Reconciling supershear transition of dynamic ruptures with low fault prestress and implications for the San Andreas Fault

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Summary

The goal of our study is to investigate the possibility of supershear rupture transition and propagation under background prestress levels significantly lower than those expected by the classical Burridge-Andrews mechanism. Such phenomena may be possible based on the results of the numerical study of Liu and Lapusta (2008) which showed that favorable fault heterogeneity can trigger secondary rupture and supershear transition, under a wide range of modeling parameters. We study this problem in a highly instrumented experimental setup that has been successfully used to reproduce a number of dynamic rupture phenomena, such as supershear transition, bimaterial effect, and pulse-like rupture propagation (Rosakis et al., 1999; Rosakis, 2002; Xia et al. 2004; Xia et al., 2005; Lu et al., 2007). The laboratory earthquake setup features a dynamic rupture along an inclined, frictional interface formed by two compressed quadrilateral sections of Homalite.

To image secondary triggering and supershear transition, we have developed a novel experimental technique (Rubino et al., 2017a; 2017d; 2017e). This technique combines ultra-high speed photography and digital image correlation (DIC) to produce maps of full-field dynamic displacements, particle velocities, stresses, and strains. We have verified the velocity measurements obtained using the new method with simultaneous, independent measurements produced by well-characterized laser velocimeters. Excellent agreement between the measurements indicates the reliability of the ultra-high speed DIC method.

Using the newly developed technique, we have imaged experimentally the dynamic variation of friction during spontaneous dynamic rupture (Rubino et al., 2017a), which is needed to design experiments of supershear transition at favorable heterogeneity. Our measurements reveal the presence of significant slip rate effects, including initial rate strengthening with increasing slip rates, followed by substantial rate weakening. By considering rupture behavior under a wide range of experimental conditions, and we have mapped out the rate dependence of steady state friction in our experiments. Our measurements are consistent with the rate-and-state friction formulations supplemented with enhanced co-seismic weakening due to flash heating (Dieterich, 1979, 1981; Rice, 2006; Beeler et al, 2008; Goldsby and Tullis, 2011).

We have used the experimentally measured frictional properties to revisit the determination of the experimental parameters that would lead to supershear transition under lower overall shear prestress than predicted by the Burridge-Andrews mechanism (Rubino et al., 2017b; Rubino et al. 2017c). Specifically, we have determined the suitable combinations of applied loading, specimen geometry, and patch properties (e.g., patch location with respect to the hypocenter and patch size). We find that configurations considered previously would not lead to supershear transition, as they featured patches that were too small. Our previous considerations were based on representative friction parameters determined by comparison of experimental outcomes with theoretical slip-weakening studies; the resulting values of friction parameters had a relatively broad range, and we chose values in the middle of that range. Our current results indicate that the actual effective slip weakening friction properties vary for different rupture scenarios and are overall closer to an end-member case of our previous inferences. Using numerical simulations, we
have found new suitable configurations and confirmed that there is still a range of experimental parameters that can be employed to study secondary triggering.

The combination of developing the imaging technique, using the technique to characterize the evolution of friction, and employing the experimentally measured frictional properties in numerical simulations to determine suitable experimental configurations will enable us to study the potential role of patches in secondary triggering and supershear transition. We are in the process of conducting the actual experiments. The project led to an important outcome of the point-wise measurements and characterization of dynamic friction evolution during spontaneously developing dynamic ruptures in the laboratory under a wide range of prestress conditions, confirming in the lab the validity of the combined rate-and-state and flash-heating formulations used to simulated earthquake ruptures.

The need to reconcile supershear propagation and low fault prestress

Supershear rupture propagation has been inferred for most large strike-slip events. Examples are 1979 Imperial Valley earthquake (Archuleta, 1984; Spudich and Cranswick, 1984), 1992 Landers earthquake (Olsen et al., 1997), 1999 Izmit earthquake (Bouchon et al., 2001), 2001 Kunlun earthquake (Bouchon and Vallee, 2003), 2002 Denali earthquake (Ellsworth et al., 2004), and 1906 San Francisco earthquake (Song et al., 2008). In order for a rupture to transition to supershear speed on a uniform fault, a high level of shear stress is required, as indicated by theoretical and numerical studies (Burridge, 1973; Andrews, 1976) and by laboratory experiments (e.g. Rosakis, 1999; Xia et al. 2004). Yet a number of observations indicate that well-developed, mature strike-slip faults that host large earthquakes operate at low overall levels of shear prestress (e.g. Noda et al., 2009, and references therein).

The apparent incompatibility of supershear propagation and low fault prestress may be possible to resolve based on the findings of Liu and Lapusta (2008). They show that initially sub-shear cracks can transition to and propagate at supershear speeds under lower prestress levels in the presence of favorable heterogeneity, such as a patch of lower strength, higher stress, or pre-existing sub-critical crack (e.g., nucleating slip patch). In their simulations, the stress field of the main rupture dynamically triggers a secondary crack which transitions to supershear speed under a wide range of conditions.

It is important to understand whether low-stressed fault can generate supershear ruptures since supershear rupture can cause much larger shaking far from the fault than sub-Rayleigh ruptures (Bernard and Baumont, 2005; Dunham and Archuleta, 2005; Bhat et al., 2007). This is of particular relevance to Southern San Andreas fault which is locked and loaded for the next large earthquake (Akciz et al., 2009; Grant Ludwig et al., 2010; Zielke et al., 2010).

Development of novel experimental technique to image secondary triggering and supershear transition

In order to image secondary triggering and supershear transition, we have developed a novel experimental technique that combines high-speed photography and digital image correlation (DIC) to produce maps of full-field dynamic displacements, particle velocities, stresses, and strains for our experiments (Figure 1; Rubino et al., 2017a; Rubino et al., 2017d). It extends our previous quasi-static technique (Rubino et al., 2015) to a fully-dynamic regime. This technique allows us to quantify the state of the patch before, during, and after dynamic rupture (e.g., Figure 2). We have fully characterized the experimental uncertainties to guarantee that the accuracy of displacement, velocity and stress measurements is adequate to characterize rupture behavior (Rubino et al., 2017d), including friction evolution and interaction of the main rupture with patches. We have also verified the velocity measurements obtained using the new method with simultaneous independent measurements produced by well-characterized laser velocimeters. Excellent agreement between the measurements indicates the reliability of the ultra-high speed DIC method.

Measuring and interpreting dynamic friction evolution

Using the newly developed technique, we have imaged experimentally the dynamic variation of friction during spontaneous dynamic rupture (Rubino et al., 2017a). This is crucial for the success of this project,
as knowing the dynamic friction properties is key to designing the appropriate experiments, especially selecting the proper size and location of the patch to be triggered by the main rupture.

Our experimental measurement demonstrate that friction evolution with slip velocity is consistent with the combined rate-and-state and flash-heating weakening formulation (Figure 3; Rice, 2006; Beeler et al., 2008; Goldsby and Tullis, 2011; Thomas et al., 2014). These measurements are unique in that they are performed locally during a spontaneously evolving rupture, rather than obtained from a combination of friction experiments where different sliding velocities are imposed from the testing apparatus and assumed to be uniform over the slipping surface. We find evidence for initial strengthening with slip rate (not shown in this report), as would be predicted by the direct effect of rate-and-state friction, followed by weakening. The significant weakening measured in our experiments cannot be explained with standard, logarithmic rate-and-state formulations that generally result in mild friction changes. However, our steady-state measurements (Figure 3) indicate that a combined formulation of low-velocity rate-and-state friction and high-velocity flash heating matches the results quite well (Rubino et al., 2017a). There is a remarkable qualitative similarity between our measurements obtained on a polymer and those obtained on quartzite rock (Figure 3, c and d; Goldsby and Tullis, 2011).

**Paving the way to observing secondary triggering**

We have used the experimentally measured frictional properties to revisit the determination of the experimental parameters that would lead to supershear transition under lower overall shear prestress than predicted by the Burridge-Andrews mechanism. Specifically, we have determined the suitable combinations of applied loading, specimen geometry, and patch properties (e.g., patch location with respect to the hypocenter and patch size). Prior to the friction quantification described in the previous section, we performed tests on specimens containing favorable patches for the case of load $P = 4$ MPa and inclination angle $\alpha = 29^\circ$. This configuration is a candidate to exhibit secondary triggering as it features a sub-Rayleigh rupture that does not transition to supershear speed (within the observation window) for a homogeneous interface. We placed patches of 3 to 6 mm wide by shaving some material from the interface. The fault-normal and shear strains are shown in Figure 2, for the case of 3 mm patch and a field of view of 13 x 8 mm$^2$. The full-field normal strain indicates a lower normal strain level around the patch, while the full-field shear strain shows strain concentrations at the edges of the patch. This case did not result in secondary triggering, and theoretical analysis with the updated friction values indicates the patch size is too small to nucleate. Our experimental measurements reveal that a secondary rupture is actually triggered at the 6-mm patch. However, the main rupture arrives at the patch location before the secondary rupture is well developed and consumes it; in other words, the patch is also too small. We have performed numerical simulations a posteriori, employing actual frictional data from the experiment. The simulations indicate that larger patches (e.g., 7-8 mm) will indeed host secondary ruptures and supershear transition. We are currently performing new tests with the same loading configuration but with larger patches.

We have also explored other promising configurations. One constraint for candidate configurations is that the prestress should be too low for supershear transition to occur under the classical Burridge-Andrews mechanism, e.g., the corresponding supershear transition distances should be larger than the sample size. This constraint is satisfied by the case of $P = 4$ MPa and $\alpha = 29^\circ$ discussed above, with a crack-like rupture. Our numerical and theoretical analysis has suggested that the configuration with $P = 12$ MPa and $\alpha = 24^\circ$ will produce sub-Rayleigh pulse-like ruptures. We have tested specimens under this loading condition with homogeneous interfaces and indeed verified that pulse-like sub-Rayleigh ruptures are produced (Rubino et al., 2017a; Rubino et al., 2017e). Figure 3a-b shows the slip-rate and shear stress time history for the case of $P = 12$ MPa and $\alpha = 24^\circ$. This experiment is particularly interesting because it exhibits a sub-Rayleigh pulse-like rupture propagating first, followed by a reflected supershear crack-like rupture. Hence this configuration will allow us to compare the triggering by crack-like and pulse-like main ruptures.
Figure 1. Imaging mini-earthquake ruptures with our ultra-high-speed full-field technique. a-b, Earthquakes are mimicked in the laboratory by dynamic ruptures propagating along an inclined frictional interface, under the applied shear and normal prestresses simulating tectonic loading applied to a fault within the earth’s crust. The level of prestress is controlled by the applied far-field loading $P$ and interface inclination angle $\alpha$. Part of the interface has a speckled pattern applied for the subsequent analysis. The picture of the San Andreas Fault, shown for visual comparison in panel (a), is obtained from www.sanandreasfault.org. c-d, The full-field time histories of displacements, velocities and stresses are experimentally obtained by capturing sequences of images with ultra-high-speed photography, and processing them with pattern-matching algorithms and highly tailored analysis. These time histories demonstrate our ability to capture the full-field information in the areas of interest, thus enabling us to study the wave fields that lead to triggering.

Figure 2. Full-field maps of the (a) fault-normal and (b) shear strains for a specimen featuring a patch of 3 mm. The field of view is 13 x 8 mm$^2$. The specimen is loaded with $P = 4$ MPa and the inclination angle of the interface is $\alpha = 29^\circ$. The normal strain map exhibits a pronounced reduction in strain level in the proximity of the patch, while the shear strain map shows strain concentrations at the edges of the patch.
Figure 3. Quantifying rupture evolution in laboratory experiments and steady-state measurements of friction. (a) Slip rate and (b) shear stress time histories for an experiment exhibiting a sub-Rayleigh pulse-like rupture propagating first, followed by a supershear crack-like rupture induced by slip interaction with the sample boundary (experimental conditions $P = 12$ MPa and $\alpha = 24^\circ$). The measurements are obtained using high-speed photography and DIC techniques. (c) Experimental measurements of steady-state friction coefficient for sustained slip at a given slip rate, based on multiple ruptures with different prestress conditions (all colored symbols except for green dots). Green dots are low-velocity measurements obtained in collaboration with Drs. Kilgore, Beeler, and Lu in a different apparatus and reported in Lu (2009). Fits to low-slip data with the standard rate-and-state friction formulation (green curve) and all data points with the combined formulation of rate-and-state friction enhanced by flash heating (black curve) demonstrate that our steady-state measurements are consistent with the combined formulation. (d) Experimental measurements of dynamic friction on quartzite samples (Goldsby and Tullis, 2011), showing qualitatively similar behavior for rocks. Note the different horizontal scale for the two plots.
Project Publications

Presentations

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References


