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# Rupture and Healing of Dynamic Fractures

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Major Tasks Addressed: F1, F2

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### Model of Dynamic Fractures in a Continuum

We have constructed a dynamic, antiplane, continuum crack model to explore the problem of the arrest of motion and the final state of stress on a fault and to investigate the organization of earthquakes both on a single fault and on a network of faults. The model is an extension of the classical Kostrov solution[1] to the growth of a planar crack imbedded in an infinite elastic medium, as modified by Chatterjee and Knopoff[2] to allow for faults with arbitrary fracture threshold and prestress. The numerical code is being modified to solve for the seismic history of a fault network. In these models, the stresses are redistributed beyond the edge of a fracture to distances that are scaled roughly by the length of the fracture, with detailed scaling that depends on the actual distribution of stress drops and displacements. This is a fully dynamical model of repetitive fractures in the presence of arbitrary prestress and arbitrary fracture threshold, using, as remarked, a 2-D model of rupture in a 3-D elastic medium. It is comparable in computational speed to existing 1-D dynamical models, thus allowing for the simulation of the evolution of seismicity on a fault network on a tectonic time scale, while taking into account long-range stress redistribution and the dynamic evolution of fractures.

#### Strength Weakening

Our models do not require the introduction of strength-weakening at crack edges simply to circumvent infinities in stress that arise from numerical solutions of the wave equation. Nevertheless there are sound physical reasons for introducing weakening connected with the real process of degradation of frictional strength. Stated another way, though our models are capable of handling the infinite stresses associated with instantaneous stress drops, we know that infinite stresses do not exist in the real world and that therefore instantaneous stress drops do not occur in the real world. Therefore we have undertaken to investigate strength-weakening processes and incorporate our results into our 2-D models.

We have shown that simple slip-weakening and velocity-weakening laws are not viable alternatives to the instantaneous stress-drop problem. First, Knopoff and Landoni have shown that quasistatic strength-weakening laws that depend linearly on velocity or slip lead to nonphysical results in 2-D dynamic antiplane systems [3]. We have found that similar conclusions hold for 1-D problems as well.

Second, we have shown from simple scaling arguments for self-similar cracks, that slip- and velocity-weakening laws that are independent of crack length result in nonphysically-high stresses for the largest earthquakes. As a self-similar crack grows in length  $L$ , the slip-weakening or velocity-weakening zone of width,  $D$ , at the edge of the crack shrinks. Maximum stress outside the rupture zone scales as a function of  $L/D$ , and thus becomes arbitrarily high as the crack continues to grow. However, if self-healing slip pulses of length,  $L_{max}$ , occur on cracks whose lengths are greater than  $L_{max}$ , then stress outside the rupture front can remain well-constrained. There is no *a priori* reason to assume that the presence of a weakening law guarantees the existence of a healing mechanism that must lead to the generation of slip pulses for large earthquakes. However, the above scaling argument provides an important constraint: *a strength-weakening law that is independent of crack length can*

*exist only if it is inextricably coupled to a healing law that guarantees the generation of slip pulses on a crack whose length is greater than some maximum.*

This constraint holds not only for weakening laws that cause  $D$  to shrink as  $L$  increases, but more generally, for any weakening law that leads to  $D \sim L^\alpha$  where  $\alpha < 1$ , including the case where  $D$  is a constant. On the other hand, weakening laws that guarantee that the width of the weakening zone scales with the length of the crack are not constrained by this condition, since  $L/D$  is now well bounded.

We have incorporated a weakening law into our 2-D model in which stress drop increases linearly from zero to some maximum as a function of distance from the edge of the crack. This law, though not ideal, is compatible with elastodynamics, whereas, as we have seen, linear slip- and velocity-weakening laws are not. We have solved two cases: the first, in which the weakening distance is constant, and the second, in which the weakening distance scales with the length of the crack. We solve the problem of a homogeneous crack of arbitrary length bounded by a barrier of linearly-increasing strength. In the dynamic solutions, the crack is able to penetrate some distance into the barrier; the depth of penetration depends on the slope of strength increase at the barrier.

In the case where the weakening zone does not scale with the length of the crack we found that we could not find any cases such that the final stress at the edge of the crack, after all motion had ceased, was less than the local breaking strength, as can be expected from the scaling argument given above. In the case where the weakening zone scales with the length of the crack, we can, on the other hand, construct solutions such that the final state of stress was everywhere less than the breaking strength, including at the crack edges.

The latter result, however, is not robust with respect to choice of fault parameters, which casts suspicion on the validity of the weakening law employed. Further, the weakening law was chosen more for ease of incorporation into our model than by any physical argument. More physically-reasonable expressions for weakening must be found.

## **Healing**

We use the 2-D model to investigate the arrest of slip and the final state of stress in problems of interest to earthquake investigation. We adopt the familiar arrest criterion that slip ceases when the particle velocity reaches zero.

We have previously shown that, in the absence of velocity weakening, motion is arrested on a bilaterally-growing crack only after reflected stress waves from two strong barriers converge at an interior site on the crack; encounter with a single barrier is not enough to arrest motion on these 2-D faults.

Further we have solved for the problem in which a gap between fault segments acts as a temporary barrier that may initiate healing in the interior of the first segment to break, prior to breakout into the second segment. The final state of slip and stress in these problems depends on how quickly fracture strength is restored once motion ceases, since, depending on the answer to this question, motion on the first segment may or may not be re-excited by breakout into the second segment. Comparisons of our model with both the 1992 Landers and 1995 Kobe earthquakes strongly suggest that the majority of fracture strength in large

earthquakes is restored within a few seconds of cessation of motion.

New work has been done to understand how various strength-weakening and friction-restrengthening laws affect the arrest of slip and the final state of stress of a dynamic fracture. We have shown that in the presence of certain restrengthening laws, healing need not wait for the convergence of stress signal from two barriers, but can be initiated at the advancing crack edge after an encounter with a local barrier. Those results were obtained for a problem with instantaneous stress drop in the breakout phase, but with the existence of a small positive healing velocity,  $\dot{u}_c$ , on the deceleration phase, below which frictional strength was restored to the value of the static friction. Further investigation has shown, however, that full restoration of strength to the static friction level at any non-zero healing velocity is nonphysical and cannot tell us anything about the general strength-weakening and healing problem.

To illustrate the difficulty, in figure 1 we show the loci of growth and healing of a homogeneous crack that encounters unbreakable barriers, together with the final stress on the crack for the cases (a)  $\dot{u}_c = 0$  and (b)  $\dot{u}_c = \epsilon$  in the limit  $\epsilon \rightarrow 0$ . The two solutions should converge in the limit  $\epsilon \rightarrow 0$ ; however, they do not converge. Indeed the stress in the second case contains an infinite stress drop at the point where the stress waves from the two barriers collide. Thus the set of allowable friction-restrengthening laws must exclude formulations in which static friction is fully restored while the particle is still in motion: healing must be progressive.

The above friction law, in which stress drops instantaneously at zero velocity on the acceleration phase, but restrengthenes at  $\dot{u}_c$  on the healing phase is also nonphysical because it involves a larger characteristic velocity in the deceleration phase than existed in the acceleration phase. In other words, friction cannot restrengthen at a velocity greater than that at which it became fully weakened. Any violation of this principle will lead to nonphysical results similar to those shown in figure 1.

For velocity-weakening/restrengthening laws that do not violate either of these two principles, we have shown, at least qualitatively, that a crack will not begin to heal instantaneously upon encounter with a barrier.

We have also solved the problem in which all of the stress drop is concentrated in a narrow asperity zone in which the crack nucleates, breaks out into a low-strength region, and is halted by unbreakable barriers. These barriers can be thought of as neighboring asperities that the dynamic crack was unable to break. Figure 2 shows the loci of the growth and healing loci for this asperity problem. Healing in these cases initiates at the edge of the crack, but not immediately upon encounter with the barrier; healing initiates after a time delay comparable to  $W/c$  where  $W$  is the width of the asperity and  $c$  is the shear wave velocity. Healing then spreads to the interior of the crack. A separate healing front can initiate independently in the center of the crack and spread bilaterally, as in the homogeneous problem. The crack comes to complete rest when the two healing fronts meet. The final stress drop in this problem is not homogeneous, but is highly peaked in the vicinity of the asperity. For extremely narrow asperities, we find that the ratio of energy to moment release is up to six times higher for the asperity problem as compared to the homogeneous problem.

## References

- [1] B.V. Kostrov, *J. Appl. Math. Mech.*, **30**, 1241-1248 (1966).
- [2] A.K.Chatterjee and L. Knopoff, *Geophys. J. Roy. Astron. Soc.* **73**, 449-473 (1983).
- [3] L. Knopoff and J. A. Landoni, submitted 1998, *Geophys. Res. Lett.*

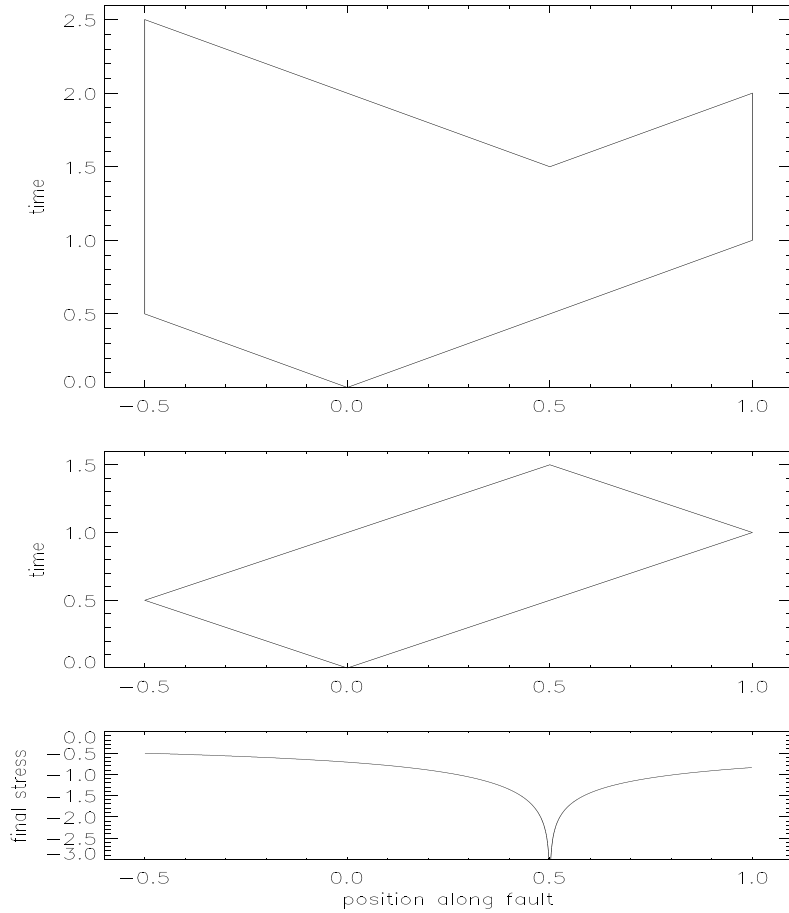


Figure 1: Non-convergence of dynamic solutions for restrengthening at infinitesimal velocities. **(a)** Growth and healing loci for a homogeneous crack bounded by unbreakable barriers at  $x = -0.5$  and  $x = 1.0$ . Frictional strength is restored to the static friction exactly when  $\dot{u} = 0$ . Healing starts in the interior of the crack and spreads to the edges. Final stress is homogeneous everywhere in the ruptured region; it is not shown here. **(b)** Growth and healing loci for the same homogeneous crack as in (a) except that frictional strength is restored at  $\dot{u} = \epsilon$  in the limit  $\epsilon \rightarrow 0$ . This solution does not converge to the case presented in (a). **(c)** Final stress for the crack in case (b). Final stress becomes infinitely negative at the point where the two healing fronts intersect.

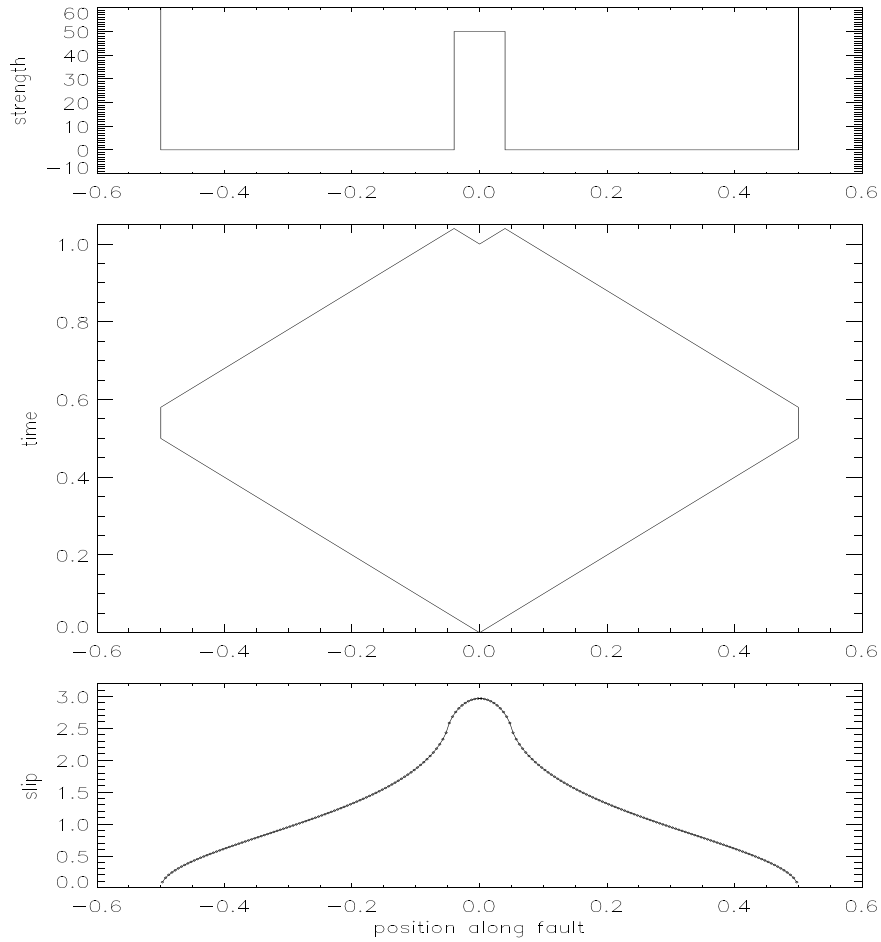


Figure 2: **(a)** Fracture strength for a fault dominated by a central asperity. Prestress is everywhere equal to the the fracture strength. **(b)** Growth and healing loci of the asperity problem. The crack initiates in the asperity and grows unimpeded to the outer barriers. Healing begins at the barriers after a time delay scaled by the width of the asperity. A separate healing front initiates in the center of the crack due the combination of the stress reflections from the two barriers. **(c)** Final slip on the fault. Slip is concentrated in the vicinity of the high-stress-drop asperity, leading to a higher energy-to-moment ratio than is typical for a homogeneous crack.