Technical Report

Evolution of frictional shear resistance in response to rapid variations of normal stress

SCEC Award # 20112

Principal Investigator: Ares Rosakis, California Institute of Technology

1. Summary of the results

Friction formulations typically assume shear resistance to be proportional to normal stress. However, when normal stress changes rapidly enough, frictional shear resistance no longer obeys proportionality to the normal stress but rather evolves with slip gradually (Prakash and Clifton, 1993). In this project, we investigate the evolution of shear stress in response to rapid normal stress variations using laboratory experiments of spontaneously propagating dynamic ruptures. Our experiments produce variations in fault-normal stress due to the interaction of dynamic rupture with the free surface, similarly to what occurs in natural thrust events (Gabuchian et al., 2014; 2017).

Our experimental measurements clearly demonstrate the delay between normal stress changes and the corresponding changes in frictional resistance, with important implications for the dynamics of thrust earthquakes near the free surface. The experiments make use of full-field measurements of displacements, strains, and stresses by combining digital image correlation (DIC) technique with ultrahigh-speed photography (Rubino et al., 2016; 2017; 2019; 2020), which thoroughly characterize rupture interaction with the free surface, including the large normal stress reductions. In particular, our results indicate that the delay in shear resistance response to variations in normal stress is associated with an evolution distance that is 2–3 orders of magnitude larger than that of rate-and-state friction. Such delay is important in other earthquake source problems that involve rapid normal stress variations, such as seismic slip on non-planar faults, on bi-material faults, and in the presence of shear-heating-induced pressurization of pore fluids.

1. Project motivation and objective

The delayed in response of frictional shear resistance to variations in normal tractions, and its proper representation in friction formulations, is critically important for investigations of several key earthquake source problems, including (i) slip on locally rough/nonplanar interfaces, a topic of particular interest in SCEC5 (Dieterich and Smith, 2009; Fang et al., 2011; Dunham et al., 2011; Duru and Dunham, 2016); (ii) the dynamics of ruptures on thrust and normal faults near the Earth's surface, which is important for near-fault shaking and tsunami generation, and which contains rapid changes in the fault-normal stress due to the interaction of rupture with the free surface (e.g., Oglesby et al. 1998; Nielsen, 1998; Oglesby et al., 2000; Madariaga, 2003; Duan and Oglesby, 2005; Ma and Beroza, 2008; Kozdon and Dunham, 2014; Gabuchian et al., 2014; 2017), (iii) dynamic rupture on faults separating crustal rocks with different elastic properties, a common case for mature strike-slip faults that have slipped many kilometers, which causes rapid fault-normal stress changes due to coupling between the fault normal stress and slip (e.g., Andrews and Ben-Zion, 1997; Cochard et al., 2000; Rice et al., 2001; Xia et al., 2005; Shi and Ben-Zion, 2006; Rosakis et al., 2007; Bhat et al., 2010; Shlomai and Finberg, 2016), and (iv) shear-heating-induced rapid pressurization of pore fluids during seismic slip, which potentially results in rapid enough effective normal stress changes (e.g., Lachenbruch, 1980; Mase and Smith, 1985; Rice, 2006; Schmitt et al., 2011).

In this project, we use laboratory experiments to investigate the evolution of shear stress in response to rapid normal stress variations in order to achieve the following goals:

- Study the normal stress variations and the corresponding shear resistance evolution produced by the propagation of spontaneous ruptures near a free surface for a broad range of experimental parameters, comprising both supershear and sub- Rayleigh ruptures;

- Explore the dependence of frictional parameters on normal stress to improve our ability to reproduce the measured friction behavior under a wide range of conditions.
- Investigate the effects of asymmetric geometry and heterogeneous frictional resistance on the ground motion and study the decay away from the fault.

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

This project addresses the following SCEC5 Research Priorities:

P4.a. Determine the relative roles of fault geometry [and] heterogeneous frictional resistance, […] in controlling and bounding ground motions.

P1.d. Quantify stress heterogeneity on faults at different spatial scales.

P3.g. Assess the importance of the mechanical properties of the near-surface.

Our experiments featuring spontaneously propagating ruptures reaching the free surface, performed under a range of experimental parameters, will contribute to determine the relative roles of fault geometry and frictional resistance in controlling and bounding ground motion, and thus address **P4.a**. Our measurements of shear stress in the near-surface region will also contribute to **P1.d** and **P3.g**.

3. Results

Friction response to rapid normal stress variations is key to study of several problems in earthquake source science, as discussed in section 1. We study this problem in a highly instrumented experimental setup that produces variations in fault-normal stress due to the interaction of dynamic rupture with the free surface. The lab earthquake setup features a dynamic rupture along an inclined, frictional interface formed by two compressed quadrilateral sections of Homalite (Figure 1). The full-field imaging technique that we have developed enables to image the motions and stress changes within a field of view (FOV) close to the free surface (Figure 2). It allows us to both obtain the dynamic details of the phenomenon as well as image the evolution of fault-normal stress, fault-parallel shear stress, and hence friction along the interface close to the free surface, and hence to study how friction evolves under the conditions of rapid normal stress variations and to distinguish between different proposed formulations. We have already been successful to characterize dynamic friction evolution in the bulk and used friction laws to describe its behavior (Rubino et al., 2017).

The motions and stress changes close to the free surface are adequately resolved by the full-field imaging technique that we have developed (Rubino et al., 2019; Tal et al., 2019). Accurate measurements of stresses near the interface are very important when digital image correlation (DIC) is applied to study the dynamics of laboratory frictional rupture. However, DIC algorithms involve small errors that can lead to non-physical discontinuities in the stress field across the interface. Using the previous SCEC award, we have developed an algorithm to locally adjust the displacements computed by DIC near frictional interfaces, such that local stress fields satisfy the continuity of traction across the interface (Tal et al., 2019).

Over the last funding period we have considered a broader range of experimental considerations. that previously done. To study normal stress variations and modulate their intensities in our experimental setup, we initially considered geometry and loading conditions similar to those employed by Gabuchian et al., (2014; 2017), which we have now extended to more load and inclination angles.

Our experimental measurements indicate that the shear resistance does not obey the traditionally assumed proportionality to the normal stress but evolves gradually. This delay is directly observed in plots of the effective friction, τ/σ, vs. slip near the free surface (Figure 3; Tal et al., 2020). For experiment 1, the effective friction initially increases to $\tau/\sigma \sim 0.6$ and then decreases with slip to $\tau/\sigma \sim 0.35$ at slip of about 25 μm. At larger levels of slip, when the impinging rupture is reflected at the free surface, σ decreases, and because of the delayed response of the frictional shear resistance τ, the ratio τ/σ increases back to a value of 0.6 at a slip of 120 μm. The friction τ/σ gradually decreases at larger slip, but as the trailing Rayleigh arrives and σ temporarily decreases, τ/σ increases again to a peak of 0.7, and later drops to 0.4.

The measurements of τ, σ, and V along the interface enable testing different formulations of frictional shear resistance, as well as constraining their parameters. We find that friction formulations without the delayed evolution of shear stress in response to normal stress changes cannot fit our experimental measurements.

We consider three models of friction behavior. In model 1, we test a formulation featuring rate-and-state friction with enhanced weakening but without accounting for delayed shear stress response to variations in normal stress. We track the evolution of τ/σ at a point on the interface near the free surface (location marked in Figure. 2s) in experiment 1 and find that the friction formulation captures the reduction of τ/σ at slip smaller than 25 μm. However, at larger slip, as σ decreases, the modeled response is significantly below the observed response because the formulation does not account for the delayed response (Figure 4d). In model 2, to account for the effects of rapid normal stress variations, we test a formulation of rate-and-state friction with enhanced-weakening featuring a delayed response of the shear stress according to the Prakash–Clifton law. This model fits the observed frictional response much better than model 1 (Figure 4d). In model 3, we improve the fit with the observed response by considering a formulation of rate-and-state friction with enhanced weakening and Prakash–Clifton law, featuring weakening parameters that depend on normal stress. This formulation is consistent with high-speed friction experiments on gabbro that were performed under different normal loads and showed that V_w (Brown and Fialko, 2012) and f_w (Niemeijer et al., 2011) decrease with σ in the form of power laws. This formulation does fit better the observed behavior in experiment 1. Once identified a formulation and its parameters that capture the measurements of experiment 1, we verify its predictive value by applying it to experiments 2 to 6, without any changes in the parameters. Remarkably, we find that the formulation in model 3, together with the parameters constrained with the data in experiment 1, allows prediction of the friction evolution near the free surface in the other experiments (Figure 4). Accounting for the normal stress dependence of the enhanced-weakening friction parameters (V_w and f_w) in the PC law mostly affect experiments performed under lower σ_0 than experiment 1, and consequently experienced smaller reductions in the friction coefficient.

Our findings clearly demonstrate the delay between normal stress changes and the corresponding changes in frictional resistance for the laboratory setting in an analog material, with important implications for the dynamics of thrust earthquakes near the free surface. In particular, our results indicate that the delay in shear resistance response to variations in normal stress is associated with an evolution distance that is two to three orders of magnitude larger than that of rate-and-state friction. Such delay is important in other earthquake source problems that involve rapid normal stress variations, such as seismic slip on nonplanar faults, on bimaterial faults, and in the presence of shear-heating–induced pressurization of pore fluids.

Publications

Tal, Y., Rubino, V., A. J. Rosakis, and N. Lapusta, Illuminating the physics of dynamic friction through laboratory earthquakes on thrust faults, *Proceedings of the National Academy of Sciences*, 117(35), 21095-2100 , 2020. https://doi.org/10.1073/pnas.2004590117

Tal, Y., Rubino, V., A. J. Rosakis, and N. Lapusta, Near-field ground motion and dynamics of thrust earthquakes revealed by laboratory measurements. Manuscript in preparation, 2021.

Presentations

Tal, Y., Rubino, V., A. J. Rosakis, and N. Lapusta, The dynamics of laboratory thrust earthquakes near the free surface, *AGU Fall Meeting*, San Francisco, CA, December 9-13, 2019.

Rosakis, A.J., V. Rubino, Y. Tal, and N. Lapusta, Following individual ruptures: a new approach for measuring dynamic friction in the lab, *AGU Fall Meeting*, held virtually, December 7-11, 2020.

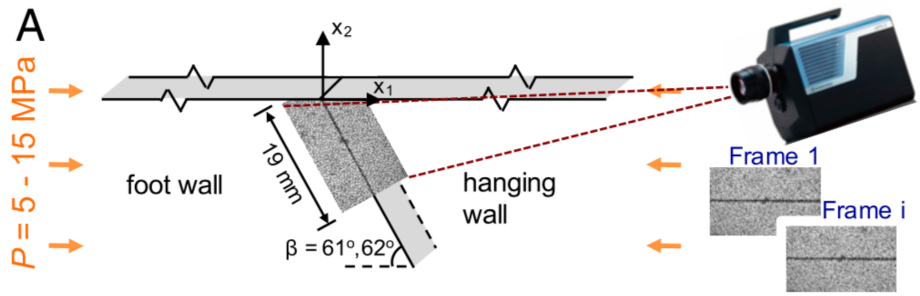

Figure 1. Experimental setup used to study the dynamics of thrust earth- quakes. (A) Experimental setup that mimics thrust faults: Dynamic shear ruptures evolve spontaneously along a frictional interface under resolved shear and normal stresses. An ultrahigh-speed camera is used to take a series of images (106 frames per s) that are analyzed by digital image correlation (DIC). The use of an analog material enables us to produce spontaneously propagating dynamic ruptures on a laboratory scale. Modified from Tal et al., 2020.

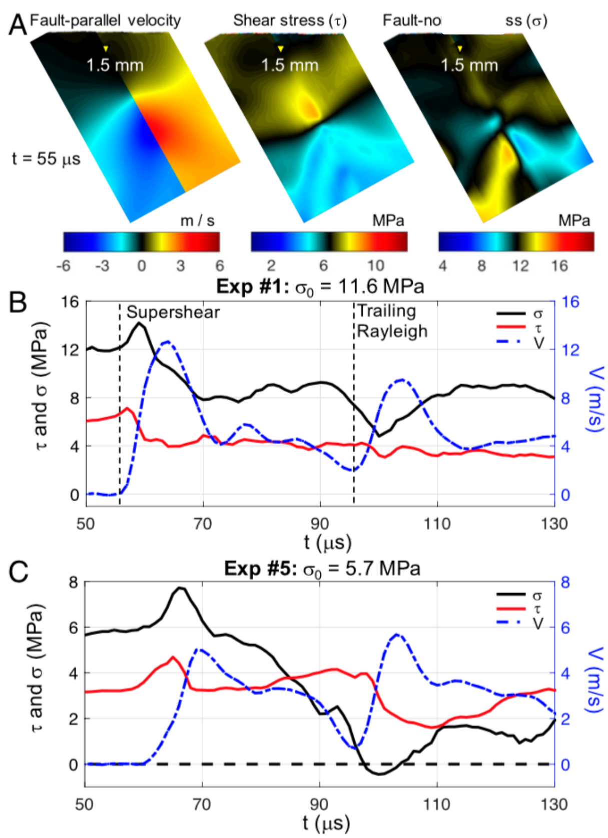

Figure 2. Experimental measurements of fault-parallel velocity, normal stress reduction, and delay in shear resistance response as the rupture interacts with the free surface (Tal et al., 2020). (A) Full-field images corresponding to the propagation of the rupture upward through the FOV during experiment 1. (B) Local time histories of τ (red), σ (black), and V (blue) near the free surface for experi- ment 1 (location marked in A). The arrivals of the rupture front and trailing Rayleigh lead to increases in V and decreases in σ. While τ initially decreases, presumably due to velocity weakening, it barely responds to the variations in σ. (C) Local time histories of τ, σ, and V near the free surface for an exper- iment performed under lower initial normal stress σ0 (experiment 5) show a complete yet transient release of σ.

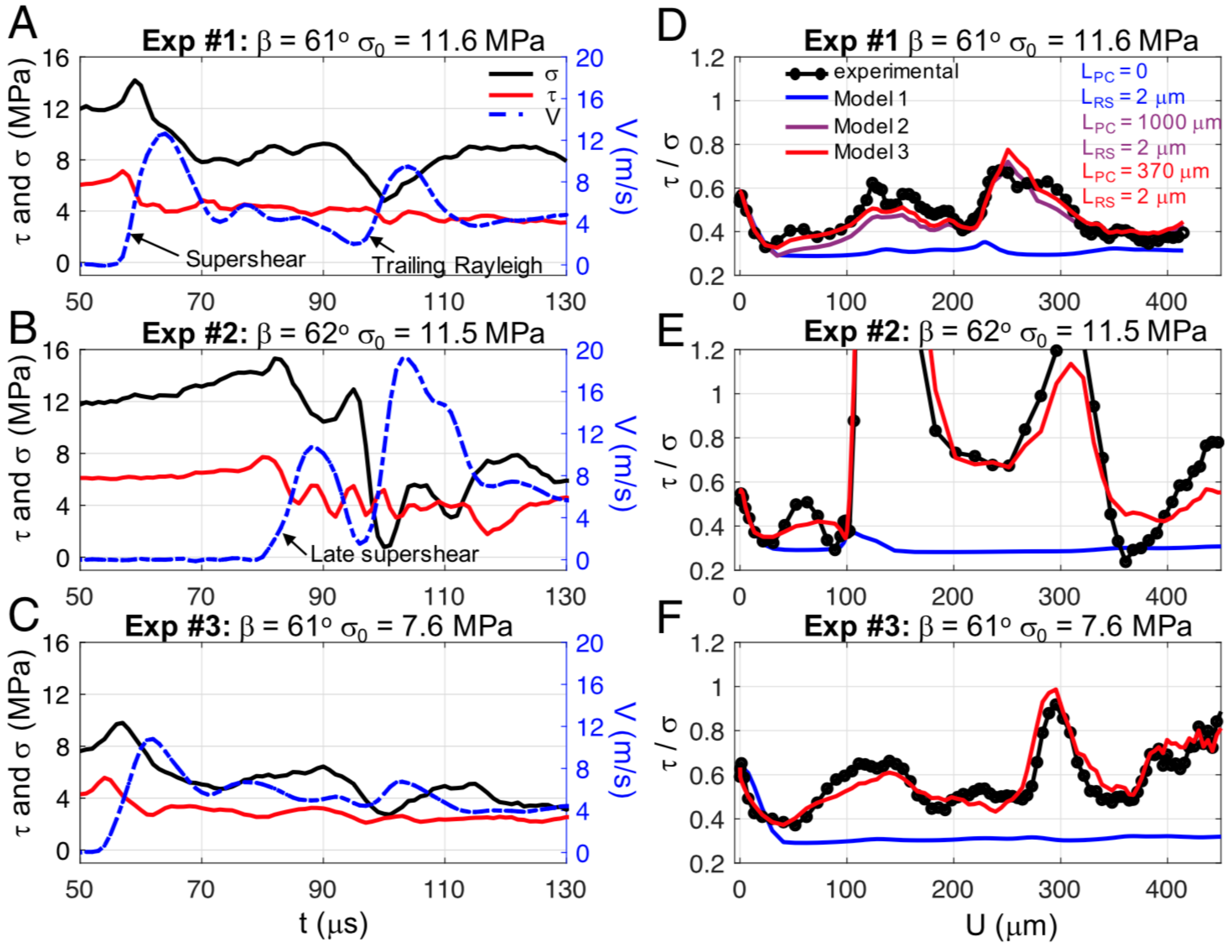

Figure 3. Experimental evidence, fitting, and subsequent prediction of pronounced delay in shear resistance response to rapid normal stress variations (Tal et al., 2020). (A–C) Temporal evolution of τ (red), σ (black), and V (blue) near the free surface (location marked in Fig. 3A) for experiments 1 to 3. Although experiments 1 and 2 were performed under similar loading conditions, a later supershear transition in experiment 2 leads to a more intense near-surface rupture with larger peak in V and larger reduction of σ. (D) Fitting of the measured effective friction τ/σ (experiment 1) for three models: 1) enhanced-weakening RS friction without account for a delayed response to variations in σ (blue); 2) enhanced-weakening RS friction that accounts for the delayed response by the Prakash–Clifton law (purple); and 3) enhanced-weakening rate-and-state friction with the Prakash–Clifton law and weakening parameters that depend on normal stress (red). The experimental data are best fit by friction model 3 with the Prakash–Clifton evolution distance that is two to three orders of magnitude larger than that of rate-and-state friction. (E and F) Comparison of the measured and predicted values of τ/σ for experiments 2 and 3 and friction model 3. The parameters constrained with the data in experiment 1 allow us to predict the nontrivial friction evolution in experiments 2 and 3, as well other experiments (not reported here).

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