Experimental study of the role of heterogeneities in the rupture propagation

Mélanie Grob

Jury:  Mokhtar Adda-Bedia  Christian Marlière
      Patrick Baud  Luis Rivera, co-director
      Knut Jørgen Måløy  Jean Schmittbuhl, director
Collaborations:

Renaud Toussaint (IPG Strasbourg)
Knut Jørgen Måløy (Physics Institute, U. of Oslo)

Post-docs
Stéphane Santucci (Physics Institute, U. of Oslo; ENS Lyon)
Olivier Lengliné (IPG Strasbourg, 2009)
Guillaume Daniel (IPG Strasbourg, 2008)

Technical support
Alain Steyer
Rupture observation

Slip distribution of 1999 Izmit, Turkey, earthquake
Bouchon et al. (BSSA, 2002)

Fracture interface
Bouchaud (J. Phys, 1997)

mode I (opening)

mode II (shear)

µm scale
Rupture modelisation

In both cases:

- Fractures along favoured surfaces ⇒ weak planes
- Fluctuations of mechanical properties along plane
- Rough shape of coseismic slip and rupture front

2D plane shear rupture

\[ \delta (y,t) \leftrightarrow a (x,t) \]
\[ \tau (y,t) \leftrightarrow G (x,t) \]
\[ \tau_c (y,\delta(y,t)) \leftrightarrow G_c (x,a(x,t)) \]

\[ \tau = \text{shear stress} \]

\[ G = \text{fracture energy} \]

Schmittbuhl et al. (PAG, 2003)
Can fracture mechanics be inferred from analysis of crack front morphology?

What are the links between small and large scales?

Can small scale heterogeneities lead to large scale heterogeneities?

How do heterogeneities influence rupture propagation?
To try to answer these questions:

- **Optical and acoustic monitoring of a crack propagation along a heterogeneous interface**

- **Analysis of fixed crack front morphology at high spatial resolution**

- **Analysis of crack front dynamics during its propagation**
Outlines

- Issue
  - Morphology of fracture fronts
  - Dynamics of rupture propagation

- Experimental setup
- Results on morphology
  - scaling analysis $\Rightarrow$ self-affinity of crack fronts
- Results on dynamics
  - scaling law distributions of velocities and acoustic emissions (AE)
- Comparison between experimental and large scale data
  - clustering of events in both cases
- Conclusions and perspectives
Experimental setup
Experimental setup

- Microscope
- Force sensor
- Linear array of acoustic sensors
- Sample

**Issue**  
Setup  
Morphology  
Dynamics  
Comparison  
Conclusions
Experimental setup

4 observation data
- Displacement (imposed ⇒ stable propagation)
- Force
- Images
- Acoustic emissions
Sample preparation

Plexiglas plates → disorder introduction → superposition → \( \sigma_N = 2 \text{ MPa} \)

Sample preparation

Annealing

Opening
Sample preparation

Issue: Too high temperature!!

Setup:

Morphology: crack front

Dynamics:

Comparison:

Conclusions:

before

after

Too high temperature!!
Front extraction

image in gray

histogram of gray levels

thresholded picture

threshold

norm of gradient

front extracted
Front extraction
Static experiments

Loading to make front advance
Unloading to take high resolution pictures of front at rest
Dynamic experiments

Loading for the duration of experiment at constant speed
Lots of images taken at high acquisition rate ($\approx 1000$ frames / s)
Front morphology analysis

height

width

0  2000  4000  6000  8000  10000  12000  14000  16000

0  500  1000  1500  2000  2500  3000
Roughness measurement

\[ \Delta y(\delta) = y(x+\delta) - y(x) \]

- Root Mean Square (RMS)

\[ \sigma(\delta) = \left( \Delta y^2(\delta) \right)^{1/2} \]
Scaling law
⇒ Self-affine structure = front shape statistically invariant under an affine transformation
\[ d_x \rightarrow \lambda_x \ d_x \ , \ d_y \rightarrow \lambda_y \ d_y \]

⇒ Determination of a roughness exponent $\zeta$

\[ \langle \sigma(\delta) \rangle_{x_0} \propto \delta^{\zeta} \]
Roughness measurement

\[ \zeta \approx 0.6 \]

Måløy & Schmittbuhl (PRL, 1997)
Delaplace et al. (1999)
Roughness measurement

$\zeta_+ = 0.35$

$\zeta_- = 0.6$

$\Rightarrow$ 2 roughness exponents
Roughness measurement

Result independent of parameters from:

- Image processing (threshold value for front extraction...)
- Optical acquisition (resolution = images taken with different magnifications of the microscope...)
- Disorder introduction procedure (sand-blasting with various beads, chemical...)
- Statistical method used to analyse the front morphology
Effects of threshold

- Issue
- Setup
- Morphology
- Dynamics
- Comparison
- Conclusions

Gray levels

- Nombre de pixels
- Gray levels

- y (mm)
- x (mm)

- -15
- -10
- -5
- seuil
- +5
- +10
- +15
Effects of threshold

\[ \zeta_+ = 0.35 \pm 0.06 \]

\[ \zeta_\gamma = 0.67 \pm 0.05 \]
Effects of resolution

\[ a = 3.8 \mu m = \]

\[ a = 2 \mu m \]

\[ a = 1 \mu m \]

\[ a = 0.5 \mu m \]

- 3.8 \mu m
- 2 \mu m
- 1 \mu m
- 0.5 \mu m
Effects of resolution

\[ \zeta_+ = 0.35 \pm 0.05 \]

\[ \zeta_- = 0.62 \pm 0.04 \]

\[ \zeta_- = 0.57 \pm 0.04 \]
Effects of disorder

\[ \zeta_+ = 0.34 \pm 0.04 \]
\[ \zeta_- = 0.23 \pm 0.05 \]
\[ \zeta_+ = 0.46 \pm 0.05 \]
\[ \zeta_- = 0.60 \pm 0.05 \]
\[ \zeta_+ = 0.33 \pm 0.06 \]
\[ \zeta_- = 0.56 \pm 0.06 \]
\[ \zeta_+ = 0.34 \pm 0.05 \]

log$_{10}(\sigma)$ vs. log$_{10}(\delta)$ graph with data points and linear fits. Notations for data markers:
- `*` chimique
- `△` chimique
- `≈ 300 µm`
- `200 µm`
- `50 µm ; a=3.8µm`
- `50 µm ; a=1µm`
Coherence of roughness measurement methods

- **Maximum-Minimum (MM)**
  \[
  \Delta(x_0, \delta) = \max_{x \in [x_0, x_0+\delta]} (y(x)) - \min_{x \in [x_0, x_0+\delta]} (y(x))
  \]
  \[
  \langle \Delta(\delta) \rangle_{x_0} \propto \delta^{\zeta}
  \]
  Schmittbuhl et al. (PR E, 1995)

- **Structure functions (SF)**
  \[
  C_k(\delta) = \left\langle \left| y(x+\delta) - y(x) \right|^k \right\rangle^{1/k}
  \]
  \[
  C_k(\delta) = \delta^{\zeta_k}
  \]
  Halpin-Healy (PR A, 1991)

- **Power spectrum (PS)**
  \[
  P(k) = \text{TF of } w(\Delta x) = \langle y(x+\Delta x)y(x) \rangle - \langle y(x+\Delta x) \rangle \langle y(x) \rangle
  \]
  \[
  P(k) \propto k^{-1-2\zeta}
  \]
  Schmittbuhl et al. (1995)

- **Average Wavelet Coefficient (AWC)**
  \[
  W[h](a) = \left\langle \left\| W[y](a,b) \right\|_b \right\rangle
  \]
  \[
  W[h](a) \propto a^{\zeta + \frac{1}{2}}
  \]
  Simonsen et al. (1998)
Coherence of roughness measurement methods

<table>
<thead>
<tr>
<th></th>
<th>RMS</th>
<th>SF</th>
<th>MM</th>
<th>PS</th>
<th>AWC</th>
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<tbody>
<tr>
<td>ζ</td>
<td>0.33 ± 0.06</td>
<td>0.35 ± 0.05</td>
<td>0.44 ± 0.05</td>
<td>0.35 ± 0.07</td>
<td>0.37 ± 0.05</td>
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<tr>
<td>ζ</td>
<td>0.65 ± 0.05</td>
<td>0.62 ± 0.04</td>
<td>0.80 ± 0.06</td>
<td>0.69 ± 0.04</td>
<td>0.73 ± 0.07</td>
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Comparison with former roughness measurements

<table>
<thead>
<tr>
<th></th>
<th>( \zeta_{//} )</th>
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<tr>
<td>modelisation</td>
<td>0.35</td>
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<td></td>
<td>Schmittbuhl et al. (1995)</td>
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<td>0.6</td>
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<td>Hansen et al. (2003)</td>
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<td>experiments</td>
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<td>Daguier et al. (1995)</td>
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<td>Delaplace et al. (1999)</td>
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Bouchaud (1997)

Bouchaud et al. (1990)

Hansen et al. (2003)
Comparison with former roughness measurements

Hypothesis:
- Coalescence processes at small scales
- Fluctuating elastic line at large scales

\[ \sigma = 0.35 \delta^* \]

with \( \delta^* \) = separating length scale
Comparison with former roughness measurements

Robust because found for former experiments too

\[ \sigma = 0.35 \, \delta^* \]

with \( \delta^* = \) separating length scale
**Conclusions on morphology**

- Two roughness regimes: $\zeta \approx 0.6$ at small length scales and $\zeta \approx 0.35$ at large length scales
- Robust for different parameter changes (disorder preparation, resolution...)
- Threshold length scale around disorder typical length

- Regime at small length scales due to coalescence processes
- Regime at large length scales due to long-range elastic interaction processes
- These roughness regimes seem universal
Front dynamics analysis

AE signal
sensor 1
sensor 2

Mean front velocity \langle V \rangle
Local velocities

Velocity matrix:

\[ V(x,y) = \frac{\alpha}{\delta t} \frac{1}{W(x,y)} \]

\( \alpha = 10 \mu m \)
\( \delta t = 1 \text{ ms} \)

150 \( \mu m/s < \langle v \rangle < 1000 \mu m/s \)
Local velocities

≠ colors and signs ⇒ ≠ disorders
≠ mean front velocities

\[ \eta = -2.5 \]

(former slower experiments = -2.5)
Måløy et al. (2006)
(speed range 0.3 \( \mu \text{m/s} \) to 40 \( \mu \text{m/s} \))
AE amplitude distribution

\[ P(A) \propto A^{-1.65} \]

≠ colors and signs
⇒ ≠ disorders
≠ mean front velocities

AE waiting time distribution

\[ P(T) \propto T^{-(1-\gamma)} \exp(-T/B) \]
\[ \gamma = 0.85 ; B = 1 \]
(idem Davidsen et al., PRL, 2007)
Conclusions on dynamics

- Distribution of velocities follows a power law ⇒ robust for different disorders and front speeds
- Preliminary results on AE show scaling law distributions of amplitudes and waiting times
Building catalogs

Velocity matrix:

\[
V(x,y) = \frac{\alpha}{\delta t} \frac{1}{W(x,y)}
\]

\[
v = \begin{cases} 
1 \text{ if } v > C \langle v \rangle \\
0 \text{ else }
\end{cases}
\]

150 \mu m/s < \langle v \rangle < 1000 \mu m/s
Building catalogs

Parameters for each event:

- Time of occurrence $t$
- Epicenter position $(x,y)$
- Moment $M \approx \text{area } A$ of event (nb of pixels):

$$M \approx E_I \times A \times \text{Opening}$$

(Seismic moment: $M_0 \approx \mu \times S \times D$ with $S=$cracked area & $D=$fault offset)

- Circles = events
- Diameter of circles $\approx \log_{10}(M)$
- Only events with $\log_{10}(M) > 1.5$ represented
Circles = events
Diameter \approx \log_{10}(M)

x – y map

x – t map
Definition of event = avalanche

Building quake catalogs similar to seismicity catalogs

Experimental catalog

Seismicity catalog

Link between the two catalogs?

What explanation for the similarities?
Homogeneous from 1984 to 2002
Complete for earthquakes with magnitude > 2.5
Area (120.5°W,115.0°W) x (32.5°N,36.0°N)
22217 events
Magnitude $M_w \rightarrow$ seismic moment $M_0$ (in N.m)

$$\log_{10}(M_0) = \frac{3}{2} M_w + 9.1$$

(Kanamori, JGR, 1977)
Gutenberg-Richter relationship: $N(M_0) \approx M_0^{-1-\beta}$

(Gutenberg and Richter, BSSA, 1944)

Seismicity data

$$P(M_0) = M_0^{-1.7}$$

Experimental data

$$P(M) = M^{-1.7}$$

15 experimental catalogs from 5 experiments, each with 3 different C values
B is a record of A if no event happens within the disc of radius AB (distance $l$) centered on A during $[t_A, t_B]$, with $t_A < t_B$ (time interval $T = t_A - t_B$).

(Davidsen et al., GRL, 2006)

- All events B happen after event A.
- Numbers represent the order of occurrence of events in the catalog.
- Records of A = B1, B3 and B4.
- Distributions of distances: $l_i = |x_0 - x_i|$
- Distributions of time intervals: $T_i = t_0 - t_i$
\[ \delta = 1.1 \pm 0.05 \]

(1.05 for SC catalog)

\[ \alpha = 0.95 \pm 0.06 \]

(0.9 for SC catalog)

15 experimental catalogs from 5 experiments, each with 3 different C levels.
Conclusions for comparison with large scale data

- Quake catalogs with a large number of events (typically a few thousands)
- Obey same scaling laws as seismicity data (Gutenberg-Richter, distribution of recurrent distances, distribution of recurrent time intervals) despite different spatial and time scales, different physical mechanisms and different geometries

- Microstructures control the dynamics of crack propagation at large scales
- Global dynamics of rupture propagation depend on event interactions
- The long range elastic coupling between heterogeneous microstructures control these interactions
Optical and acoustic monitoring of a crack propagation along a heterogeneous interface at high spatial resolution or high time rate

Two roughness regimes, $\zeta = 0.6$ at small and $\zeta = 0.35$ at large scales, separated by a typical length scale, robust for different parameter changes

Distributions of quakes ranked in catalogs obey same scaling laws as seismicity data (Gutenberg-Richter, distribution of recurrent distances, distribution of recurrent time intervals) despite different spatial and time scales, rupture mechanisms and configurations
Comparison between AE time series and optical catalogs

Acoustic emissions probably due to local depinning of the rupture front

Building catalogs from AE analysis to compare with optical events
Comparison with other large scale data sets

Doubre et al. (Geology, 2005)

InSAR
1997-2005 slip history

Slip front morphology analysis

Asal Rift
Thanks for your attention...

For sale!

Good prices !!!!

a whole bunch of Plexiglas cakes, cooked with love...