Comment on “The wrinkle-like slip pulse is not important in earthquake dynamics” by D. J. Andrews and R. A. Harris

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1. Introduction

[1] Andrews and Harris [2005] (hereinafter referred to as AH) found in several numerical simulations that effects associated with prescribed stress heterogeneities and time-weakening friction can suppress those generated dynamically by rupture on a bimaterial interface, and concluded that the wrinkle-like rupture mode is generally not important for earthquake dynamics. Their results are based on selective cases, rather than a systematic parameter-space study, and they do not form the basis for a general conclusion. Moreover, most of their cases are associated with conditions for which the bimaterial effects are weak due to combination of assumed parameter values, mixed rupture modes, relatively small propagation distance, and coarse grid. Considerations of a larger body of theoretical results and observations suggest that the wrinkle-like rupture may be relevant to earthquake dynamics.

[2] Weertman [1980] showed analytically that mode II slip pulse on a bimaterial interface governed by Coulomb friction produces dynamic changes of normal stress that depend on the slip function, material properties and direction of rupture propagation. Subsonic propagation in the direction of slip of the compliant solid reduces dynamically the normal stress, whereas propagation in the opposite direction increases the normal stress. Adams [1995] showed analytically that mode II rupture on a bimaterial Coulomb interface has a strong dynamic instability that transfers energy during propagation to shorter wavelengths, leading to pulse sharpening and increasing slip velocity with propagation distance. The discussed effects are pure mode II phenomena on a bimaterial interface, and they do not exist for mode III rupture or in a homogeneous solid. For additional theoretical background, see Ranjith and Rice [2001] and Ben-Zion [2001].

[3] The analytical properties of mode II slip pulse on a bimaterial interface render numerical simulations of such rupture highly challenging. Very fine grid is needed to capture the sharp features associated with the pulse, while large propagation distance is required to reach a dynamic regime that is relatively free of initial transients and reflects the attractor of the evolving dynamic behavior. Andrews and Ben-Zion [1997] simulated mode II ruptures on a bimaterial Coulomb interface with a nucleation consisting of a localized stress drop having a favored propagation direction. They observed wrinkle-like slip pulses with properties compatible to the analytical results of Weertman and Adams. Similar pulses were found in subsequent simulations with increasing refinements and incorporation of additional physical ingredients, including a nucleation mechanism that generalizes the procedure of Andrews and Ben-Zion to a symmetrically expanding source without a preferred direction and slip-weakening friction [Shi and Ben-Zion, 2006].

[4] An assessment of the possible relevance of the wrinkle-like pulse to earthquake dynamics should focus on situations associated with mode II ruptures. Important such cases are large earthquakes on plate-bounding strike-slip faults. These earthquakes (referred to below as the “target” earthquakes) saturate the seismogenic zone, propagate predominately as mode II rupture, and are likely to be affected primarily by the elastic properties of the bounding crustal blocks (rather than the myriad of possible small-scale heterogeneities). As discussed below, the simulations of AH address in a rather limited way the dynamics of the large target earthquakes.

2. Initial Stress

[5] AH show that asymmetric distribution of initial stress can affect the rupture directivity. The same may be found with asymmetric distribution of other model attributes. However, in the absence of a symmetry-breaking mechanism, stress and other physical parameters on a vertical planar fault should be statistically symmetric over space-time scales associated with the large target earthquakes. The only symmetry-breaking mechanism in this problem is the tensile vs. compressive changes of normal stress at the opposite rupture tips on a bimaterial interface [Weertman, 1980]. Simulations of evolving stress histories on a heterogeneous strike-slip fault indicate that large earthquakes occur only when the stress, generated by the numerous small to moderate events and tectonic loading, is relatively smooth [Ben-Zion et al., 2003]. Observed potency-magnitude scaling relations of small and large earthquakes are compatible with those results [Ben-Zion and Zhu, 2002]. The above considerations suggest that a proper initial stress for simulations concerned with large earthquake dynamics is a relatively homogenous distribution.

3. Nucleation

[6] Natural faults are likely to be probed by various nucleation processes including (1) stable crack growth to a critical size, (2) coalescence of distributed microcracks to
a small seed region, (3) failure of a strong asperity/barrier, (4) local pore pressure reaching fracture threshold. AH use a standard nucleation corresponding to (1), while Andrews and Ben-Zion and related later works used a procedure corresponding to (2)–(4). The latter is not necessarily less realistic than the former, as stated by AH.

4. Dimensionality

[7] As mentioned, the dynamic bimaterial effects occur only for mode II rupture. This can be modeled most directly with 2-D in-plane calculations, understood to represent events that saturated the seismogenic zone and continue to propagate as mode II ruptures. Modeling the initial transient regime, where small earthquakes grow as mixed modes II and III, requires 3-D calculations. However, this transient regime is not important for the problem at hand. Moreover, the wrinkle-like pulse becomes progressively stronger (owing to the Adams instability) during continuing propagation of large events as mode II rupture [see, e.g., Ben-Zion and Huang, 2002]. Studies attempting to understand dynamic properties of the wrinkle like pulse should be based on large propagation distance of mode II rupture. The 3-D calculations in section 2 of AH cover only the early transient mixed-modes regime.

5. Numerical Grid Size

[8] The wrinkle-like pulse is associated with small-scale features and the Adams instability reduces dynamically the width of the pulse during propagation of mode II rupture. The grid size used in section 2 of AH is too coarse to resolve the dynamical bimaterial effects, as acknowledged by the authors. If the calculations leading to Figures 2 and 3 of AH are repeated with sufficiently fine grid and larger propagation distance, considerably stronger wrinkle-like pulses will emerge. The employed coarse-grid and mixed-mode regime imply that the results in section 2 of AH have little (if any) relevance to dynamic properties of the large target earthquakes.

6. 2-D Calculations

[9] Section 3 of AH with mode II calculations using finer grid is relevant to the large target earthquakes. The results show a significant wrinkle-like pulse at large propagation distance, although the high-frequency oscillations in Figure 5 suggest that the employed grid and/or constitutive relation are not fully appropriate. We note that the used time-weakening friction has the unrealistic feature that the breakdown-zone size increases with propagation distance, leading to increasing energy absorption at the rupture tip. In contrast, calculations with slip-weakening friction have generally opposite trends and will lead to sharper dynamical features. Incorporating in the simulations rate-dependent friction compatible with lab data is likely to produce strongly asymmetric ruptures.

7. Discussion

[10] The problem of rupture on a bimaterial interface is highly challenging due to the nature of the evolving dynamic fields and physical length scales. The early numerical simulations on this topic considered relatively simple cases corresponding generally to the analytical studies of Weertman [1980] and Adams [1995]. The results showed that rupture along a bimaterial interface can occur as a wrinkle-like pulse with dynamic properties that may be relevant to important aspects of large earthquakes. Following analytical and numerical works clarified the importance of using constitutive laws that regularize the Adams instability, small numerical grid size, and large propagation distance that would allow separation of early transients from long term properties of the evolving fields [e.g., Cochard and Rice, 2000; Ben-Zion and Huang, 2002].

[11] Other works expanded the numerical parameter-space study to investigate effects of additional ingredients that may be important for natural earthquakes. These include slip-weakening friction [Harris and Day, 1997; Shi and Ben-Zion, 2006], stress heterogeneities [Ben-Zion and Andrews, 1998; AH], low-velocity fault zone layer and simultaneous ruptures on multiple planes (G. B. Brietzke and Y. Ben-Zion, Examining tendencies of in-plane rupture to migrate to material interfaces, submitted to Geophysical Journal International, 2005), and dynamic generation of plastic strain in the bulk [Ben-Zion and Shi, 2005]. The results of AH contribute to this broad parameter-space study. However, most of their simulations were done for cases not very sensitive to the dynamic bimaterial effects. The one exception is their 2-D case with large propagation distance and the related results include a prominent wrinkle-like pulse. In contrast to the assertion of AH, a systematic parameter-space study with many model realizations indicates that a material contrast with a drop of friction can have, for realistic ranges of frictional and material contrast values, a favored propagation direction for large earthquakes [Shi and Ben-Zion, 2006]. The broad parameter-space study associated with all the above works indicates that rupture along a bimaterial interface can exhibit a diversity of phenomena. However, the results also show collectively that the ruptures tend to evolve with propagation distance, for ranges of conditions, toward a wrinkle-like pulse with properties similar to those found in the early studies.

[12] Conclusions on the relevance of the wrinkle-like slip pulse to natural earthquakes should come from observations. Rubin and Gillard [2000] observed asymmetric along-strike distribution of aftershocks on the San Andreas fault. Dor et al. [2006a, 2006b] observed asymmetric rock damage across faults of the San Andreas system. The best explanation at present for those results is a statistical preference for wrinkle-like ruptures with preferred or more vigorous propagation direction, since the asymmetries correlate with the velocity structures as predicted for wrinkle-like ruptures, and the measurements were done near-vertical near-straight fault sections.

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References


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