Unstable Unilateral Rupture at Bimaterial Interface with Slip-Weakening Friction Model

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Abstract

Under some circumstances, pulse-like rupture propagation at a bimaterial interface becomes strongly asymmetric, and can be characterized as unilateral in the sense that slip diminishes and eventually dies out in one direction while growing unstably in the other. Pulse-like ruptures capable of this mode of evolution can sometimes be induced for inplane (2D) models with strongly velocity-weakened friction (Ampuero and Ben-Zion, 2007), but have not been seen for 2D slip-dependent friction models (e.g., Harris and Day, 1997). However, we have found that 3D effects (leading to pulse-like rupture) can induce the strongly asymmetric rupture mode even with purely slip-weakening friction. In the slip-weakening case, rupture of faults much longer than their down-dip width initially develops in a crack-like, bilateral mode, and subsequently (due to stopping phases from the top and bottom edges) evolves into two separate slip pulses traveling in opposite directions (e.g., Day, 1982). Under a restricted range of initial conditions, when the fault is at a bimaterial interface (we have so far investigated wavespeed contrasts of ~20%), the slip pulse in the preferred direction propagates indefinitely, while the one in the non-preferred direction dies out. This mode only occurs when the rupture initiates from a localized stress concentration and then propagates into a lower-stress background for which the critical dimension for unstable rupture is tuned closely to the fault width. When initial conditions permit this mechanism to originate, the subsequent propagation distance in the non-preferred direction depends on the value of the quotient $(1+\mu_s)/(1-\mu_d)$, where μ_s and μ_d are, respectively, the static and dynamic friction coefficients (with the die-out distance reducing for high values of this quotient and increasing or transitioning to bilateral rupture for low values). For a surface-rupturing fault, similar relations govern the transition of the rupture mode, provided one interprets the width of the fault as the half-width of an equivalent embedded fault. Both free surface effects and initial normal stress also have some effect on the die-out distance of the non-preferred pulse. If there is no tensile limit imposed on the fault stresses, the preferred-direction slip velocity grows indefinitely with propagation distance, but when fault opening (mode I displacement) is permitted in order to enforce a tensile limit, pulse slip-velocity approaches a steady state value. Whether this 3D mechanism is important in real earthquakes may depend upon a number of phenomena that we have yet to explore, including its sensitivity to natural heterogeneities in initial and frictional stresses, the extent to which it may be amplified by velocity-dependent friction, and the effect of stress limits imposed by off-fault material damage.

Fault model

Break down strength drop $\Delta\tau_b = 18.24 MPa$ for all the models

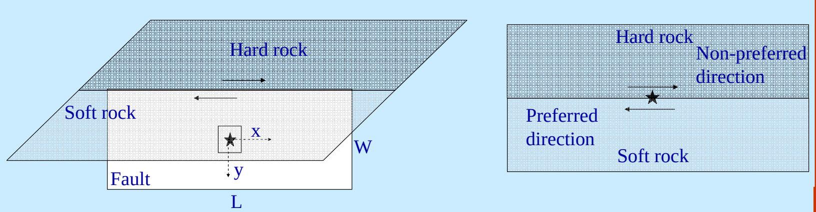


Figure 1. Fault model for testing 3D dynamic rupture simulation at bimaterial interface. Left figure, 3D perspective; right figures, top view, where preferred and non-prefered rupture directions are defined. Star indicates hypocenter. The high-velocity side (Hard rock) has the P and S wave speeds respectively 6000m/s and 3464m/s, and the low-velocity side (softer rock) has wave speeds 20% lower. Both rocks have density 2670 kg/m3. The square patch in left figures is the nucleation

Pre-stress and 3D effects, and unilateral rupture mechanism

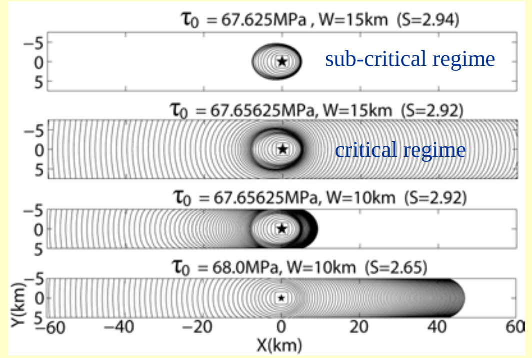


Figure 2. Rupture-time contours (0.5 sec intervals) for four fault models with fault length 120km. The top model (prestress τ_0=67.625MPa) has sub-critical rupture, which we define as rupture induced by a stress perturbation imposed in the nucleation zone, but which cannot grow to the critical dimensions required for sustained propagation in the uniform background stress field. The second model (τ_0=67.65625Mpa, W=15km) has critical rupture. Notice that the change from critical to sub-critical regime takes place when pre-stress is reduced by a tiny amount, (less than 0.05%). The third models is the same as the previous one, except that fault width W is now restricted to 10 km instead of 15km. Suddenly the behavior changes dramatically, and the unilateral mode emerges due to the 3D effect. The fourth frame shows results from a slightly (0.5%) higher prestress, in which case the unilateral transition occurs at about 4 times the propagation distance seen in the previous case.

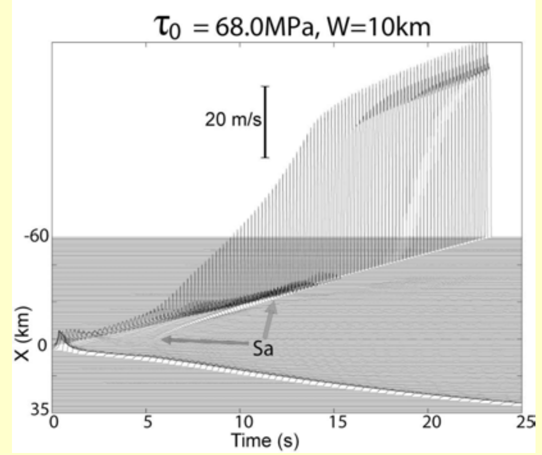


Figure 3. Time history of slip velocity for points along the axis of in-plane motion (x axis) for the case shown at the fourth frame of Figure 2 (τ_0=68.0Mpa and W=10km). The label Sa identifies the S wave generated at the top and bottom of the fault (stopping faces) that leads to pulse-like rupture (3D effect) capable of exciting unilateral rupture.

Open fault effects

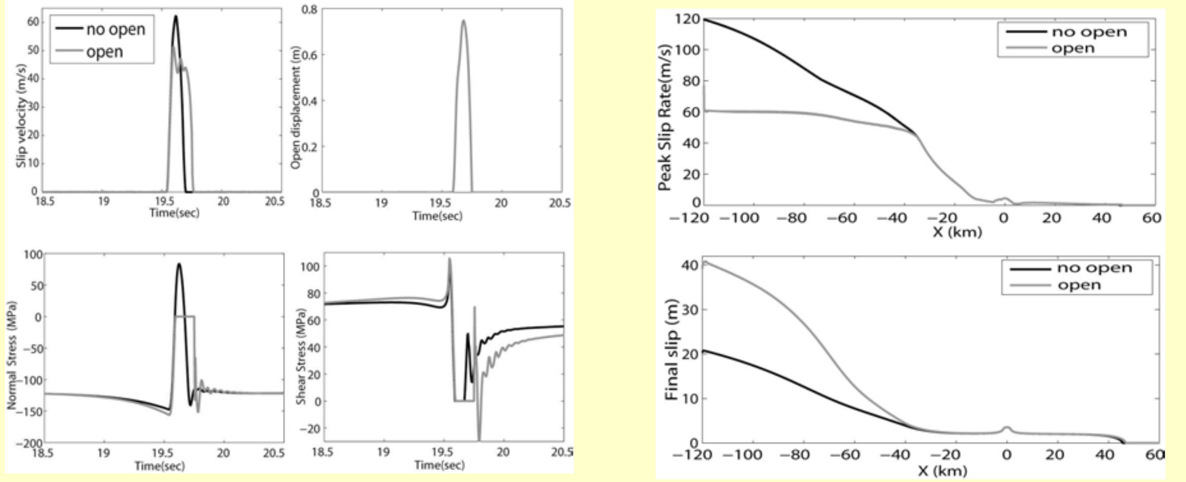


Figure 4. Left figure: time history of slip velocity, mode I (fault opening) displacement, normal stress and shear stress components for a point -50 km along the X axis (inplane), in preferred direction, for the case shown at the fourth frame of Figure 2 (τ_0=68.0Mpa and W=10km). Peak slip velocity and final slip along the X axis of the same model is also shown in the right figure. If there is no tensile limit imposed on the fault stresses, the preferred-direction slip velocity grows indefinitely with propagation distance, but final slip is increased. But when fault opening (mode I displacement) is permitted in order to enforce a tensile limit, peak slip-velocity approaches a steady-state value while the slip velocity pulse width continues to increase.

Effects of $S_f = \frac{1+\mu_s}{1-\mu_d}$

$\sigma_0 = 120$

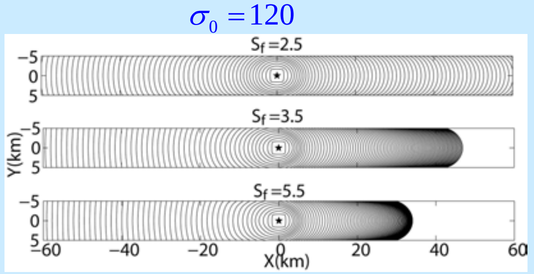
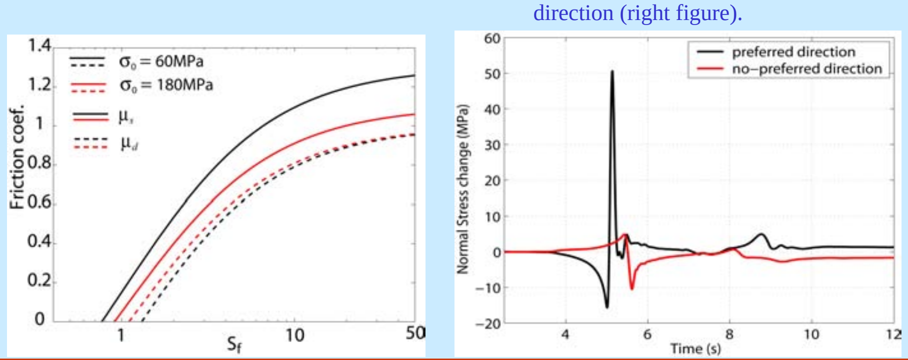


Figure 5. When the unilateral rupture mechanism takes place, the propagation distance in the non-preferred direction depends on the value of S_f, which relates the static and dynamic friction coefficients. As show in the top figure, this die-out distance is inversely related to the S_f value, and there appears to be a transition to steady-state bilateral rupture when S_f falls below a critical value. This seems to be because the dynamic friction coefficient increases with S_f increment (left side of bottom figure), then the transitory dynamic stress drop in the non-preferred direction suffers a reduction, due to the normal stress perturbation acting in compression on the non-preferred direction (right figure).



Free surface effects

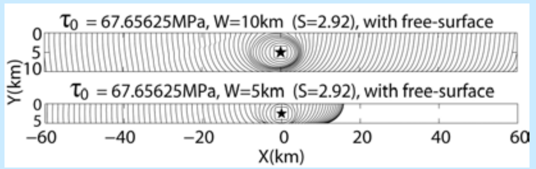


Figure 7. Rupture-time contours (0.5 sec intervals) for two model with free-surface rupture. The top model is the same as the third model of Figure 2. But this time the rupture is bilateral, due to the free-surface effect. But when the width W is reduced to half (bottom model) the behaviour changes to unilateral rupture.

Effects of initial normal stress σ_0

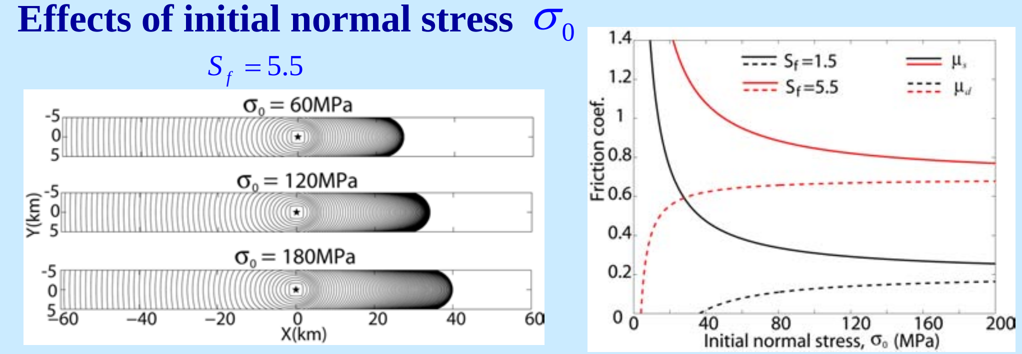


Figure 6. When the unilateral rupture mechanism takes place, the propagation distance in the non-preferred direction is also slightly affected by the initial normal stress. As shown in the left figure, this distance increases for high values of initial normal stress. The right figure shows the change of friction coefficients with initial normal stress, for our models with breakdown strength drop ($\Delta\tau_b$) and S_f constant

Conditions for unstable unilateral rupture derived numerically for 20% of material contrast

Geometrical constrain

$$\frac{W}{L_{nucl}} \approx \frac{20}{3}; \quad 2 \le \frac{h_i}{L_{nucl}} \le \frac{8}{3},$$

where: i=1 and 2

$$L_{nucl} = \sqrt{\frac{3}{10}} L_c \ ; \ L_c = \frac{\bar{\mu} d_0 (S+1)}{\pi \Delta\tau}$$

$\tau_0 =$ Initial shear stress, $\sigma_0 =$ Initial normal stress
$\tau_s = \mu_s \sigma_0$,Initial static friction strength
$\tau_d = \mu_d \sigma_0$,Initial dynamic friction strength
$\Delta\tau_0 = \tau_0 - \tau_d$,Initial dynamic stress drop
μ_s and μ_d = static and dynamic friction coefficient
d_0 = Critical slip-weakening
$\bar{\mu}$ = shear modulus average

Nominal strength (S) $S = \frac{\tau_s - \tau_0}{\tau_0 - \tau_d}$

$S < 2.9$ (unilateral rupture)
$S > 2.9$ (Subcritical rupture)

Friction coeficient ratio (S_f)

$S_f > 2.6$ (unilateral rupture)
$S_f \le 2.6$ (bilateral rupture)