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**Faulting with Dynamically Self-Chosen Rupture Paths  
and Non-Planarity in Complex Fault Systems**

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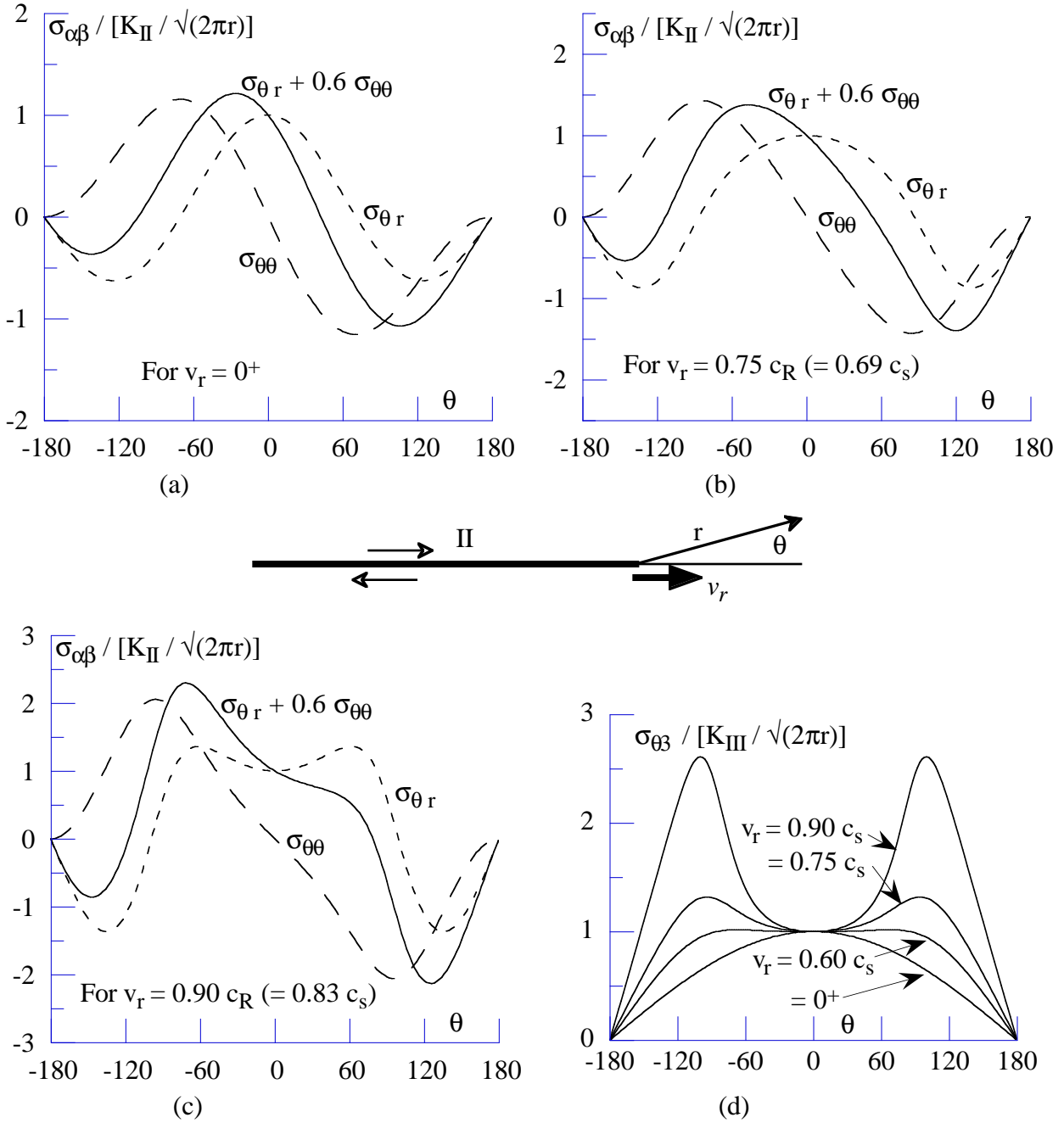
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(studies with Michael Falk, Alexei Poliakov, Renata Dmowska and Nobuki Kame)

The aim is to understand the factors which control how faults choose to follow a geometrical complexity like a branch or kink in rupture path, e.g., from an intersection with another fault, and how rupture on a major fault interacts with the damaged border zone which will generally exist alongside it. In addition to trying to develop a basic conceptual understanding, we are devising numerical rupture dynamics procedures to address such features as non-planarity of fault surfaces, step-overs in fault networks, smaller faults or fractures in the region bordering a main fault zone, and simultaneous activation of competitive rupture paths. The focus is on methodology in which the rupture path is not specified a priori but, rather, is dynamically self-chosen as the rupture moves through a geometrically complex fault system.

***Development of high dynamic stressing off the main fault plane, fault encounters with bends and branches, and induction of secondary faulting in damaged border zones:*** We have studied singular elastic crack models and non-singular slip-weakening models for which the residual dynamic shear strength  $\tau_r$  on the fault can be considered as effectively constant at distances from the rupture tip larger than the slip-weakening (process) zone size (Dmowska et al., *EOS* 2000; Poliakov and Rice, *EOS*, 2000). An important feature is growth of the maximum off-fault shear stress with an increase of velocity of rupture propagation  $v_r$ . High off-fault stress may contribute to the explanation of the following: (i) secondary faulting (activation of damaged border zone, like observed along the exhumed San Gabriel and Punchbowl faults), (ii) bifurcation of fracture path onto a branching fault (Johnson Valley to Landers faults) or co-propagation on both the original and branched faults (1979 Imperial Valley and Brawley faults), (iii) jump of a rupture to a sub-parallel segment (Landers and Izmit events), and (iv) intermittent propagation and possible self-arrest of a rupture as  $v_r \rightarrow c_{lim}$ .

A dip slip rupture can be approximated by a mode III crack at its ends along strike; a strike slip rupture by a mode II crack. Thus a start is to compare Coulomb stress changes ahead of crack tips for those two crack types. Fig. 1 shows plots, based on the  $1/\sqrt{r}$  part of the crack tip singular field only, of stresses that could control kinking onto a sub-fault which bends away from the main fault. Evidently, these effects become very large as  $v_r \rightarrow c_{lim}$ . We expect that the singular field, or field very close to the rupture tip, will largely determine whether the path begins to follow a kink. Thus from Fig. 1 the extensional side of a mode II fault is most favored for kinking, although at high speeds kink paths to either side see substantial Coulomb shear stressing. However, our evaluation of stresses at larger distances suggest that the initial stress state is also decisive for determining whether the process, once started, can be continued along the kink direction. In general we find that stress states with high fault-normal compression ( $-\sigma_{yy}^o$ ), i.e., with  $(-\sigma_{yy}^o) > (-\sigma_{xx}^o)$  where  $x$  is fault-parallel, favor continued growth on the extensional side of the rupture whereas those with  $(-\sigma_{yy}^o) < (-\sigma_{xx}^o)$  favor growth on the compressional side.



**Fig. 1.** (a), (b) and (c): Dynamic crack tip singular fields, for right-lateral mode II rupture at different rupture speeds  $v_r$ . Shear and tensile stress amplitudes along potential bend faults at angle  $\theta$ , and their Coulomb combination with  $f = 0.6$ , are shown. (d): Dynamic singular fields for mode III at different  $v_r$ .

To study the location and directions of highest stressing on secondary faults bordering a major fault zone, we have determined, for the particular slip-weakening model (i) isolines of the maximum ratio of shear stress to Coulomb shear strength for the local rupture-altered stress state, and (ii) directions of potential fractures (planes on which that ratio is maximum) around a crack tip. This augments a study by Rubin and Parker (USGS Open File Rpt. 94-228). For both rupture modes

we found that the zone of potential secondary faulting is very sensitive to  $\sigma_{xx}^o / \sigma_{yy}^o$ , and that it (i) contracts in front of the rupture while (ii) it stretches in the direction perpendicular to the main fault as  $v_r \rightarrow c_{lim}$  and (iii) decreases (in all directions) with an increase of  $\tau_r$ . At low  $\tau_r$  (relative to the slip-weakening strength drop  $\tau_p - \tau_r$ ), directions of the secondary faults tend to be perpendicular to the main fault, and for high  $\tau_r$  they tend to be parallel. The main difference between modes is an asymmetry of secondary faulting for mode II compared to symmetrical faulting for mode III. Our calculations predict activation of faults in the damage zone of the size in the range of  $(0.1 - 1) \omega_o$  in vicinity of the main fault, where  $\omega_o$  is the slip-weakening zone size at low propagation speeds.

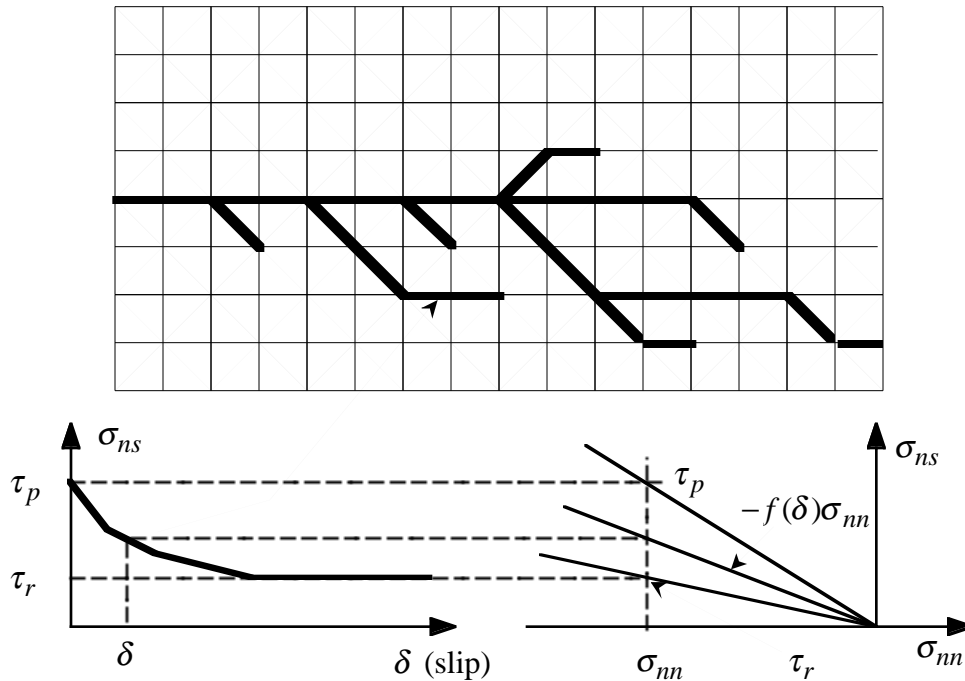
The study is in preparation for the next step of numerical modeling of spontaneous activation of kink paths and secondary faulting during dynamic rupture. For that we are developing two approaches. One involving a finite element approach is described next. Another is work with postdoctoral fellow N. Kame, who has developed elastodynamic boundary integral equation methods that can be applied for faults with non-planar, possibly branched, paths.

***Finite element methodology with self-chosen rupture paths and interactions with damaged fault border zone:*** We have developed a version of the Needleman cohesive surfaces finite element program (e.g., Xu and Needleman [*J. Mech. Phys. Solids*, 1994]). This has so far been done for tensile cracking (Falk, Needleman and Rice [*5th Europ. Mech. Mat. Conf.*, 2001]), to try to duplicate known results as a first step. The aim is to use such methodology to study dynamic interactions of a shear rupture with the damaged (fractured, faulted) border zone along major faults. Chester et al. [*JGR*, 1993] and Chester and Chester [*Tectonophys.*, 1998] have identified such regions along the exhumed traces of the San Gabriel and Punchbowl faults. The approach employs triangular finite elements in 2D, or tetrahedral in 3D, and allows each element boundary, or some subset of them, to be a potential surface of failure. That is, nodes at the ends of the boundary segment are actually pairs of nodes which can displace relative to one another so that a certain weakening constitutive relation between the tractions and relative displacements is met. This is a coupled relation between the tensile and shear stress, and the opening and slip displacement discontinuities, as a kind of generalized slip-weakening, in seismological terminology. It is satisfied in weak form, in the sense demanded by insisting on validity of the principle of virtual work for all displacement fields consistent with the finite element interpolations.

This approach allows the rupture path to be self-chosen in the calculation, rather than prescribed a priori. It had predicted results for onset of spontaneous side branching from a rapidly growing tensile crack which have some resemblance to observations (e.g., Sharon and Fineberg [*Phys. Rev. B*, 1996]). In the tensile crack case, that is the key to explaining why the (average) rupture speed never reaches the theoretical limit of  $c_R$ , except when weak planes are present, and why the velocity of rupture propagation becomes severely oscillatory. If possible to be extended to shear faulting, the approach may contribute to understanding why ruptures have the speeds that they seem to have from slip inversions, typically 0.7 to 0.9  $c_s$  (but with occasional inference of super-shear propagation), and may provide a mechanism for a severely unsteady instantaneous rupture speed, with implications for strong ground motion and perhaps also for explaining how ruptures can stop in the absence of a strong barrier.

We have been modifying the original Needleman formulation in two ways: First, his formulation includes an initially linear, stable, part of the constitutive relation between tractions and relative displacements, before larger displacements in the unstable weakening range are reached. This is convenient numerically but results in the unpleasant feature that as element size is reduced towards zero, all of the elastic compliance of the medium is contributed by the spring-like linear behavior at the element boundaries. We have developed a method in which there is precisely zero slip or

opening displacement at the element boundaries until a threshold stress condition is reached. This requires writing new routines which check for the magnitude of all force components between node pairs that could potentially slip or open relative to one another at the start of each time step, and checking to see if the threshold condition has been overreached. This has actually led to a major conceptual puzzle, because the results are unexpectedly different from those of the original Needleman procedure. Although an array of element boundaries does partially fail near a fast-moving tensile crack tip, the crack never shows macroscopic branching like in the previous formulation (Falk et al., [ibid]). The second modification, on which postdoc A. Ploiakov has been working, is to introduce frictional failure within the Coulomb framework into the procedure. The basic concepts are illustrated in Fig. 2, although it is emphasized that the figure is only a schematic and a working code is not yet available. This will not have reached a mature stage at the time of his pending departure and other group members will continue the work.



**Fig. 2** Schematic of finite element grid in which rupture paths are dynamically self-chosen, because each element boundary (or some selected subset of them, defining a network of faults) is a potential surface of slip-weakening failure. Here  $\sigma_{nn}$  and  $\sigma_{ns}$  are normal and shear stress on an element boundary, and  $\sigma_{ns} = -f(\delta)\sigma_{nn}$  during weakening, at least if  $\sigma_{nn} < 0$ .

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