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Asymmetric rupture of large aspect-ratio faults at bimaterial interface in 3D

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[1] Normal stress perturbations accompany propagating mode II rupture along an interface separating materials of contrasting elastic compliance. The extent to which those perturbations may produce significant, observable rupture asymmetries (i.e., final slip distribution heavily weighted toward a preferred propagation direction) in earthquakes is uncertain, but previous numerical simulations predict such asymmetry when frictional resistance is velocity dependent, with sufficient post-rupture re-strengthening to produce pulse-like rupture. We show, by numerical simulations in 3D, that purely geometrical effects leading to pulse-like rupture can also induce strong asymmetries (and under very limited conditions can even evolve into strictly unilateral rupture), even when frictional rate dependence is neglected. The effect is studied here in a context that can only apply to strike-slip earthquakes large enough to rupture the entire seismogenic thickness, but the results suggest that other geometrical effects leading to pulse-like rupture will interact with a compliance contrast in a similar manner.
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1. Introduction

[2] Rupture at the interface between solids of contrasting elastic compliance has been the subject of extensive theoretical and numerical studies [e.g., *Weertman*, 1980; *Adams*, 1995; *Andrews and Ben-Zion*, 1997; *Harris and Day*, 1997; *Cochard and Rice*, 2000; *Ranjith and Rice*, 2001; *Ma and Beroza*, 2008; *Ampuero and Ben-Zion*, 2008], as well as scale-model experiments [*Xia et al.*, 2005]. In a propagating mode II rupture, the compliance contrast induces a normal stress perturbation proportional to the slip gradient [*Weertman*, 1980], which can be large near the rupture front. This perturbation affects the fault frictional resistance if, as usually assumed, friction is sensitive to effective normal stress. Moreover, because the sign of the normal-stress perturbation at a rupture front depends upon rupture propagation direction, this effect on frictional resistance is asymmetric with respect to rupture direction and can introduce asymmetries in the rupture velocity and/or the slip-velocity. Following convention, by positive (or preferred) direction (Figure 1g) we refer to that direction of mode II rupture for which normal stress perturbations are favorable to propagation at subshear speed, corresponding to the direction of displacement of the more compliant side of the fault.

[3] *Andrews and Ben-Zion* [1997] demonstrated through numerical simulations that these asymmetries can lead to emergence of a self-sustaining slip pulse (the "wrinkle pulse") propagating unilaterally in the positive direction, as proposed by *Weertman* [1980]. Those simulations were for a simplified model in which the friction coefficient never weakens at or following the onset of sliding, so the asymmetrical wrinkle pulse dominates the dynamics. *Harris and Day* [1997] added frictional weakening and found that a consistently bilateral rupture propagation mode emerged, though with the wrinkle-pulse dynamics still present and reflected in asymmetric slip rates in the two propagation directions. Subsequent simulations have shown that rupture asymmetry depends upon the balance between the competing effects of friction coefficient changes and normal-stress fluctuations [e.g., *Ben-Zion and Shi*, 2005], and we distinguish three classes of such simulations.

[4] 1. Irreversible reduction of friction coefficient. All simulations published to date (2D examples include *Harris and Day* [1997], *Ben-Zion and Shi* [2005], *Shi and Ben-Zion* [2006], and *Rubin and Ampuero* [2007]) are consistent in showing bilateral rupture (accompanied by significant asymmetries in slip velocity, and sometimes in rupture velocity) whenever the friction coefficient is allowed to fall irreversibly (on the timescale relevant to an individual rupture event) to a dynamic friction value that is below the minimum required to stabilize the fault under the initial static stress conditions, i.e., to below τ_0/σ_0, where τ_0 and σ_0 are the initial values of shear and normal stress. This behavior has been verified in 3D as well [e.g., *Andrews and Harris*, 2005; *Harris and Day*, 2005], and was also found in the laboratory experiments of *Xia et al.* [2005]. For natural earthquakes, rupture-front asymmetries associated with this type of model have been proposed to explain observed asymmetries in aftershock distributions [*Rubin and Ampuero*, 2007] and ground motion amplitudes [*Ma et al.*, 2008]. Additional theoretical results of *Dunham and Rice* [2008] still showed bilateral, asymmetric, rupture (in 2D) when the effect of mismatching poroelastic properties was added to this class of model.

[5] 2. Little or no weakening of the friction coefficient. When the friction coefficient does not weaken to below τ_0/σ_0, interface rupture can still be induced by imposing an energetic nucleation event, and such simulations frequently show unilateral rupture, albeit with small slips and very short rise time. Most such work has been in 2D [e.g., *Brietzke and Ben-Zion*, 2006], but *Brietzke et al.* [2007] have recently performed simulations in 3D showing very narrow, self-sustaining, unilateral pulses in an angular zone about the positive mode II direction.

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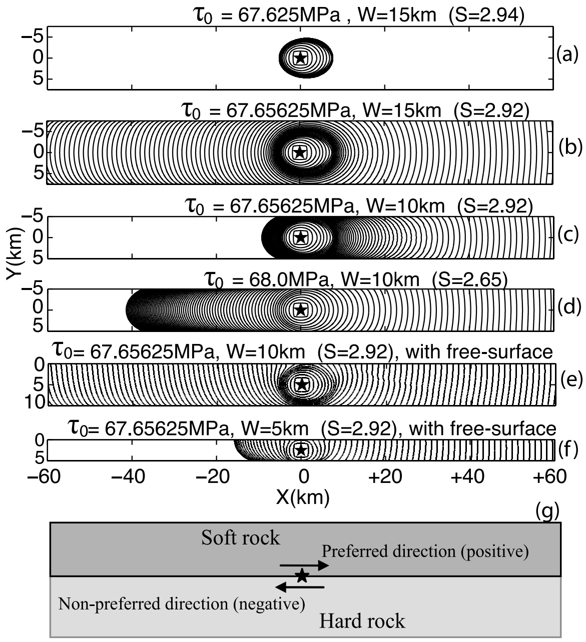

Figure 1. Rupture-time contours (0.5 sec intervals) for six fault models with fault length 120 km. (a, b, c, and d) Models are embedded (no-freesurface); and (e and f) models with free-surface. The first The shear prestress (τ_0), fault width (W) and parameter $S = (\tau_s - \tau_o)/(\tau_o - \tau_d)$ are as indicated, where τ_s, τ_d and τ_o are respectively the initial static strength, initial dynamic strength and initial stress. (g) A top view of fault model, where preferred (positive) and non-prefered (negative) rupture directions are defined. Star indicates center of nucleation zone.

[6] 3. Transient weakening of friction coefficient. Interesting new behaviors emerge when the friction is strongly velocity dependent, as suggested by recent experimental studies [e.g., *Beeler et al.*, 2008], such that the friction coefficient falls to relatively low values immediately behind the rupture front, but can recover to near its initial value as sliding velocity falls thereafter. *Ampuero and Ben-Zion* [2008] show that a pulse mode of rupture is then possible under a fairly wide range of conditions, as already well established in the case of a homogeneous medium [e.g., *Beeler and Tullis*, 1996; *Zheng and Rice*, 1998]. In the bimaterial case, Ampuero and Ben-Zion show cases in which the negative-directed pulse decays in amplitude, or even stops entirely, while the positive-directed pulse remains self-sustained. Moreover, whether or not the resulting simulated events become unilateral in a strict sense, the prompt recovery of frictional strength behind the rupture front permits large asymmetries to become frozen into the final displacement field, and Ampuero and Ben-Zion call this effect macroscopic asymmetry. Macroscopic asymmetry developed by this or a similar mechanism may be a contributor to damage asymmetry identified from geological observation by *Dor et al.* [2006], though *Duan* [2008] suggests that the latter may arise from small-scale asymmetry in rupture-tip dynamic stresses, irrespective of whether macroscopic rupture asymmetry emerges, as also pointed out by *Rubin and Ampuero* [2007].

[7] The mechanism discussed in the previous paragraph relies on prompt restrengthening of the friction coefficient in response to slip-speed reductions. Since much uncertainty remains as to the nature of friction at typical coseismic sliding speeds, it is of interest to assess additional mechanisms that might further promote strong compliance-contrast-induced rupture asymmetry.

[8] In this paper, we use numerical simulations to reveal a purely 3D effect that can generate strongly asymmetric rupture even under pure (irreversible) slip weakening of the friction coefficient. This 3D mechanism is only operative for high-aspect ratio faults, so its effect is limited to strike-slip events that rupture the entire seismogenic thickness. In that case, single-material numerical models indicate that rupture evolves into a pair of slip pulses with opposite propagation directions [*Day*, 1982], similar to the pulse mode that can occur under velocity-dependent friction, and we explore whether similar asymmetries can arise for rupture at a compliance contrast.

2. Three-Dimensional Numerical Model

[9] Simulations are done using the 3D finite difference code of *Day* [1982], described in detail by *Day et al.* [2005]. The method uses viscoelastic regularization that damps short-wavelength slip-rate perturbations whose exponential growth (for a bimaterial contrast for which the generalized Rayleigh wave exists, as in our case) would otherwise extend to arbitrarily short wavelength and render the problem ill-posed [*Adams*, 1995; *Cochard and Rice*, 2000; *Ranjith and Rice*, 2001]. Numerical tests confirm that, thus regularized, the solutions are grid-size independent provided the frictional transition at the rupture front is resolved.

[10] The cases studied are idealized to isolate the 3D effect of high-aspect-ratio rupture geometry. We use linear slip-weakening and frictional parameters use by *Day et al.* [2005], with rupture initiated from a slightly overstressed 3×3 km square patch. We introduce a compliance contrast, in the form of a 20% wavespeed reduction on one side of the fault (with no contrast in density or Poisson's ratio), and the effect of fault length is essentially removed from the problem by making the length L much greater than fault width W (so that, when we examine rupture development far from the fault ends, L is essentially eliminated as a significant parameter). We then examine effects of variations in fault width and shear prestress level τ_0 (cases a–d, Figure 1), as well as effects of a free surface (cases e–f, Figure 1) and tensile limit. Calculations are done using a computational cell size of 50 m, and additional tests at reduced cell size confirm that the solution is grid independent, to a good approximation. Common characteristics to all models are: Poisson's ratio 0.25, max S wavespeed 3464 m/s, min S wavespeed 2771 m/s, static friction coefficient 0.677, dynamic friction coefficient 0.525 (corresponding to 63 MPa at the initial normal stress), critical slip 0.4 m, initial normal stress 120 MPa, initial nucleation-zone shear stress 81.6 MPa.

3. Results

[11] Figure 1 shows rupture-time contours of each of the six cases explained above, of which cases a-d are for

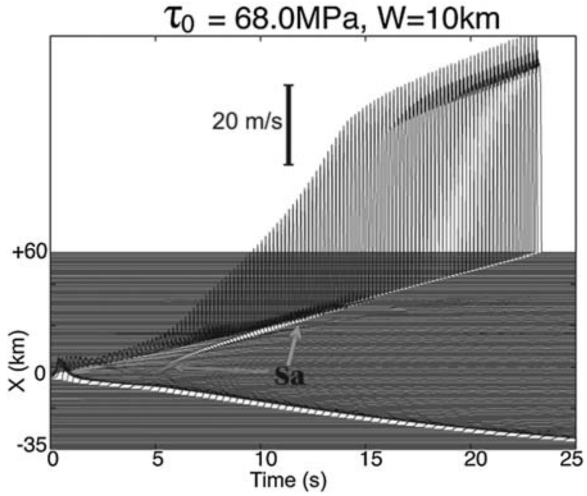

Figure 2. Time history of slip velocity for points along the axis of in-plane motion (x axis), for the case shown in Figure 1d. The label Sa identifies the S waves generated at the top and bottom of the fault.

buried ruptures. Figure 1a, for a model with τ_0 equal to 67.625 MPa and W equal to 15 km, is an example of what might be termed sub-critical rupture: after being induced by the sudden overstressing in the nucleation zone, rupture arrests before progressing to an area large enough to destabilize the fault under these conditions of ambient shear stress (and given the simplified frictional model). Figure 1b shows a case (τ_0 = 67.65625 MPa and W = 15 km) in which the fault is given an extremely small shear prestress increase (a fractional increment of $\sim 5 \times 10^{-4}$). In this case, the rupture propagates bilaterally over the entire fault without arresting. It fills the full available length of the fault, 60 km in the case shown in Figure 1, and we have verified the bilateral character numerically for up to 100 km in each direction. So far, this 3D behavior is consistent with all previous 2D models with slip-dependent frictional weakening: rupture is either subcritical, in the above sense, or bilateral. We have examined extremely fine prestress adjustments between cases a and b, and find no prestress range for self-sustained unilateral rupture in this case (i.e., with other parameters fixed). The change of prestress affects the rupture propagation systematically, however. As the pre-stress is reduced, the rupture propagation asymmetry increases and rupture speed decreases in the negative direction, until we reach the level where rupture is unsustainable (in both directions).

[12] Figure 1c shows results for case c, which is the same as case b except that fault width W is now restricted to 10 km instead of 15 km. Suddenly the behavior changes dramatically, and a unilateral rupture mode emerges. Rupture dies out in the negative direction, but progresses without limit in the positive direction. Figure 1d 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, and the transition disappears completely at higher prestress levels. As these examples show, the unilateral mode becomes possible only when the fault width W is below some threshold that depends upon prestress, frictional parameters, and nucleation dimension.

[13] Case e (Figure 1e), is a modification of case c (which ruptured unilaterally) such that the top edge of the fault coincides with a free surface. In this case, the rupture mode reverts to bilateral. Then, in case f (Figure 1f), the free-surface is retained, but the fault width W is now restricted to 5 km, and the behavior returns to the unilateral mode (with the rupture distance in the negative direction becoming approximately $3W$). These examples suggest that, for fault models rupturing the free surface, the bilateral/unilateral transition (in this idealized model) is still controlled by fault width (for a given prestress level and frictional parameters), in a similar manner to that operating in the simpler, buried-rupture models; however, the critical threshold width for transition to unilateral rupture is reduced by approximately a factor of two.

[14] We can relate this result to the behavior of single-material simulations for a long, narrow fault [e.g., *Day*, 1982], in which case the actively slipping part is initially crack-like (a simply-connected patch) around the hypocenter, but subsequently bifurcates as diffractions from the fault edges arrest sliding behind separate pulses traveling in opposite directions. In the bimaterial case, normal stress changes amplify and de-amplify, respectively, these separated positive- and negative-direction pulses, and sliding arrest at their trailing edges freezes in the resulting asymmetry (see Figure 2), much as in the velocity-dependent friction case. The negative-direction pulse can even die out completely if it is sufficiently damped by enhanced frictional losses induced by the compliance contrast. This only happens if its frictional loss rate exceeds the rate at which elastic energy is released from the prestressed volume. The rate of elastic energy release increases with the along-strike pulse length, which is initially proportional to W [*Day*, 1982], whereas the normal-stress changes responsible for the enhanced frictional damping are largely confined to the narrow strip of high slip gradient just behind the rupture front, roughly independent of W. This may explain why, with other parameters fixed, there is a W threshold above which rupture becomes exclusively bilateral (though still asymmetric) in this simplified model.

[15] We performed a few additional simulations that permitted opening to occur when required to prevent tensile fault-plane stresses (which the previous calculations did not), using the method described by *Day et al.* [2005]. Figures 3 shows, for case d, the effect on slip, slip rate and fault-plane tractions, of permitting fault opening. As shown in Figures 3a and 3b, when tensile stress is relieved by opening, the strong rupture-velocity and displacement asymmetry of case d are preserved. The maximum slip velocity in the positive-direction pulse is reduced, however, and reaches a limit after long propagation distance. This velocity reduction can be roughly understood from dislocation theory applied at the bimaterial interface. *Weertman* [1980] notes that a propagating discontinuity in fault-normal displacement induces a shear stress change proportional to the along-fault derivative of the discontinuity, and, furthermore, the constant of proportionality is equal in magnitude but opposite in sign to the normal-stress change induced by the corresponding fault-parallel displacement discontinuity (this can also be demonstrated by a reciprocity

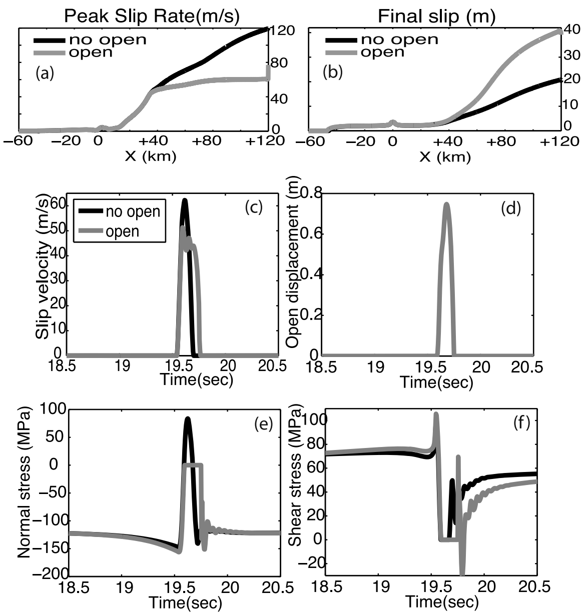

Figure 3. (a) Maximum slip velocity and (b) final slip along the axis of in-plane motion (x axis) for the case shown in Figure 1d. (c) A slip velocity, (d) opening displacement, (e) normal and (f) shear traction components, for a point +50 km along the X axis (inplane), in preferred direction, for the case shown Figure 1d. Black and gray curves correspond, respectively, to models with no-open and open fault.

argument). Thus fault opening introduces shear stresses (or, more precisely, would do so if shear motion were constrained) that counter the effects of the drop in frictional resistance.

4. Discussion

[16] The foregoing results confirm the suggestion of *Ampuero and Ben-Zion* [2008] that macroscopic asymmetry can arise from bimaterial interface rupture whenever pulse-like rupture develops, regardless of origin (i.e., whether the pulse mode arises from the frictional behavior, or, as in this study, from essentially geometrical effects such as sliding arrest due to edge diffractions). The geometrical mechanism identified here, while by itself only effective under a rather restricted range of initial conditions, may act in concert with velocity-dependent friction to enhance the effect of the latter. Moreover, other geometrical factors leading to pulse-like rupture, such as localized high-slip patches [e.g., *Day et al.*, 1998], are likely to produce similar effects at a bimaterial interface. Still open questions are whether compliance-controlled rupture asymmetry has significant predictable effects in real earthquakes, given competing effects of across-fault hydrological [e.g., *Dunham and Rice*, 2008] and damage asymmetries [e.g., *Sammis et al.*, 2008; H. S. Bhat et al., The effect of asymmetric damage on dynamic shear rupture propagation: 2. With mismatch in bulk elasticity, submitted to *Journal of Geophysical Research*, 2008], as well as the complications introduced by rock strength limits and along-fault heterogeneities in stress and material properties.

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