Asymmetric off-fault damage generated by bilateral ruptures along a bimaterial interface

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We perform numerical simulations of spontaneous dynamic rupture governed by a slip-weakening law along a bimaterial interface (fault) with off-fault damage in the form of Coulomb plastic yielding. Off-fault plastic yielding stabilizes the wrinkle-like slip pulse in terms of a decreasing rate of slip velocity growth. With a variety of model parameters, ruptures on the fault are bilateral, while off-fault plastic strain distribution between the two rupture directions is highly asymmetric.


1. Introduction

Ruptures along an interface with a constant friction between two different elastic materials preferentially propagate in one direction with reduced normal stress in the form of the wrinkle-like slip pulse [e.g., Weertman, 1980; Andrews and Ben-Zion, 1997; Ben-Zion, 2006a, 2006b]. On the other hand, with a slip-weakening friction law on the interface, ruptures take the form of bilaterally propagating cracks [e.g., Harris and Day, 1997; Andrews and Harris, 2005, 2006; Harris and Day, 2005, 2006] with the slip pulse as a part of the solution.

Dynamic rupture on a bimaterial interface with generation of plastic strain in the bulk has been studied by Ben-Zion and Shi [2005] by assuming a constant friction on the interface. They found that plastic strain was generated only on the stiffer side of the fault within a stripe of roughly constant width due to unilateral rupture propagation in the positive direction (the slip direction of more compliant material, and the other direction is defined as the negative direction). This has been used to explain recent geological observations of damage asymmetry along sections of the San Andreas, San Jacinto, and Punchbowl faults in southern California [Dor et al., 2006a, 2006b]. The observed damage asymmetry was further argued as an indicator of a preferred northwestward rupture propagation direction along these sections. However, as speculated by Rubin and Ampuero [2007], the observed damage asymmetry is not necessarily indicative of predominantly unidirectional ruptures. Rather, it could be indicative of a bimaterial effect. However, they did not explicitly incorporate nonelastic off-fault deformation in their models.

In this paper, we include both the stress breakdown process in the form of slip-weakening friction at the rupture tip and off-fault plastic yielding in 2D plane strain models. This type of work has only been conducted briefly by Templeton and Rice [2006]. With a variety of initial stress conditions and other model parameters, we find that all ruptures along a bimaterial interface in our study are bilateral with asymmetry between the two propagation directions in fault normal stress change and slip velocity on the fault and the off-fault plastic strain distribution.

2. Method

We use a finite element code EQdyna [Duan and Oglesby, 2006, 2007; B. Duan and S. M. Day, Inelastic strain distribution and seismic radiation from rupture of a fault kink, submitted to Journal of Geophysical Research, 2008] to simulate spontaneous dynamic rupture propagation on a fault and wave propagation in an elastic or elastoplastic medium. The code has been verified against Andrews [2005] on an identical faulting model and has been used to study seismic radiation from a fault kink (Duan and Day, submitted manuscript, 2008) and the effects of low-velocity fault zones on dynamic ruptures [Duan, 2008]. A Mohr-Coulomb yield condition given by \( \tau \leq c - \sigma \tan \phi \) is used to characterize elastoplastic behavior of the medium, where \( \tau \) and \( \sigma \) are shear and normal (positive in tension) stresses in any orientation at a point and \( c \) and \( \phi \) are cohesion and the internal frictional angle, respectively. Dynamic analyses of rupture propagation on a bimaterial interface and wave propagation in an elastoplastic medium are highly nonlinear and are prone to numerical instability [Cochard and Rice, 2000; Andrews, 2005]. These calculations can be stabilized by introducing a regularized friction law on the fault [Cochard and Rice, 2000] and time-dependent relaxation of the stress state toward the yield condition [Andrews, 2005].

If the off-fault material yields (i.e., the yield condition is violated), stress adjustment is performed in stress deviator domain as outlined by Andrews [2005]. The adjusting factor to a stress component should be \( 1 - \left(1 - \frac{1}{\tau_{\text{max}}} \right) \left[1 - \exp(-\Delta t/\tau_{\text{vis}})\right] \) (S. M. Day, personal communication, 2006), rather than \( (Y/\tau_{\text{max}})[1-\exp(-\Delta t/\tau_{\text{vis}})] \) given by Andrews [2005], where \( Y \), \( \tau_{\text{max}} \), \( \Delta t \) and \( \tau_{\text{vis}} \) are yield stress, maximum shear stress over all orientations at a point, the simulation time step, and the viscoplastic relaxation time, respectively.

We employ a time-regularized friction law to regularize normal stress response. The law has a similar form to the one used by Dunham and Rice [2008], \( d\tau_{\text{r}}/dt = -\tau_{\text{r}}/\tau_{\text{r}}^{*} \), in which \( \tau_{\text{r}} \) is the regularizing time over which the fault strength \( \tau_{\text{r}} \) evolves toward the product of the frictional coefficient \( \mu \) and the normal stress \( \sigma \) on the fault. The frictional coefficient \( \mu \) obeys a linear slip-weakening law: \( \mu(\delta) = \mu_{s} - (\mu_{s} - \mu_{d})\min\{\delta, D_{0}\}/D_{0} \), where \( \mu_{s} \), \( \mu_{d} \), \( \delta \), \( D_{0} \) are...
the static and dynamic coefficients of friction, slip on the fault, and the critical slip distance, respectively.

Rupture is initiated artificially within a nucleation patch with a half length of $L_c$ by forcing ruptures to grow bilaterally at a fixed speed (2 km/s in this study). Outside of this nucleation patch, ruptures propagate spontaneously at faster speeds. Square elements with a uniform nodal spacing of $\Delta x$ are used to discretize the medium within a main region surrounding the fault. A much larger buffer region surrounds the main region with gradually increasing element size to prevent model boundary reflections from contaminating results we examine.

3. Results of a Set of Simulations on a 2D Model

We perform a set of simulations on a 2D strike-slip fault to examine interactions of rupture propagation on a bimaterial interface and off-fault plastic strain generation. The model geometry is given in the inset of Figure 1a. Ruptures initiate at the center of the fault $x = 40$ km (shown as a star). The positive rupture direction for this geometry is to the right of the initiation point. We compare three simulations: bimaterial medium with elastic off-fault response (denoted as ELA), bimaterial medium with elastoplastic off-fault response (denoted as PLA), and homogeneous medium with elastoplastic off-fault response (denoted as HOM). The material properties and computational parameters for PLA are given in Table 1. The more compliant material has a reduction of 20% in seismic velocities relative to the stiffer material. $\Delta x$, $D_0$, and $L_c$ are chosen to be self-consistent and the values of two normal stress components and cohesion correspond to a depth of about 6 km [Ben-Zion and Shi, 2005]. Uniform initial stress field and uniform Coulomb yield parameters are assumed in the entire model. The only difference in ELA is to assign cohesion a very large value to avoid off-fault plastic yielding and in HOM is to assign values of $V_{p1}$ and $V_{s1}$ (the faster material) to the entire model.

Snapshots of slip velocity and fault normal stress along the fault from the calculation PLA at three times with an equal interval are shown in Figure 1. To test convergence, we also run a simulation with a finer element size of $\Delta x = 12.5$ m. The results from the two resolutions basically overlap, suggesting the 25 m element size already provides good convergence. Predominant features of rupture propagation along the interface with off-fault plastic yielding are: (1) rupture is bilateral; (2) peaks of tensile change (less compressive) of normal stress in the positive direction and compressive change (more compressive) in the negative direction just behind the rupture tips are associated with peaks in slip velocity;

![Figure 1. Snapshots of (a) normal stress and (b) slip velocity on the fault every 4.6 s for the simulation PLA: bimaterial with off-fault plastic yielding with two numerical resolutions. A resolution of 25 m provides good convergence. The inset in Figure 1a gives the model geometry in this study.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $\rho$</td>
<td>2670 kg/m$^3$</td>
</tr>
<tr>
<td>$V_{p1}$</td>
<td>6000 m/s</td>
</tr>
<tr>
<td>$V_{s1}$</td>
<td>3464 m/s</td>
</tr>
<tr>
<td>$V_{p2}$</td>
<td>5000 m/s</td>
</tr>
<tr>
<td>$V_{s2}$</td>
<td>2887 m/s</td>
</tr>
<tr>
<td>$\sigma_{xx}$, $\sigma_{yy}$</td>
<td>$-100$ MPa</td>
</tr>
<tr>
<td>$\sigma_{xy}$</td>
<td>45 MPa</td>
</tr>
<tr>
<td>$\mu_a$</td>
<td>0.6</td>
</tr>
<tr>
<td>$\mu_d$</td>
<td>0.35</td>
</tr>
<tr>
<td>$\tan \phi$</td>
<td>0.75</td>
</tr>
<tr>
<td>$c$</td>
<td>45 MPa</td>
</tr>
<tr>
<td>$\Delta x$</td>
<td>25 m</td>
</tr>
<tr>
<td>$D_0$</td>
<td>0.7 m</td>
</tr>
<tr>
<td>$L_c$</td>
<td>2800 m</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>0.00125 s</td>
</tr>
<tr>
<td>$t^*$</td>
<td>0.0125 s</td>
</tr>
<tr>
<td>$T_v$</td>
<td>0.007 s</td>
</tr>
</tbody>
</table>
(3) all these peaks (amplitudes) increase with the rupture propagation distance; (4) magnitudes of the above changes in normal stress and peak slip velocity are much larger in the positive direction than in the negative direction, particularly at large propagation distances; (5) change of normal stress just in front of the rupture tips is compressive in the positive direction and is tensile in the negative direction; (6) a generalized Rayleigh wave (the wiggle behind the rupture front) propagates in the positive direction.

Results from the three simulations are compared in Figure 2. The above features of asymmetry in fault normal stress change and slip velocity are much more profound in ELA. In particular, fault normal stress becomes tensile in the positive direction at times \( t_2 \) and \( t_3 \). Because we allow the fault to open in this situation, the fault normal stress is limited by 0 Pa. The peak of slip velocity becomes very high and increases obviously as rupture propagates. A sharp slip pulse that is separate from the main crack by a patch with zero slip velocity, which corresponds to compressive

Figure 2. Snapshots of (a) normal stress and (b) slip velocity on the fault every 4.6 s for three simulations PLA, HOM, and ELA to demonstrate effects of bimaterial interface and off-fault plastic yielding on rupture dynamics.

Figure 3. Magnitude of plastic strain at time 15 s for two calculations (a) HOM and (b) PLA. Bimaterial interface results in highly asymmetric plastic strain distribution between the two rupture propagation directions.
change in normal stress just behind the slip pulse, develops at time $t_3$ in the positive direction in ELA. These are features of the wrinkle-like slip pulse in the case of elastic off-fault response [e.g., Andrews and Ben-Zion, 1997; Cochard and Rice, 2000]. However, off-fault plastic yielding significantly suppresses normal stress reduction associated with the slip pulse and the peak slip velocity on the fault. In particular, tensile normal stress is not reached in PLA. Asymmetry between the two rupture directions discussed above do not appear in HOM. Fault normal stress variation with relatively smaller amplitude observed in HOM is a result of off-fault yielding [Andrews, 2005], and it is symmetric between the two rupture directions.

[12] Figure 3 shows the distribution of plastic strain magnitude at time 15 s from the calculations of HOM and PLA. Off-fault plastic yielding occurs in the two dilatational quadrants and plastic strain distribution is symmetric between the two rupture directions in HOM. However, highly asymmetric plastic strain distribution is observed between the two rupture directions in PLA: plastic strain is much stronger and the zone of plastic yielding is much wider in the positive direction than those in the negative direction at the same rupture distance. This asymmetry in off-fault damage must be a result of different stress variations away from the fault between the two directions due to the existence of the bimaterial interface. In particular, dynamic changes of normal stress components are asymmetric, similar to those shown in Figures 1a and 2a on the fault. The strong asymmetry in off-fault damage (plastic strain) is indicative of the existence of the bimaterial interface in this model, not an indicator of a preferred unilateral rupture in the positive direction.

4. Discussion

[13] Asymmetry in plastic strain distribution observed in the above PLA model persists when we change initial stress levels and/or Coulomb yield parameters. Figure 4a is an example of lower initial stress level and lower cohesion with $\sigma_{xx} = \sigma_{yy} = -50$ MPa, $\sigma_{xy} = 22.5$ MPa, and $c = 25$ MPa, which are similar to those used by Ben-Zion and Shi [2005] for a depth of about 3 km. Other parameters are the same as in Table 1. The rupture in this calculation is bilateral, while plastic strain is mainly generated in the positive direction with very minor plastic strain in the negative direction. Figure 4b is another example with very low cohesion $c = 5$ MPa and other parameters as in Table 1. In this case, plastic strain is generated in both rupture directions but with asymmetry in both magnitude of plastic strain and the width of the plastic yielding zone. Thus, asymmetric damage (plastic strain) is indicative of a bimaterial interface, and the level of asymmetry depends on initial stress field and off-fault material strength.

[14] To test whether or not the peak slip velocity in the positive direction increases further as in Figure 1b, we perform a calculation on a model with a much longer fault with a half length of 100 km and model parameters the same as those for Figure 4b. We find that peak slip velocity (not shown) increases continuously with the rupture distance in the positive direction but with a decreasing rate. A similar trend applies to normal stress change. Thus, off-fault plastic yielding can stabilize the wrinkle-like slip pulse in the sense of decreasing the rate of slip velocity growth. Once again, the rupture is bilateral. Asymmetric plastic strain (not shown) with features similar to Figure 4b is generated in the model.

[15] Nucleation mechanisms can have effects on dynamic ruptures along a bimaterial interface [e.g., Ben-Zion, 2006b]. The mechanism used in this paper employs the concept that the dynamic rupture starts when a stable crack grows to a critical size, which is commonly used in rupture dynamic studies. Other mechanisms used in previous work on bimaterial problems involve a relatively small and strong nucleation process, such as a localized region of elevated
pore pressure, which introduces a favored propagation direction within the nucleation phase and could result in preferentially unilateral rupture propagation [e.g., Shi and Ben-Zion, 2006].

[16] Friction laws that govern the stress breakdown process at the rupture tip also play a role in bimaterial problems. As speculated by Ben-Zion [2006b] and demonstrated by Ampuero and Ben-Zion [2008], with strongly velocity-weakening friction, ruptures can occur as large-scale pulses with a preferred propagation direction. Although friction appears velocity dependent at the small scale, numerous processes likely occur at the macroscopic scale, such as poroelastic interactions [Dunham and Rice, 2008] and off-fault material failure that expands the weakening scale lengths [Andrews, 2005; Duan and Day, submitted manuscript, 2008]. Thus, it remains uncertain at present how much differently a realistic combination of these effects would behave, compared with a simple slip-weakening friction law used in this study (S. M. Day, personal communication, 2008). Furthermore, the feature of systematic damage asymmetry associated with bilateral ruptures along a bimaterial interface is robust regardless of friction laws.

[17] The width of the plastic strain zone increases with the rupture propagation distance in a uniform initial stress field in all our models. This feature of plastic strain distribution is consistent with Andrews [2005] for a homogeneous medium, while it is in contrast to that obtained by Ben-Zion and Shi [2005] for a bimaterial medium with a constant fault friction in which the width of plastic zone is roughly constant. In real fault systems, the initial stress field is more likely nonuniform. In particular, the shear stress level may decrease away from the fault, which can limit off-fault damage generation to a certain width near a fault. Furthermore, with more damage on the stiffer side of the fault in the positive direction due to one rupture, the material on this side should be weaker (i.e., lower values of cohesion and/or internal friction) than the other side and is prone for more damage in subsequent earthquakes. The cumulative effect of many such bilateral ruptures on a bimaterial interface could produce an asymmetric damage pattern across the fault compatible with the observations of Dor et al. [2006a, 2006b].

5. Conclusions

[18] Spontaneous dynamic ruptures, governed by a slip-weakening friction law on a bimaterial interface with the resulting off-fault damage, are bilateral within a wide range of model parameters. Off-fault damage is highly asymmetric between the two rupture directions and between the two sides of the interface. This damage asymmetry is a general part of bimaterial effects and is not necessarily an indicator for unilateral ruptures. Therefore, the damage asymmetry observed in the field by other researchers may be a result of many bilateral ruptures along a bimaterial interface.

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