (SCEC contribution 1250).

E. G. Daub and J. M. Carlson (2008), A constitutive model for fault gouge deformation in dynamic rupture simulations, *J. Geophys. Res.* **113**, B12309, DOI:10.1029/2007JB003577 (SCEC contribution 1155).

E. G. Daub, M. L. Manning, and J. M. Carlson (2008), Shear strain localization in elastodynamic rupture simulations, *Geophys. Res. Lett.* **35**, L12310, DOI:10.1029/2008GL033835 (SCEC contribution 1164).

Presentations:

E. G. Daub, "Deformation and localization in earthquake ruptures and stick-slip instabilities," Soft Condensed Matter Seminar, University of Pennsylvania, February 2009.
E. G. Daub, "Modeling strain localization and stick-slip instabilities in amorphous materials," poster presentation, Dynamics Days, San Diego, January 2009.
E. G. Daub, "Accounting for gouge-scale strain localization in dynamic rupture simulations," oral presentation, AGU Fall Meeting, San Francisco, December 2008.
M. L. Manning, "Effective temperature and shear bands in amorphous solids," Soft Condensed Matter Seminar, University of Pennsylvania, October 2008.
E. G. Daub, "The physics of shear bands and strain localization in dynamic earthquake rupture," Geophysics Seminar, University of Southern California, September 2008.
M. L. Manning. "Effective temperature and localization in disordered solids," Princeton Center for Theoretical Science Fall Conference," oral presentation, Princeton, NJ, September 2008.
E. G. Daub, "Shear strain localization in dynamic rupture and stick-slip models," poster presentation, SCEC Annual Meeting, Palm Spring, September 2008.
E. G. Daub, "Shear strain localization in elastodynamic rupture simulations," oral presentation, SSA Annual Meeting, Santa Fe, April 2008.
M. L. Manning, "Rate-dependent strain localization," oral presentation, American Physical Society March Meeting, New Orleans, March 2008.