INTRODUCTION

High stress concentration close to a dynamic rupture front can produce rock damage (reduction of elastic modulus) in the material surrounding the fault. Off-fault yielding and energy absorption in the damage process should reduce the amplitude of the ground motion. However, the reduced elastic modulus in the damaged zone can amplify locally the motion and create a waveguide that may allow the motion to propagate with little geometric attenuation. In addition, the asymmetric damage generated in the slip mode may produce bimaterial interfaces that might be observable in the field. Previous studies incorporated plastic yielding in simulations of dynamic rupture (Andrews, 1975; Lyakhovsky et al., 1997). We show two cases $\Psi_c = 1.4^{10}$ and $\Psi_c = 5.6^{10}$: both $\Xi \pm 1$. The damage variable $\Psi_c$ increases with the amount and extent of damage, and requires increasing $\Psi_c$ in order to avoid loss of continuity. Slip is normalized by $D_f$, distances by $x/D_f (\mu / (\mu_s - \mu_g))$, and times by $\mu_s / (\mu_s - \mu_g)$. A novel feature of the present study is the inclusion of a bimaterial interface.

CONTINUUM DAMAGE MODEL

We adopt the continuum damage formulation by Lyakhovsky et al. (1997) including damage-related plasticity as introduced by Hamid et al. (2006) and modified for 2D plane strain. The free and second-constant of the 2D elastic strain tensor are defined as $\varepsilon_1 = \varepsilon_1 + \varepsilon_2$ and $\varepsilon_2 = \varepsilon_1 + \varepsilon_2$, respectively. A strain invariant is defined as $\varepsilon_1 = \sqrt{\varepsilon_1 \cdot \varepsilon_1}$. The following non-linear stress-strain relation is assumed:

$$\sigma_{ij} = (\lambda + \gamma e) \varepsilon_1 \delta_{ij} + (2\mu - \gamma e) \varepsilon_{ij}$$

where $\gamma$ is an additional elastic modulus. The elastic moduli depend on a scalar damage variable, $\omega$, that varies between $0 \leq \omega \leq 1$ (unbroken and $\omega = 1$ otherwise). The evolution equation for the damage variable is

$$\dot{\omega} = \omega(1 - \omega)\varepsilon_{ij} $$

(4)

The total strain is the sum of an elastic and a plastic contribution, $e = e^p + e^p$. The evolution of the plastic strain is driven by the damage variable:

$$\dot{E}_{pl} = \varepsilon_{ij} C_{pl} \varepsilon_{ij}$$

where $\varepsilon_{ij} = \varepsilon_{ij} - \frac{e_{ij}^d}{\Xi}$ is the deviatoric part of the stress tensor. The parameter $C_{pl}$ is of order $1/10$ and is related to the seismic coupling coefficient $0 < \Xi < 1$ by

$$C_{pl} = \frac{1 - \gamma}{\mu} $$. 

(5)

SLIP WEAKENING DYNAMIC CRACKS

We consider a planar fault governed by linear slip weakening friction. $\mu(D) = \max(\mu_e, \mu_s - (\mu_s - \mu_g) D/D_s)$, with $\mu_e = 0.6$ and $\mu_g = 0.1$. The initial conditions are defined by the angle $\Psi$ between the maximum principal stress and the fault plane, and by the strength excess parameter $\Psi_c = (\mu_s - \mu_g)/(\mu_s - \mu_g)$. We show two cases $\Psi_c = 1.4^{10}$ and $\Psi_c = 5.6^{10}$: both $\Xi \pm 1$. The distance between two consecutive events is set to $x = 1/10 (\mu_s - \mu_g)$ and the plasticity parameter is $C_{pl} = \mu_g/(\mu_s - \mu_g)$.

VELOCITY WEAKENING DYNAMIC PULSES

We consider now a fault governed by a rate and state dependent friction law, with strong velocity weakening at high slip rates ($\alpha = 1/\nu$), and regularization by a direct effect (Ampuero and Ben-Zion, 2008). The damage variable $\omega$ for $\Psi = 1.4^{10}$ and $\Psi = 5.6^{10}$: both $\Xi \pm 1$. The dependence on $\Psi$ is consistent with theoretical expectations (Pollak and et al., 2002):

$$\dot{\omega} = \frac{\varphi}{1 + \nu/\nu_c} + \frac{1}{1 + \varphi/\nu_c}$$

and $\varphi = \nu/\nu_c$. Slip-weakening and velocity-weakening are limit cases (high and low $\alpha$). The expression shown below has strong velocity-weakening, and results in saturated pulse-like rupture. Rupture is triggered by a slightly overestimated pulse.

NUMERICAL METHOD

We implemented the continuum damage constitutive law in SEM2DPACK (Ampuero, 2008), a 2D spectral element code for seismic wave propagation and earthquake dynamics. The spectral element method is a high order spatial discretization technique that inherits the geometric flexibility of the finite element method and the accuracy of spectral methods. The practical implementation is analogous to that of any explicit time-marching finite element method.

SUMMARY AND PERSPECTIVES

- We have successfully implemented a continuum damage rheology in a 2D spectral element code, to explore the role of off-fault rock damage in earthquake dynamics.
- Slip-weakening crack ruptures show self-similar growth of the off-fault damage zone and reduction of peak slip velocity and rupture speed, as also observed in simulations with viscous damping. Dynamics indicate that the off-fault damage zone can have wave speeds much lower than $3/10$.
- We show here limited to moderate damage (before loss of connectivity). Further extension through an additional plastic mechanism will allow to unravel stronger effects. Intriguingly, in simulations that reached loss of connectivity, failure was preceded by detachment of a daughter pulse from the main rupture front, reminiscent of a wrinkle-like pulse detachment mechanism operating in bimaterial faults. Actually, dynamic damage generates locally a bimaterial interface.

References