Interaction between earthquake rupture and dynamic off-fault damage

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Earthquake source dynamics: the standard modeling approach

Planar strike-slip fault

Slip-weakening friction

Initial stress $\sigma_0(x,z)$

Basic ingredients:
- linear elastic medium (wave equation)
- a pre-existing fault (split nodes)
- **Friction**: a non linear relation between fault stress and slip (a mixed boundary condition)
- initial conditions (stress)

$G_c = \text{fracture energy}$
Earthquake source dynamics: the standard modeling approach

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Slip-weakening friction

$G_c = \text{fracture energy}$
Poorly known earthquake physics

Laboratory friction experiments

Missing fault constitutive law!
+Scaling problem

San Andreas fault

Which physical processes are dominant?
- Friction
- Dynamic damage around the fault
- Thermal pressurization of fault zone fluids
- Dilatancy of the fault gouge
- Flash heating, melting, lubrication
- …
Typical structure of a fault zone from field observations of exhumed sections of the San Andreas fault (Chester et al.)

Direct observation of the structure of an active fault zone: geophysical borehole across the Nojima fault (Japan)

When was the fault zone damage generated?

- during the initial stage of fault formation and growth (geological time-scales)
- or during earthquakes (dynamic time-scales)

How much of the apparent fracture energy goes into off-fault damage?
(e.g. new fracture surfaces)
Chester et al. (Nature, 2005) “Fracture surface energy of the Punchbowl fault, San Andreas system”

Total “fracture” energy ~ 300 seismological estimates
Product of many events? (here $10^4$)
Account for healing?
Linear elastic fracture mechanics (LEFM) predicts a stress singularity at the rupture front. The stress concentration must be physically accommodated by nonlinear material behavior (damage, plasticity, micro-fractures).

Kostrov, Freund, Husseini, Kikuchi, Ida, Andrews (60-70s)
Predictions from a steady pulse rupture model (Rice, Sammis and Parsons, 2005)

Characteristic size of off-fault damage zone:

\[ R^*_o = \frac{9\pi F(0)}{16} \frac{\mu G}{(\tau_p - \tau_r)^2} = \frac{9\pi}{16(1 - v)} \frac{\mu G}{(\tau_p - \tau_r)^2} \]

Estimates range from 1m to 1km

Contours of Coulomb stress outside the fault plane (>1 means failure)

Shear failure zone

Tensile zone
Laboratory mode I rupture (opening) in plexiglas with controlled energy flux.

Wilson et al. (Nature, 2005) “Particle size and energetics of gouge from earthquake rupture zones”
Reches and Dewers (EPSL, 2005) “Gouge formation by dynamic pulverization during earthquake rupture”

Fracture zone of the Bosman fault, a new fault in a deep South African mine (M3.7, max slip 0.4 m): coalescing fractures filled with gouge powder

Measured grain size distribution + multiple fracture branches
→ surface energy ~ 2-10 MJ/m²
Modeling of secondary micro-cracks generated by dynamic ruptures

Figure 8. Two perspectives of the final stage of crack evolution for the 2000 Tottori earthquake dynamic simulation. The gray surface represents the shear crack on the pre-existing fault, and the dashed lines represent the tensile cracks.


Yamashita (2000)
Strain weakening visco-plasticity outside the fault plane

Only $\frac{1}{4}$-medium is shown

The thickness of the dissipation zone increases as the rupture grows → the “apparent” fracture energy increases with rupture length

Andrews 2005
Linear elastic fracture mechanics (LEFM) predicts a stress singularity at the rupture front. The stress concentration must be physically accommodated by nonlinear material behavior (damage, plasticity, micro-fractures).

A perspective from fracture mechanics

Kostrov, Freund, Husseini, Kikuchi, Ida, Andrews (60-70s)
Continuum damage rheology (Lyakhovsky et al, 1997; etc)

Assumptions in deriving constitutive equations for damage:
- A damage parameter $\alpha$ represents micro-crack density: from $\alpha=0$ intact rock, to $\alpha=1$ completely damaged rock
- Represent the effect of diluted micro-cracks on elastic energy by effective medium theory
- Linear relation between elastic moduli and $\alpha$
- Mohr-Coulomb yield criterion for the onset of damage
- Kinetic evolution of $\alpha$ consistent with energy conservation and positive entropy production
- Damage-induced plastic deformation

Features:
- Evolving elastic moduli
- Different moduli in compression and tension
- Damage-induced anisotropy
Continuum damage rheology
(Lyakhovsky et al, 1997)

- Non-linear stress-strain relation:

\[
\sigma_{ij} = (\lambda - \gamma/\xi) I_1 \delta_{ij} + (2\mu - \gamma\xi) \epsilon^{e}_{ij}
\]

- Elastic coefficients linearly related to damage variable

\[
\begin{align*}
\lambda &= \lambda_0 \\
\mu &= \mu_0 + \gamma_r \xi_0 \alpha \\
\gamma &= \gamma_r \alpha
\end{align*}
\]

- Damage evolution and damage-related plasticity

\[
\dot{\alpha} = \begin{cases} 
C_d I_2 (\xi - \xi_0) & \text{if } \xi > \xi_0 \\
0 & \text{otherwise}
\end{cases}
\]

\[
\dot{\epsilon}^{p}_{ij} = \begin{cases} 
\tau_{ij} C_v \dot{\alpha} & \text{if } \dot{\alpha} \geq 0 \\
0 & \text{otherwise}
\end{cases}
\]

\[
\tau_{ij} = \sigma_{ij} - \frac{1}{3} \sigma_{kk} \delta_{ij}
\]
Continuum damage outside the fault

Dynamic simulations with a 2D spectral element code (Ampuero et al, SSA 2008) : slip-weakening fault (crack-like rupture) and off-fault damage

Slip rate damped by off-fault dissipation

Dynamically generated bimaterial effect on fault normal stresses
Continuum damage outside the fault

Dynamic simulations with a 2D spectral element code (Ampuero et al, SSA 2008)

Velocity-weakening fault (pulse-like rupture) and off-fault damage

Pulse-like ruptures are generally more sensitive to local fluctuations than crack-like ruptures

Dynamic off-fault damage changes the stability of pulse ruptures and reduces peak slip rate
Off-fault dissipation and rupture on non-planar faults

SEM dynamic rupture on non-planar faults (Madariaga and Ampuero 2005)

With off-fault visco-plasticity (Duan and Day 2008)
Interesting problem: rupture branches out spontaneously when not guided by a weak fault plane
Conclusions

Off-fault anelasticity results from stress concentration at the rupture front, and can’t be avoided unless other mechanism limits rupture speed (e.g. heterogeneities)

Important feedbacks:
- the energy dissipated outside the fault can modify rupture properties: reduces rupture speed and peak ground motions
- Damage is asymmetric and can dynamically generate a bimaterial fault

Some open questions:
- Reliability of field estimates of off-fault dissipated energy
- Off-fault constitutive laws: require laboratory experiments under dynamic conditions
- Coupling to other processes (fluid and thermal coupling)
- Effect of multiple cycles, or pre-existing damaged zones

Computational challenge: strain localization and mesh-dependency