Modeling slip precursors at frictional interfaces

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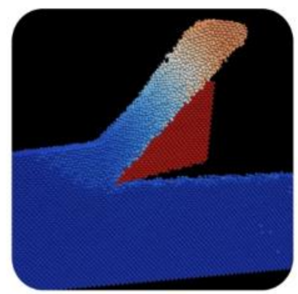
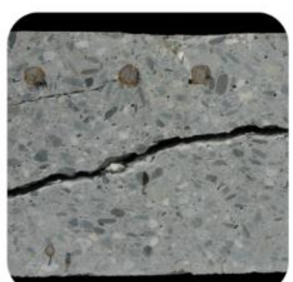
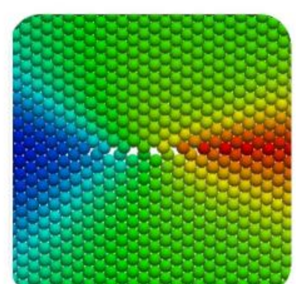
Jean-Paul Ampuero



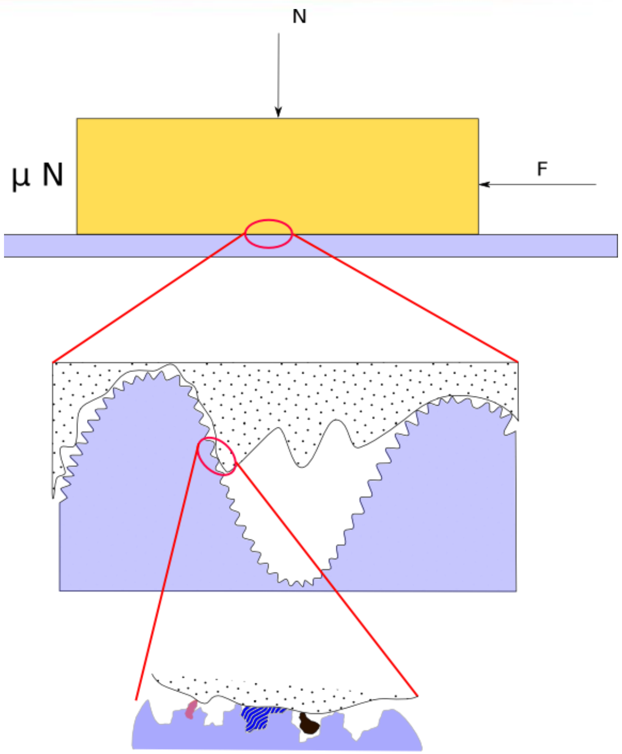




Motivation

Microscopic origins of friction ? (nm)

What happens inside an earthquake ? (km)

(rated by livescience as top mystery)



Challenge of scales (time and length)

Complex physics (plasticity, surface roughness, third body interactions, adhesion, chemistry…)

Development of multiscale numerical models

(FE, spectral methods, discrete/continuum) :

1) open-source codes (manuals, tutorials); lsms.epfl.ch

2) High-Performance Computing, parallel and scalable

Conclusion

"Friction is fracture"

"Friction is fracture"

"Friction is fracture"

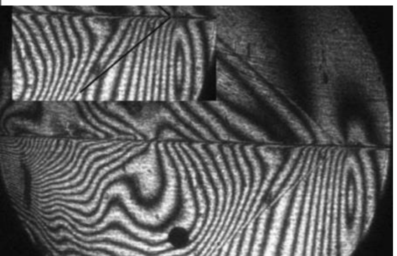
Acknowledged by many (Rice and others…),
but novelty is that it can demonstrated **quantitatively**
(at least in model experiments…)

Two examples:

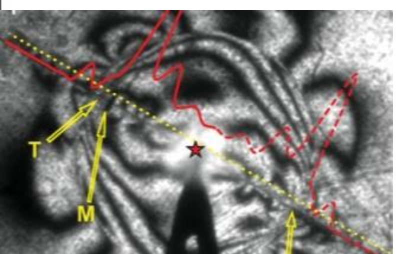
1) Front dynamics: friction tip velocity
   Tip stresses predicted by LEFM (not shown today)
2) Precursors lengths predicted by LEFM

Lab earthquakes

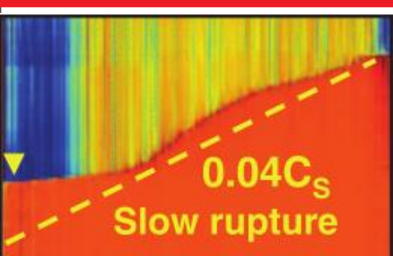
Experimental results for quasi-static shear loading



Coker, *Lapusta*, *Rosakis*
JMPS 2005

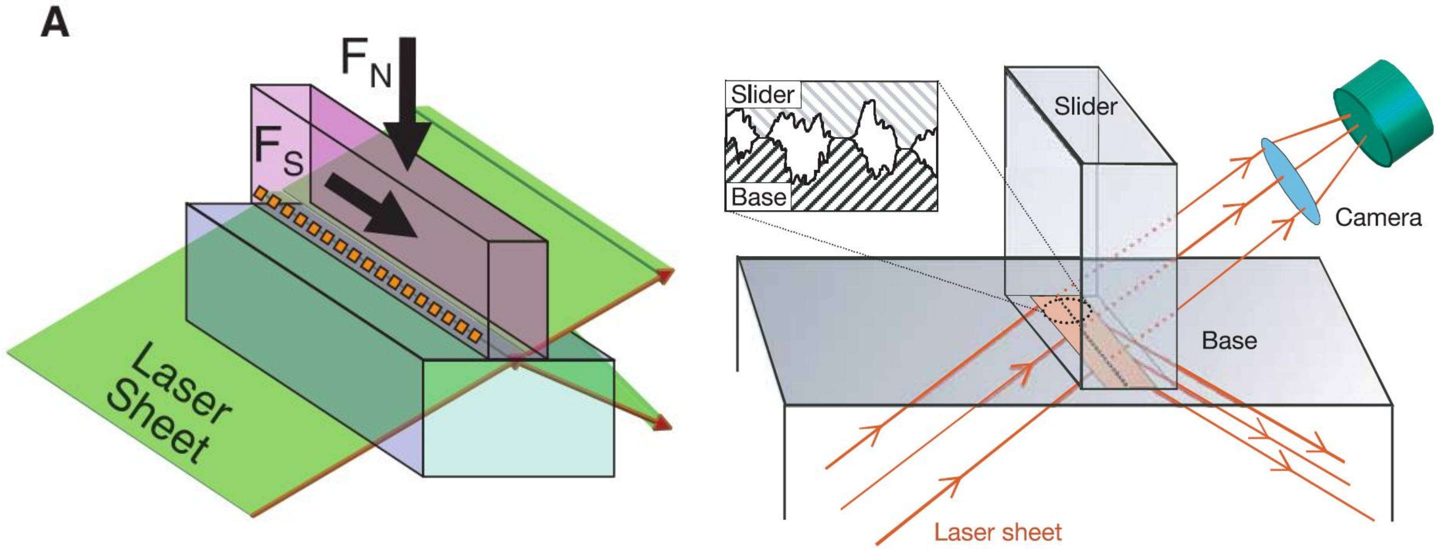


Lu *et al.*
PNAS 2007

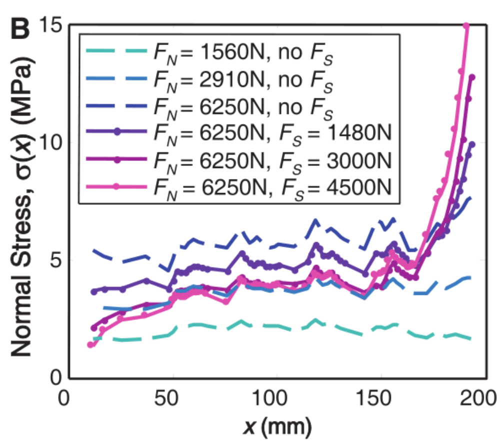


Ben-David, Cohen, Fineberg, Science 2010

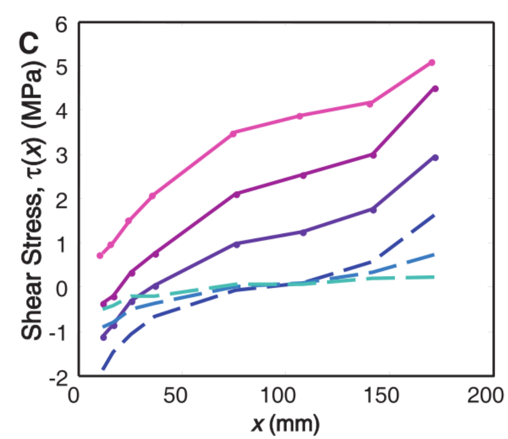
PMMA Interface under Quasi-static Shear Loading



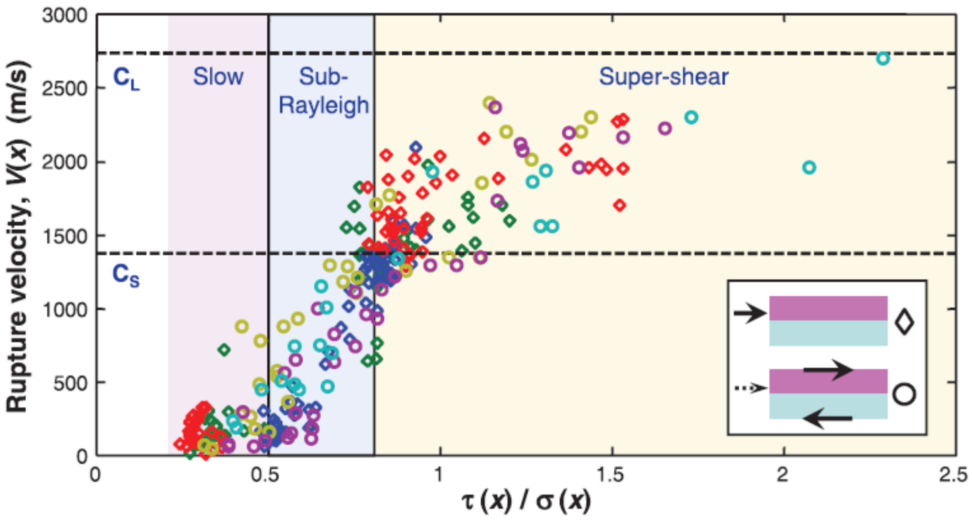
Normal Stress Distribution



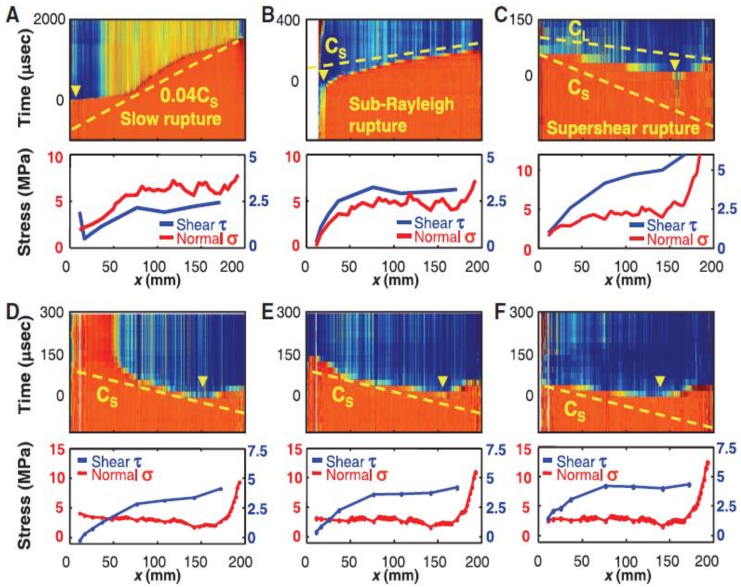
Shear Stress Distribution



Lab earthquakes experiments



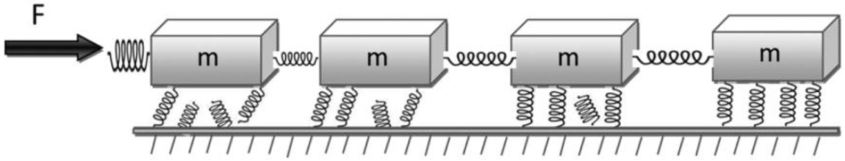
Ben-David, Cohen & Fineberg, *Science*, **330**, (2010).



Modeling approaches

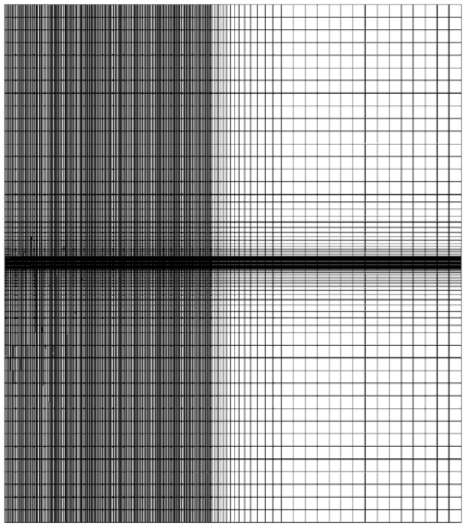
Our choice: Finite-Element Method

Spring-Mass Model

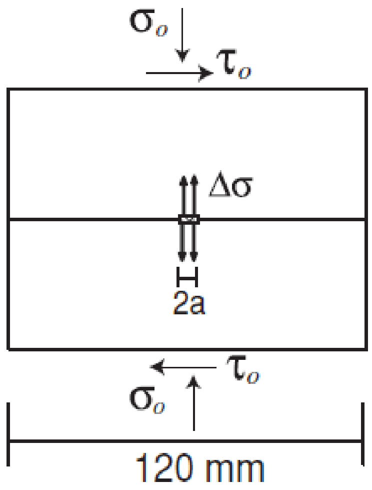


Braun, Barel & Urbakh, *Phys. Rev. Lett.*, **103** (2009).
Maegawa *et al.*, *Tribol. Lett.*, **38** (2010).
Trømborg *et al.*, *Phys. Rev. Lett.*, **107** (2011).
Amundsen *et al.*, *Tribol. Lett.*, **45** (2012).

Finite-Element Method



Coker *et al.*, *J. Mech. Phys. Solids*, **53** (2005).
Di Bartolomeo *et al.*, *Tribol. Int.*, **43** (2010).
Kammer *et al.*, *Tribol. Lett.*, **48** (2012).
Di Bartolomeo *et al.*, *Tribol. Int.*, **52** (2012).



Spectral Boundary-Integral Method

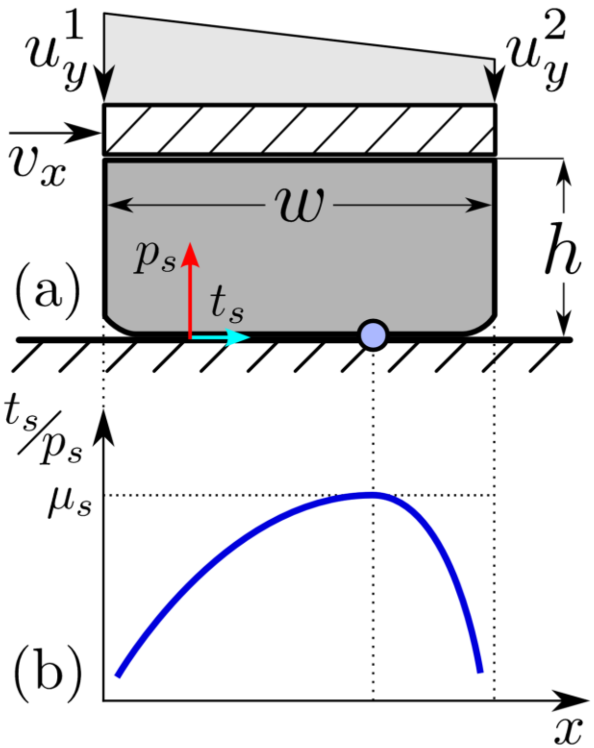
Breitenfeld & Geubelle, *Int. J. Fract.*, **93** (1998).
Liu & Lapusta, *J. Mech. Phys. Solids*, **56** (2008).
Lu *et al.*, *Geophys. J. Int.*, **177** (2009).

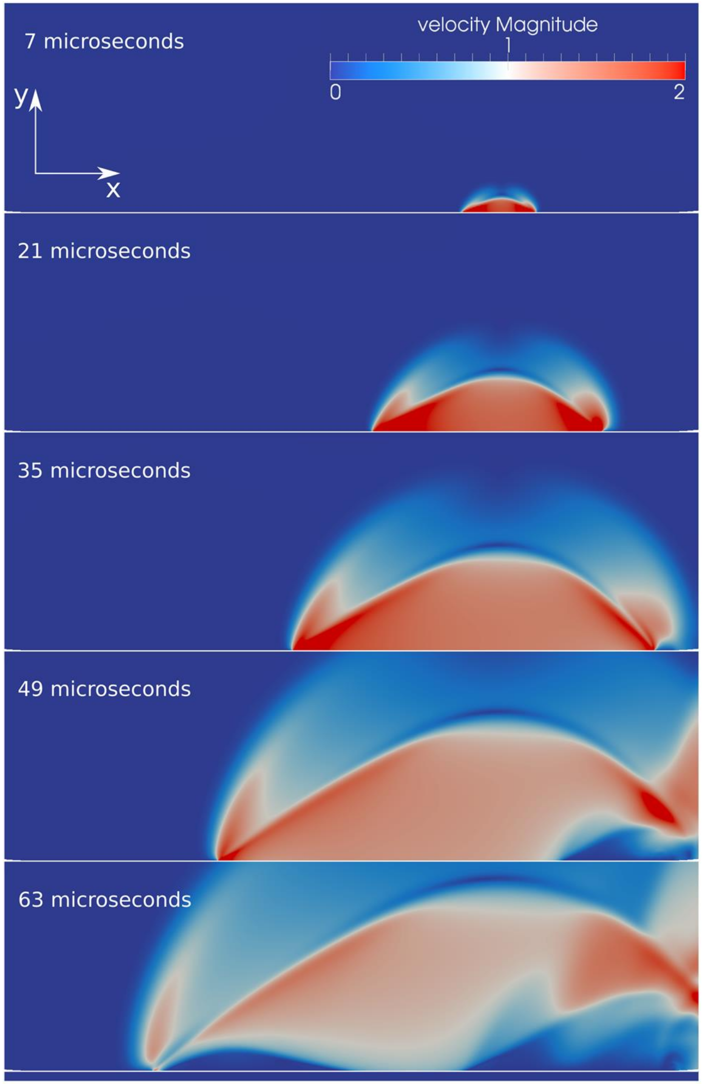
FE model

Kammer et al., Tribol. Lett, 2012

Linear elastic material
Velocity weakening friction

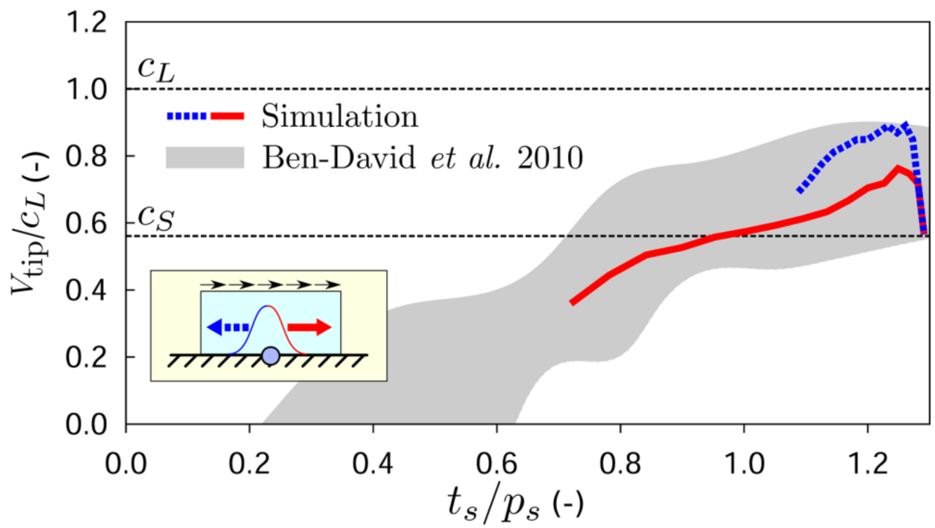
$$\mu = \mu_s + (\mu_k - \mu_s)(1 - \exp(-|v|\sqrt{(\mu_s - \mu_k)/\alpha})),$$

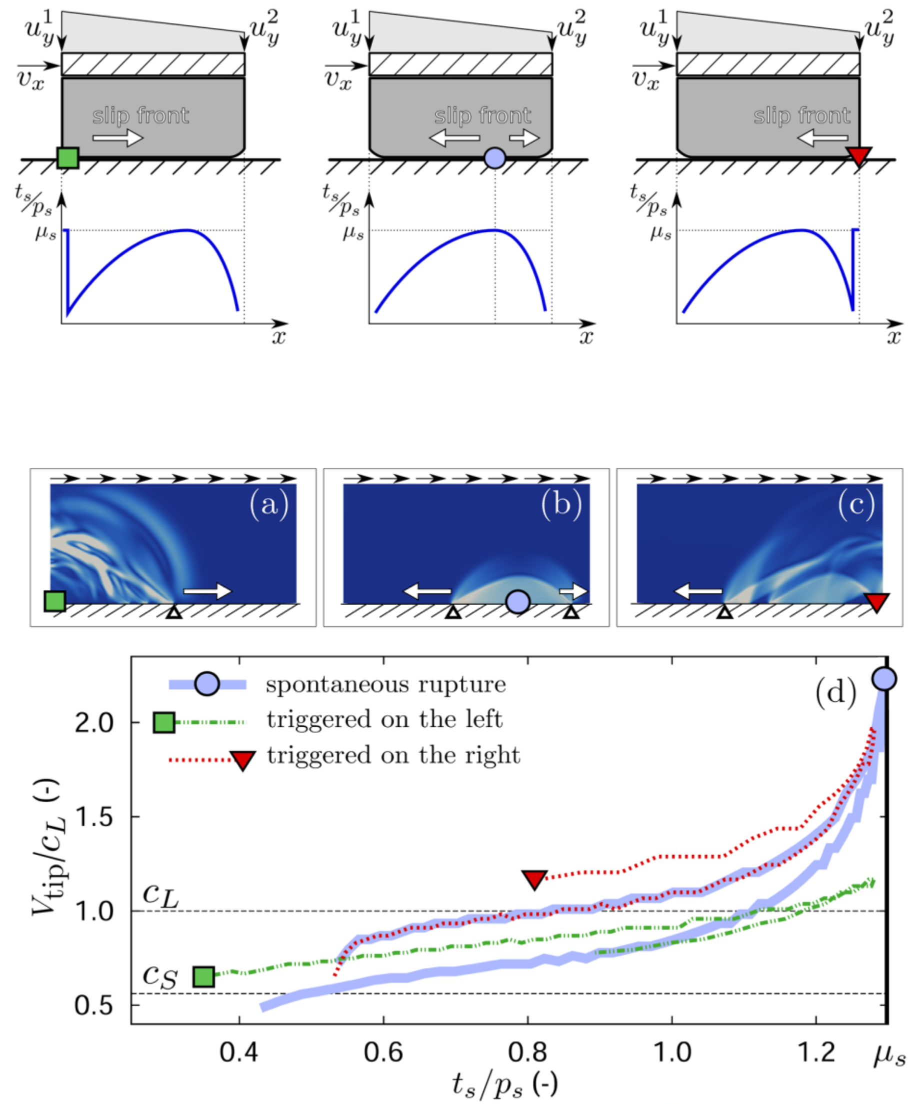




General trend captured

But non uniqueness of Vtip

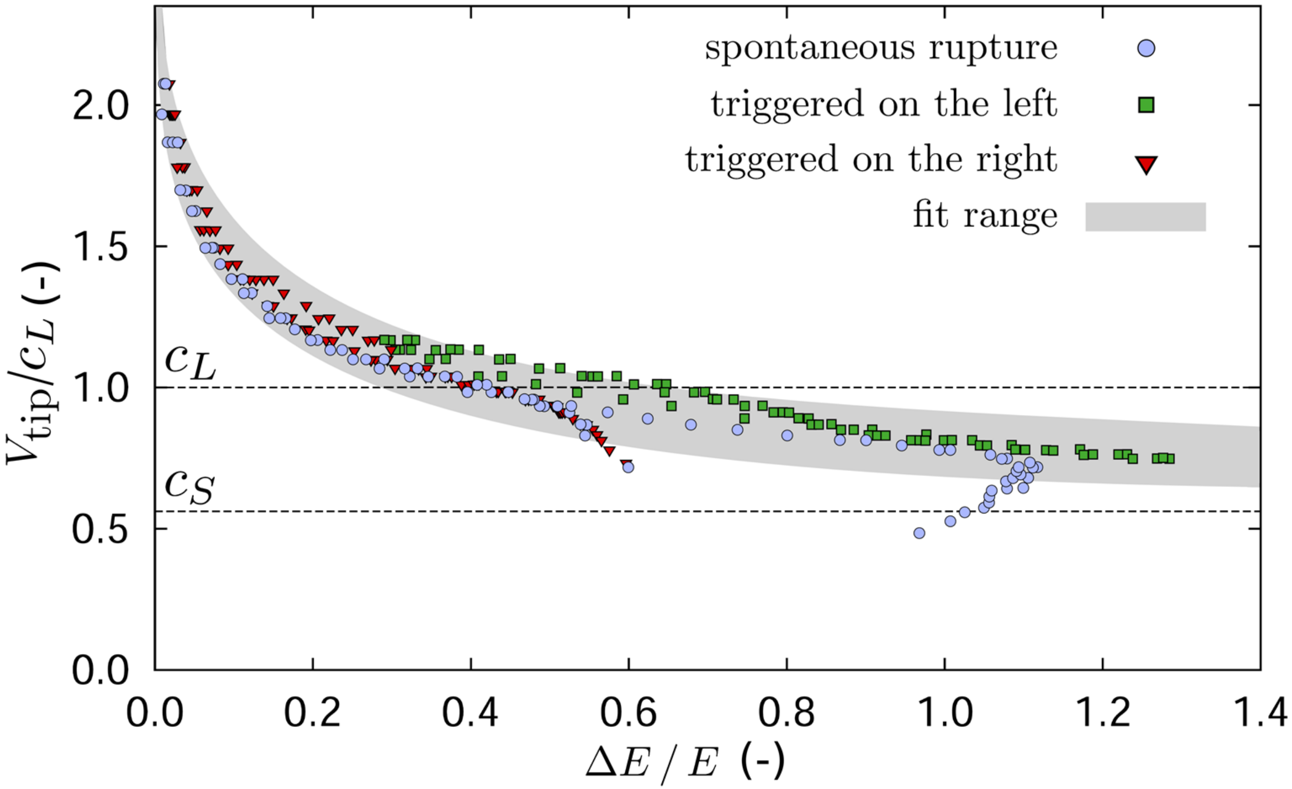




Non uniqueness of Vtip as function of interace stresses observed for a variety of cases

Friction is fracture 1

Energetic approach of fracture (dynamics matter)

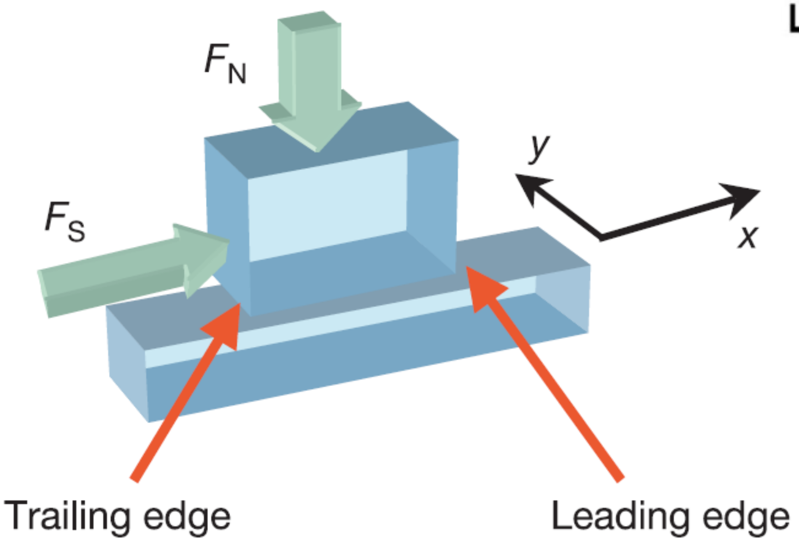


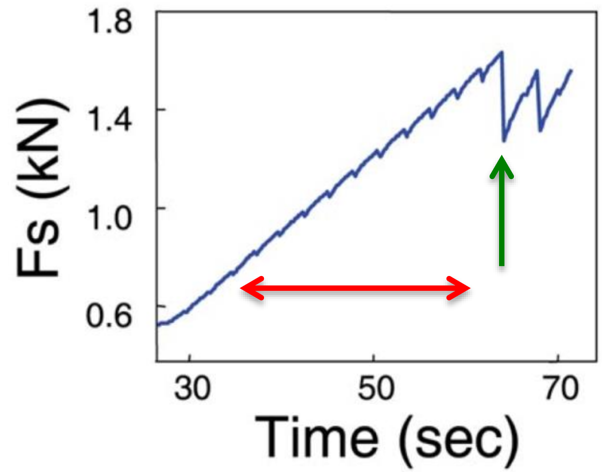
$$\Delta E / E = \frac{E_{\text{needed}} - E_{\text{stored}}}{E_{\text{stored}}}$$

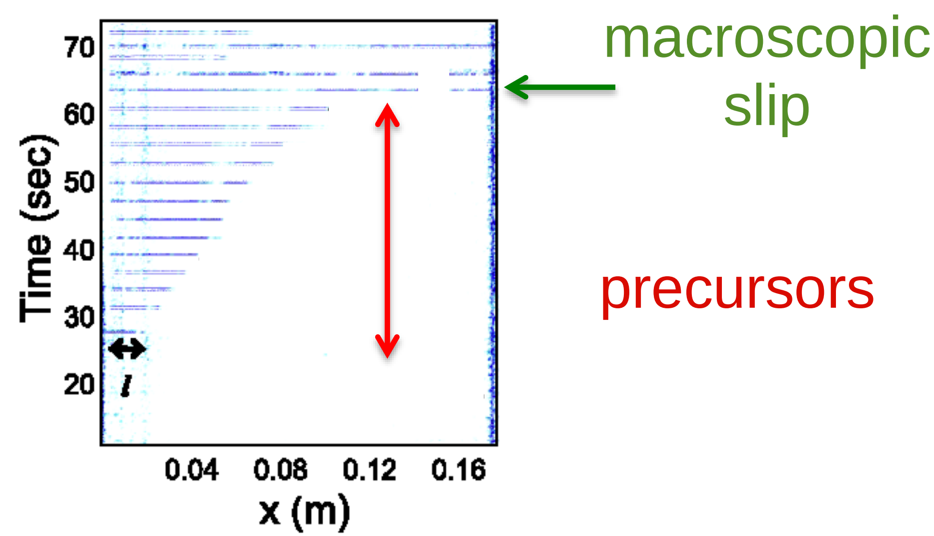
Kammer *et al.*, *Tribol. Lett.*, **48** (2012).

On slip precursors

Experimental observations: stress drops occur before global sliding

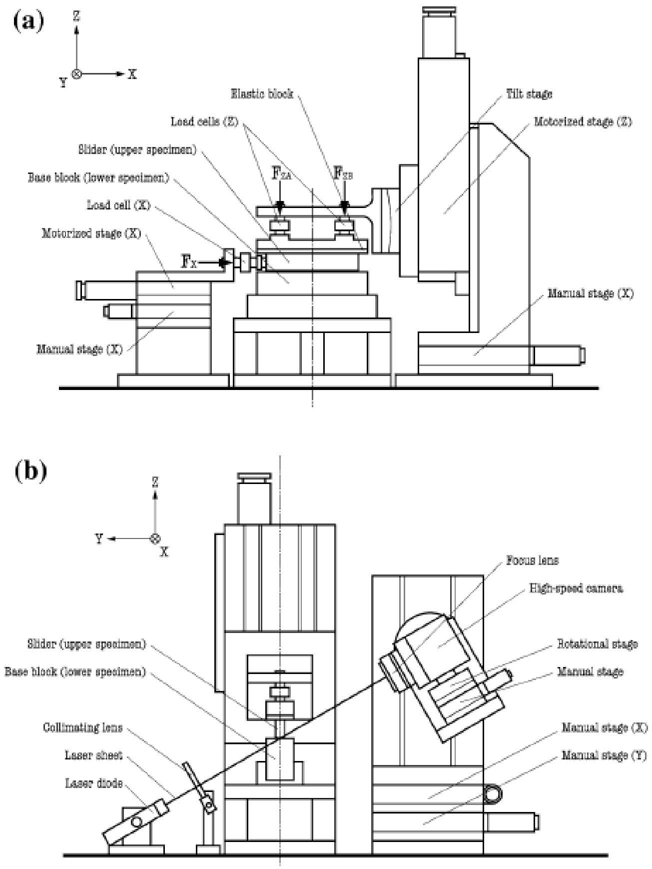


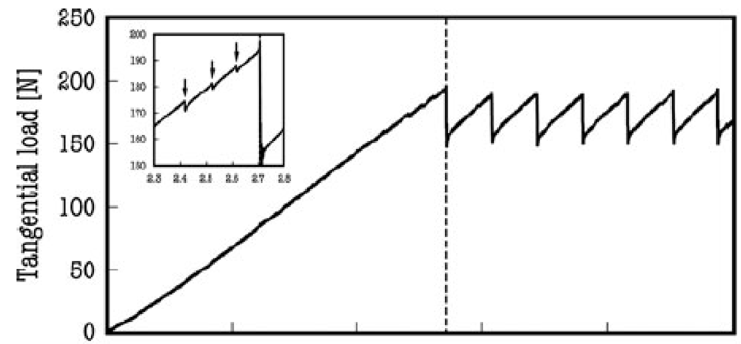


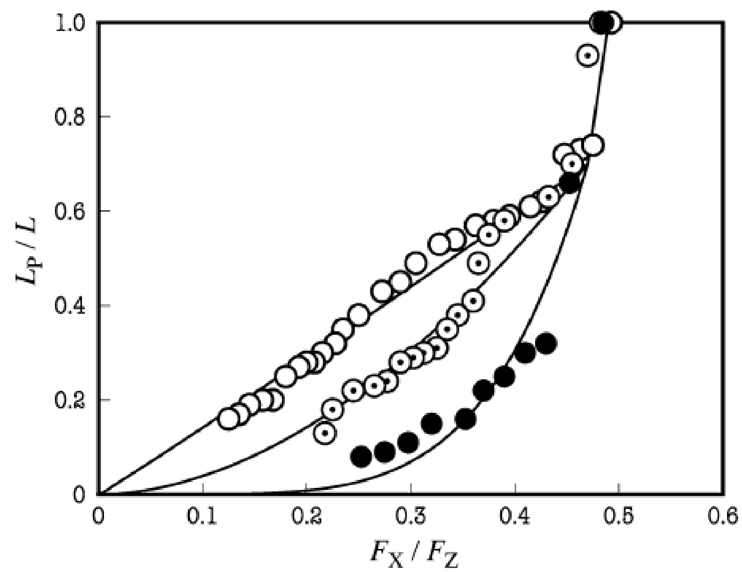


Rubinstein, Cohen & Fineberg, *Phys. Rev. Lett.*, **98**, (2007).

Experiments







Slip at a frictional interface between two viscoelastic plates (PMMA) under quasi-static normal and shear load.

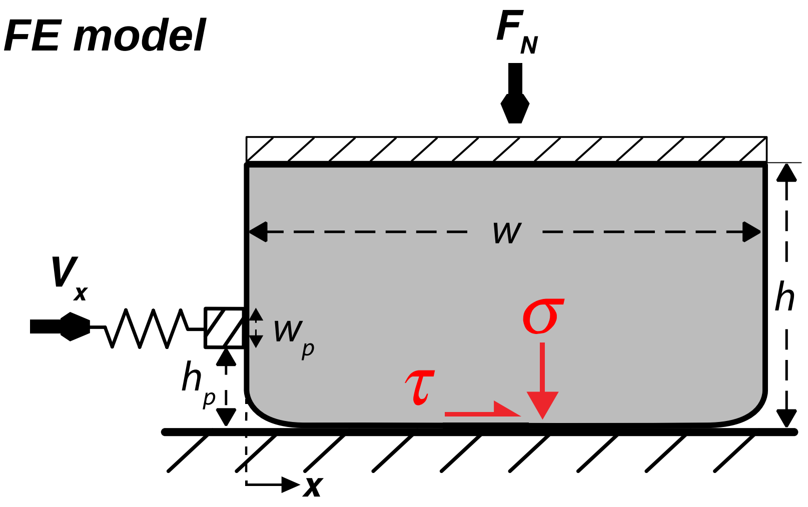
- Precursors under non-uniform loading

Maegawa, Suzuki & Nakano, *Tribol. Lett.*, **38**, 313-323 (2010).

Configuration of numerical model

Radiguet, Kammer, Molinari, PRL, 2013

2D FE model



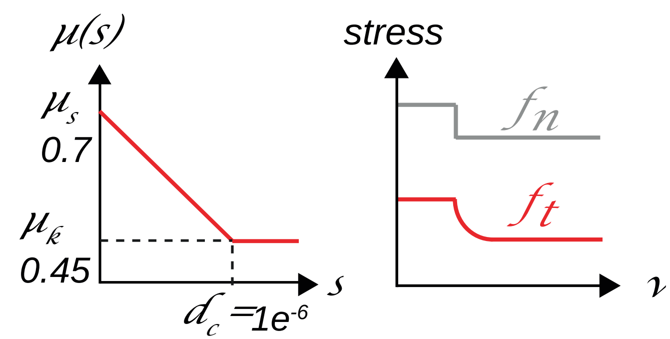
Loading

- Top: constant normal force F_N
- Loading via spring, constant V_x

Interface

- Linear slip weakening friction law

- Prakash-Clifton (simplified) regularization of frictional strength



Viscoelastic material modeled using the standard linear solid model (*Zener, 1948*).

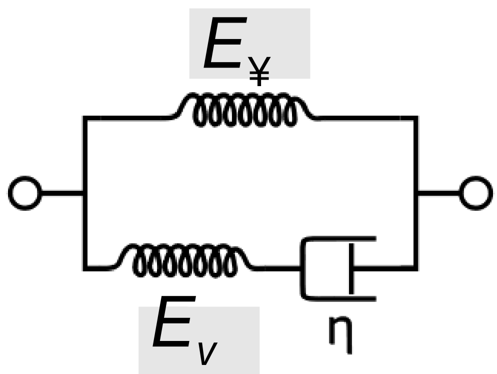
$E_{¥} = 3\,GPa$

$E_v = 2.6\,GPa$

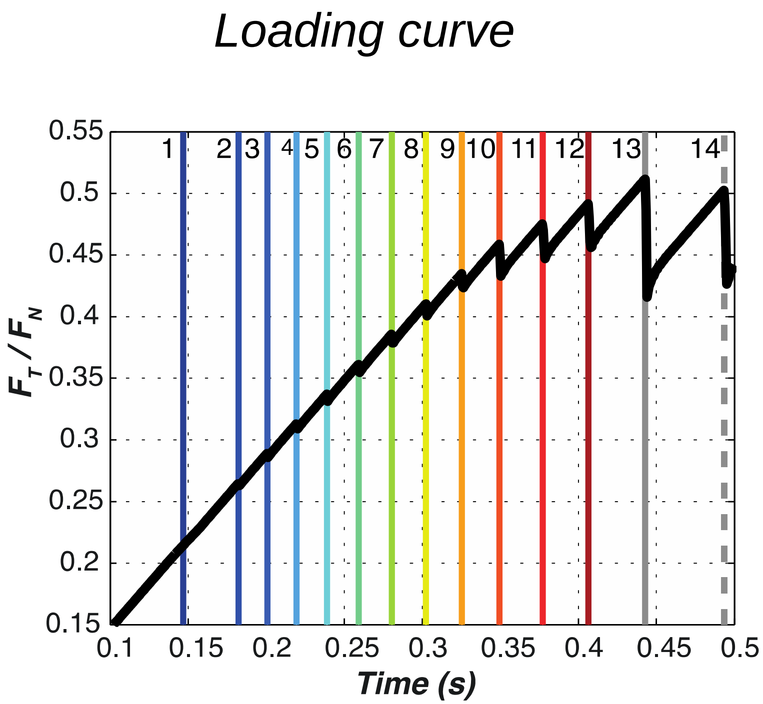
$E_0 = E_{inf} + E_v$

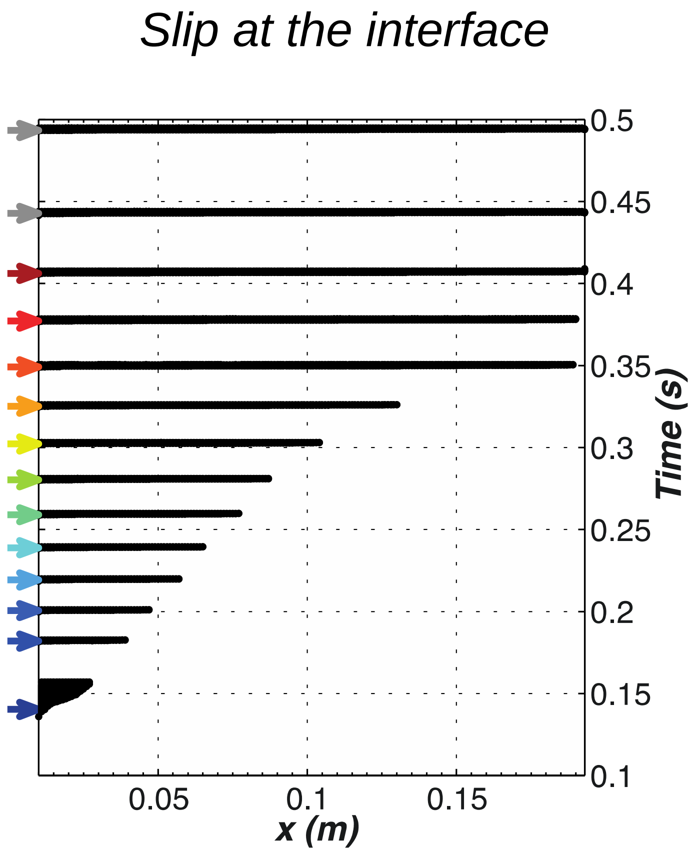
$h = 5.10^6\,Pa.s$

$t_v = h / E_v = 1.7\,ms$



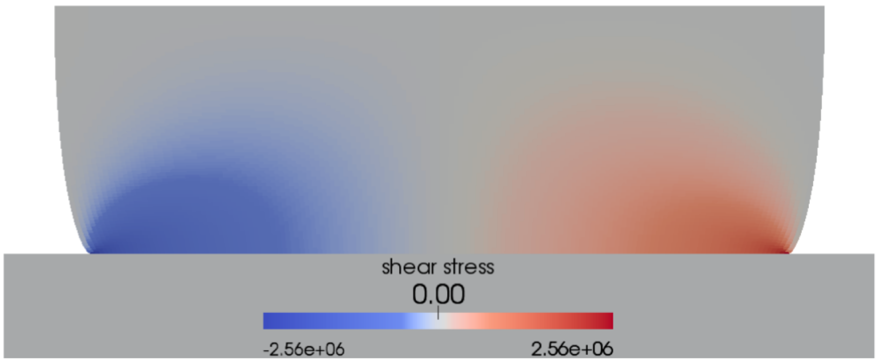
Global behavior

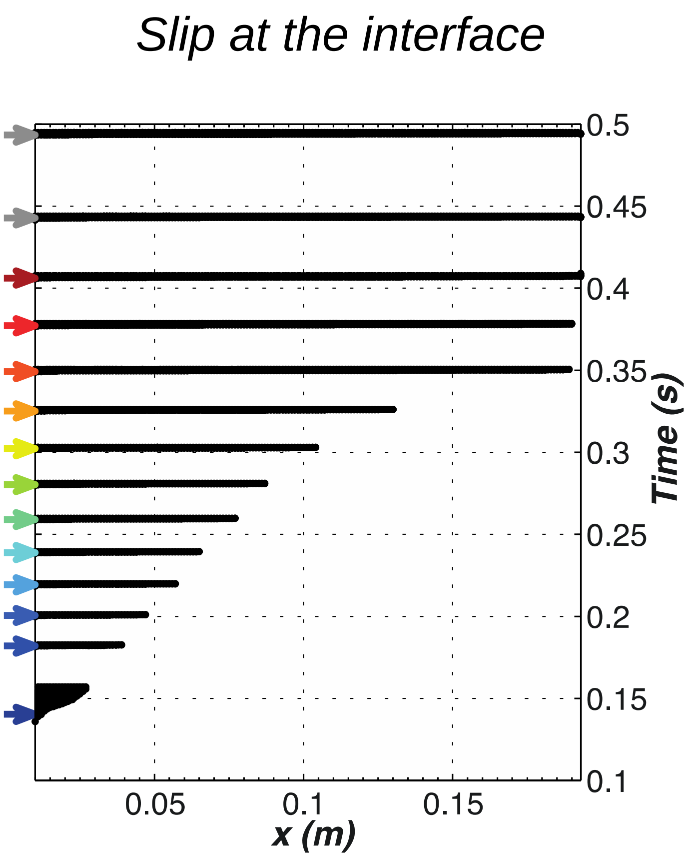




Global behavior

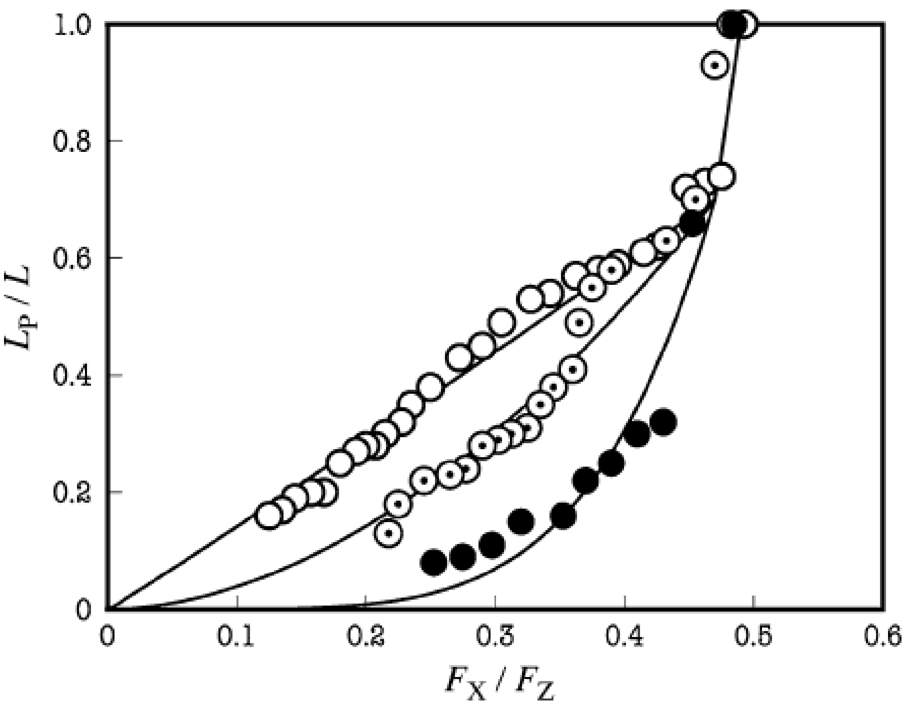
Frustrated Poisson expansion

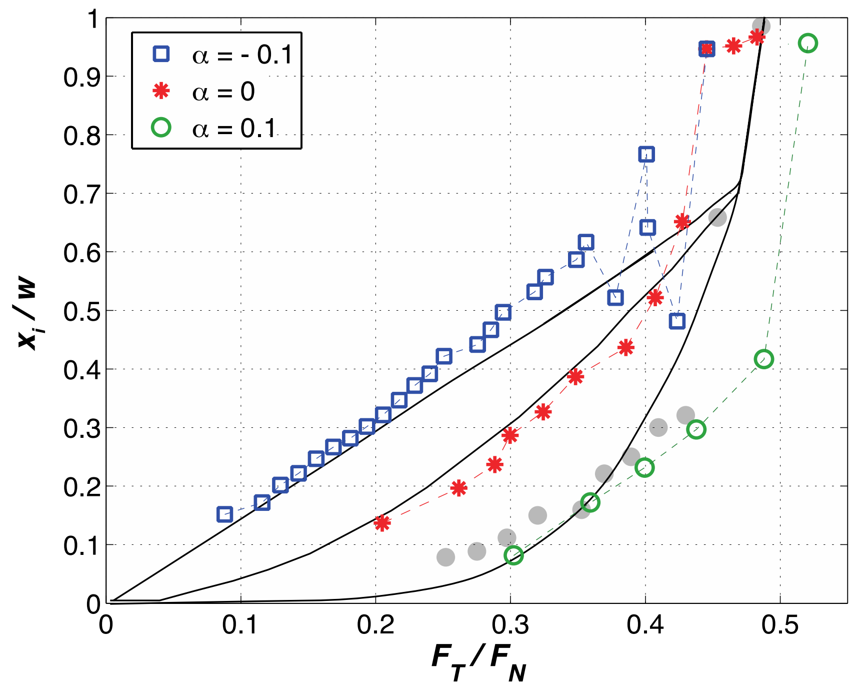




Comparison numerics/experiments

Simulations predict precursor lengths



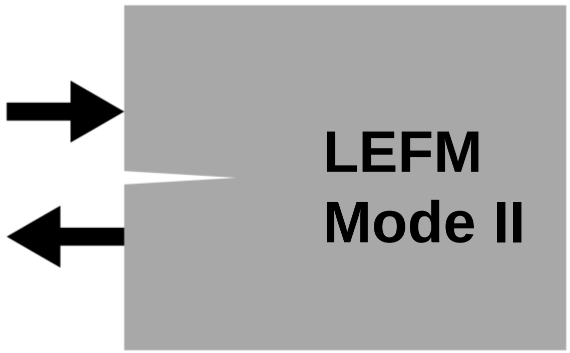


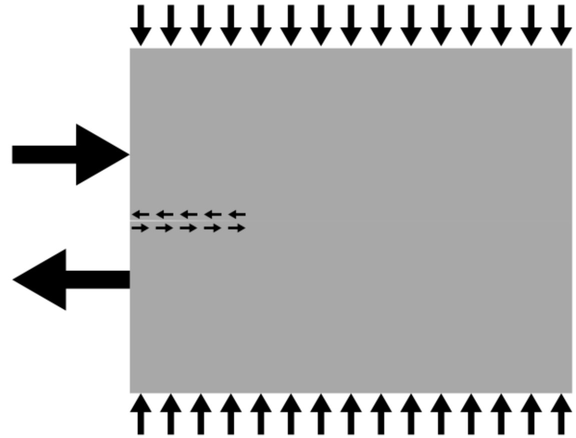
Maegawa, Suzuki & Nakano, *Tribol. Lett.*, **38**, 313-323 (2010).

Analytical model

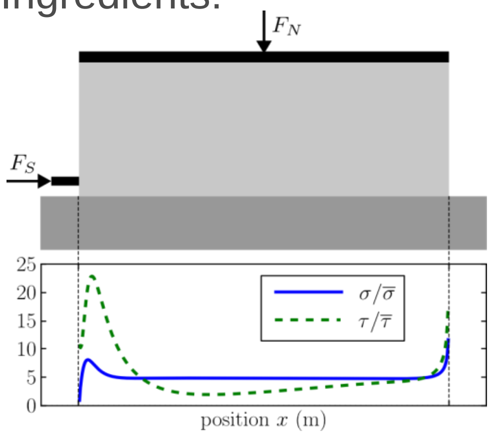
Can LEFM predict precursor lengths?

Kammer, Radiguet, Ampuero, Molinari, Tribol. Lett., 2015

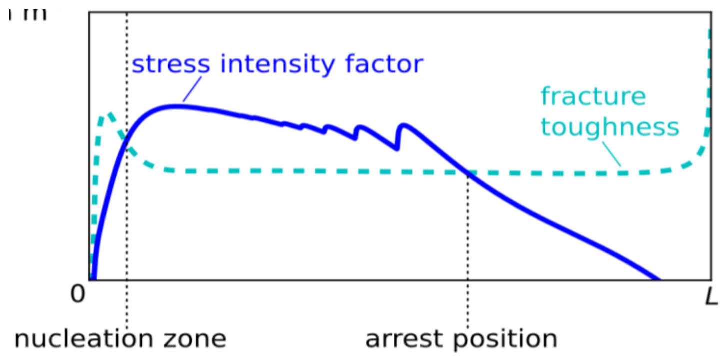




Ingredients:

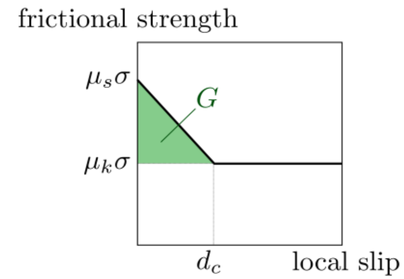


Interface stresses from FE calculation
(only numerical ingredient)



Arrest criterion

$$K^{-}_{II}(l) = K_{IIc}(l) \quad \text{and} \quad \frac{\mathrm{d}K^{-}_{II}(l)}{\mathrm{d}x} < \frac{\mathrm{d}K_{IIc}(l)}{\mathrm{d}x}$$

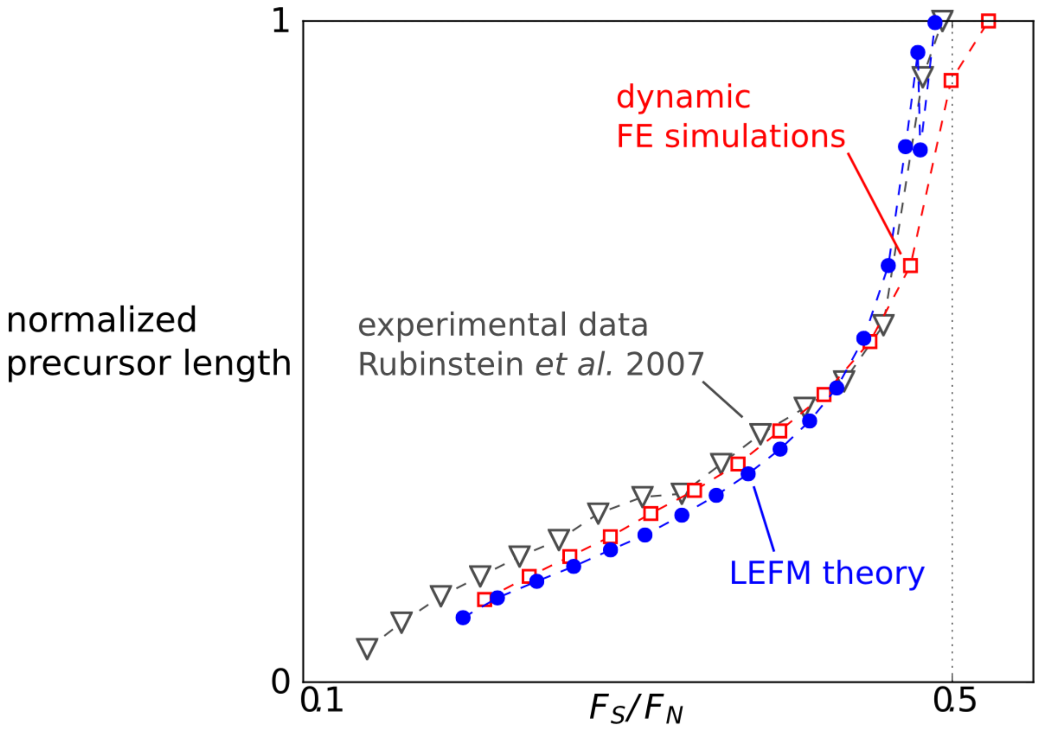


$$K_{IIc}(x) = \sqrt{E_0 G(x)} = \sqrt{E_0 \frac{(\mu_s - \mu_k)d_c}{2}\sigma_r(x)}$$

$$K_{II}(a) = \frac{2}{\sqrt{\pi a}} \int_0^a \frac{\Delta\tau(s)F(s/a)}{\sqrt{1-(s/a)^2}}\mathrm{d}s$$

Friction is fracture 2

LEFM model predicts precursor length; no fit parameters



Conclusions

- Numerical and analytical models of slip activities at a PMMA interface
- Importance of energetic consideration to predict slip front velocity
- Model is able to reproduce experimentally observed precursors; and LEFM fully explains results (of simple, very careful, experiments)

- Current work: adding complexity, heterogeneous interfaces, …