Friction/Fracture of Hydrogels

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- Friction and sliding dynamics at a multicontact interface
- Plasticity of confined material in frictional junctions
- Friction/fracture of transient networks (hydrogels)

What are Hydrogels ?

ex. gelatin, polyacrylamid, … cartilage

=

crosslinked polymer network + solvent

Elasticity :

$G = kT/\xi_{el}^3$

$\xi_{el} \approx 10$ nm ; G = 1–10 kPa

$\nu \approx 0.5$ (water) $\Rightarrow E = 3G$

Diffusion :

$D_{coll} = kT/(\eta_s \xi_{hydro})$

$\xi_{hydro} \sim \xi_{el}$; $D_{coll} \approx 10^{-11}$ m²/s

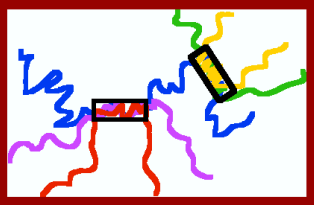
A poroelastic medium …
gels vs. rocks ?

$\kappa \approx \xi^2 \approx 10^{-17}$ m² (10^{-5} darcy)

$D_{coll} << D_{rock} = E\kappa/\eta_s \approx 10^{-2}$ m²/s

Gel families…

Chemical gels
(typ. polyacrylamid)
covalent crosslinks
→ permanent



Physical gels
(eg. gelatin)
weaker crosslinks (eg. H-bonds)
→ usually thermoreversible

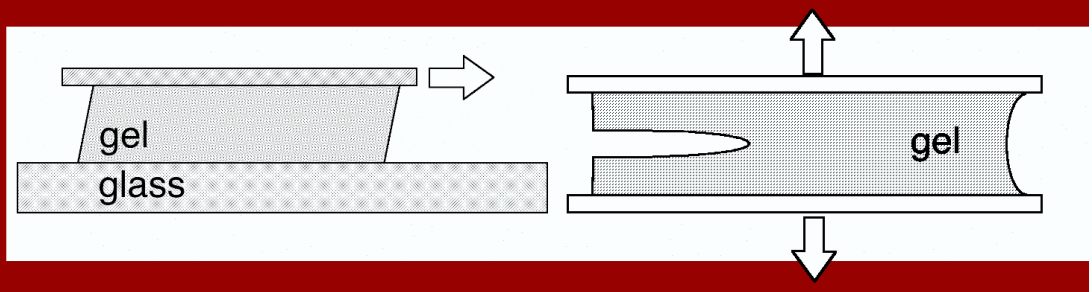
- Transient networks
- Thermal history-dependent
- Neverlasting aging G(t)
- Slow creep

Behavior upon sliding …
adhesive vs. repulsive surface/gel interaction
→ solid friction (threshold) vs. Lubrication
(cf Gong & Osada)

Gelatin gel : a model system

- c = 5–15 wt% → G(c) = 1– 10 kPa (G"/G' < 10^{-1} @ f < 1 kHz)
- water/glycerol → tunable (1:4) solvent viscosity η_s

easy to cast, easy to handle …



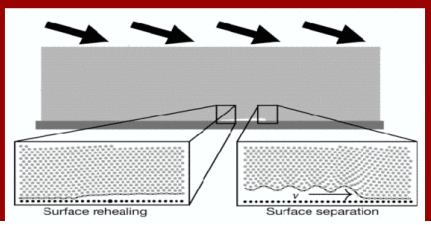
Interfacial fracture/sliding

Mode I crack propagation

The Friction/Fracture symbiosis…

Sliding at *extended* interfaces
- compliant materials, e.g. gels
- smooth surfaces, e.g. float glass
- large systems, e.g. faults

Friction and fracture are intricated
- Friction law ⇒ mode II crack regularisation and healing (Rice & Cochard, Ben-Zion, …)
- Fracture feature ⇒ Amontons' friction law (Gerde & Marder)

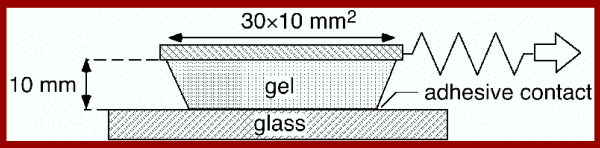


- Schallamach (decohesion) waves
  - – strong adhesion
  - – large deformations
    - → see also Gerde & Marder
- Heaton (slip) pulses
  - → from inversion of sismic data
- Adams pulses (theoretical)
  - – elastic contrast
  - – coulomb $\sigma = \mu p$
    - → related to « ill-posedness »
- Still widely open problems :
  - → role of the friction law ?
  - → role of elastic dissymetry
  - → location in parameter space (e.g. V…) ?

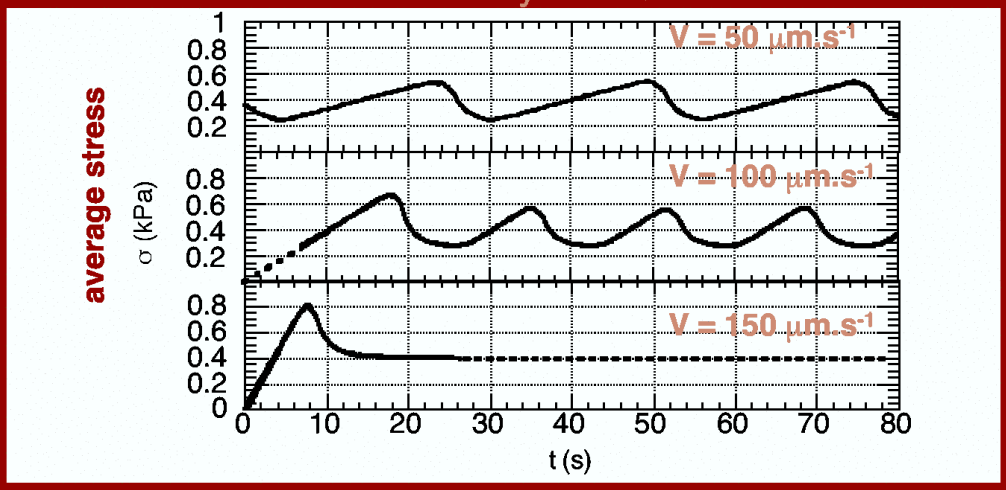
Self-healing slip pulses at a gelatin/glass interface

Baumberger et al. PRL 88 (2002) 75509 ; Eur. Phys. J. E 11(2003) 85

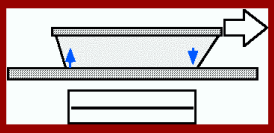
Finite-size gel blocks driven at constant remote velocities V = 10–2000 μm/s



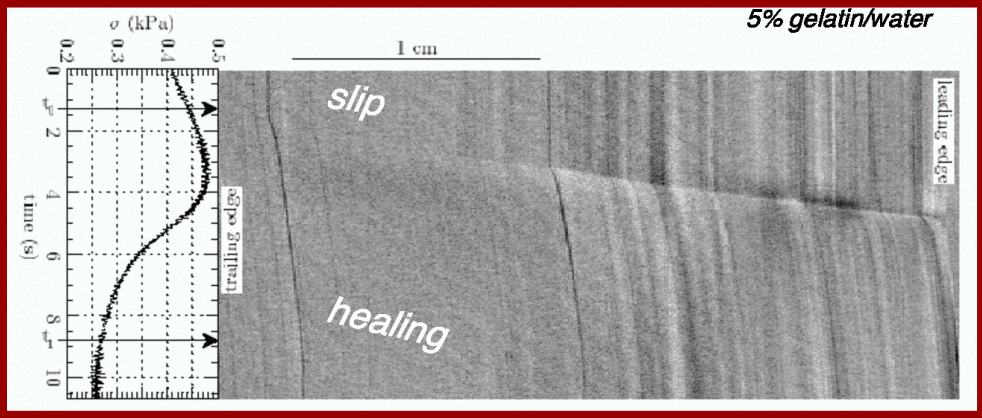
Global dynamics



→ at V = V_c : a finite amplitude bifurcation…without hysteresis suggests internal degrees of freedom …

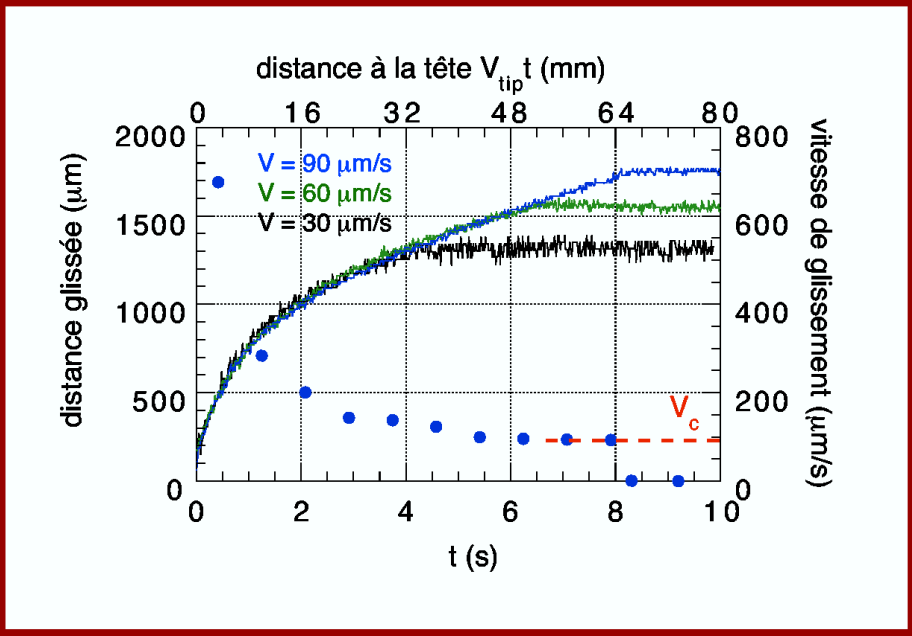


Spatio-temporal representation of the slip field



- V_{tip} = 8 mm/s ⇒ *subsonic* crack ($c_s = (G/\rho)^{1/2}$ ~ m/s)
- no decohesion ⇒ *slip* pulse

Healing occurs at *finite* slip velocity



→ sliding is *not* possible at $v < V_c$

Physical origin of V_{tip} and V_c ?

NB. $V_{tip} << V_c << c_s$

→V_{tip} scales with the *poroelastic* velocity $V_{poro} = D_{coll}/\xi$

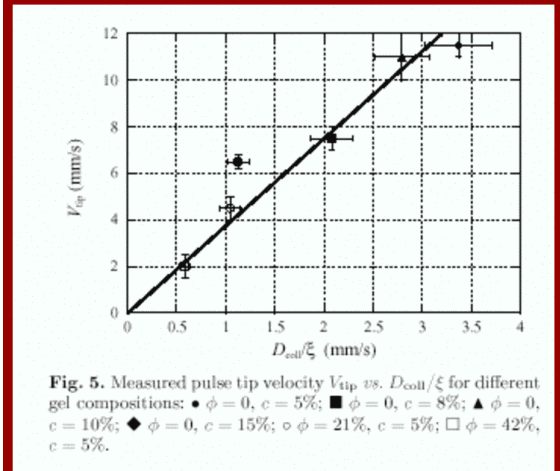


Fig. 5. Measured pulse tip velocity V_{tip} *vs.* D_{coll}/ξ for different gel compositions: • $\phi = 0$, $c = 5\%$; ■ $\phi = 0$, $c = 8\%$; ▲ $\phi = 0$, $c = 10\%$; ◆ $\phi = 0$, $c = 15\%$; ○ $\phi = 21\%$, $c = 5\%$; □ $\phi = 42\%$, $c = 5\%$.

Qualitative picture :

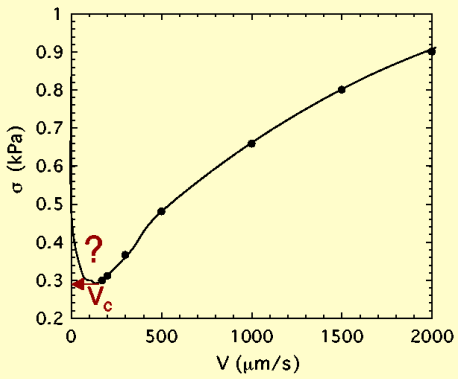
- once nucleated the crack accelerates
- bond rupture generates a signal at $\omega \sim V_{tip}/\xi$ with $q \sim \xi$ (here, the process zone size)
- it resonates with the diffusive, slow Biot mode $\omega = D_{coll}\, q^2$ when $V_{tip} \approx V_{poro}$
- excess energy is then very efficiently dissipated

Question :

Is it possible to propagate a crack at $V > V_{poro}$?

→ sudden healing, on the spot, at $v = V_c$
suggests an *instability* mechanism …

Rheological instability ?



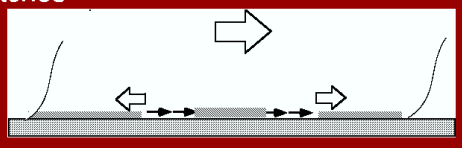
Qualitative picture « à la Schallamach »

• The number of adhesive bonds n(t) is a dynamic variable
With :
✓ τ = rebonding time
✓ r/V = time of flight over an adhesive site of capture radius r
→ $n(V > r/\tau) = 0$
→ $\sigma \approx \eta(V)\, V/\xi$ (OK with experiments)
⇒ $V_c \approx r/\tau$

• Taking for $r \approx$ a few Å yields
$\tau = r/V_c \approx$ a few 10^{-6} s $\sim \tau_{Rouse}$

Sum-up of the self healing pulses phenomenology

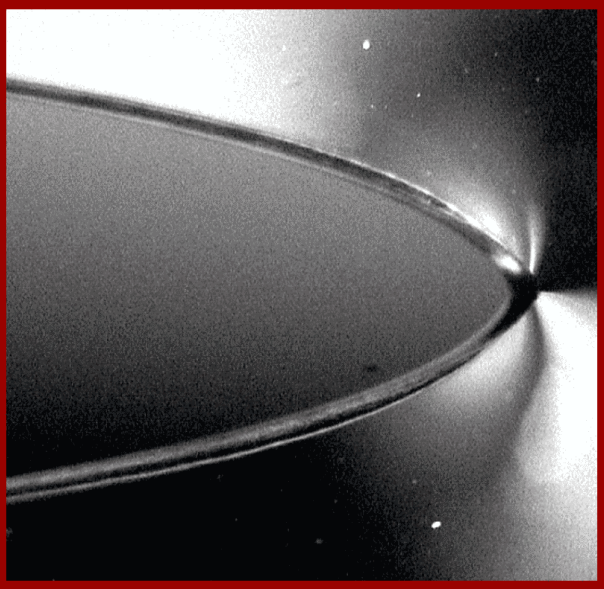
• SHP are observed in a finite size block with strong elastic contrast
– nucleation at the edge under tension
– *propagation at a poroelastic velocity*
– process zone ~ ξ
• healing a finite slip velocity V_c fixed by some characteristic pinning time
– *the existence of a minimum in $\sigma(v)$ is crucial*
– no SHP for $V > V_c$
• the work provided by the remote drive is essentially dissipated by friction
(i.e. viscous dissipation in the fluid interfacial layer at a shear rate ~ V_c/ξ)
• SHP are also observed in an edge-free annular geometry
– cf. Rubio & Galeano [PRE 50 (1994) 1000, Europhys. Lett. 49 (2000) 410]
– ∃ steady states with n pulses running at constant $V_n < V_{poro}$
– nucleation from stressed or weak patches
– *two pulses may conter propagate*
[cf. e.g. Ben-Zion *et al, 2005 submit. Geophys. J. Int*]

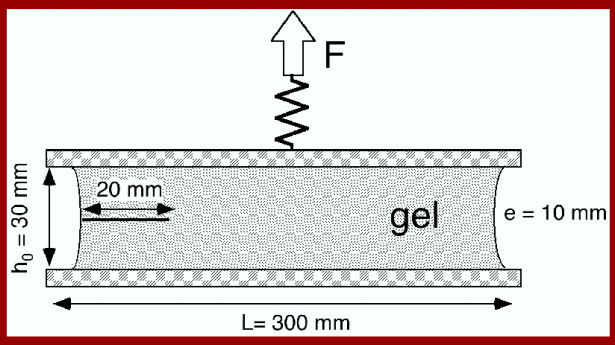


→ Is there anything relevant to fault dynamics ?

Mode I crack dynamics in gelatin gels

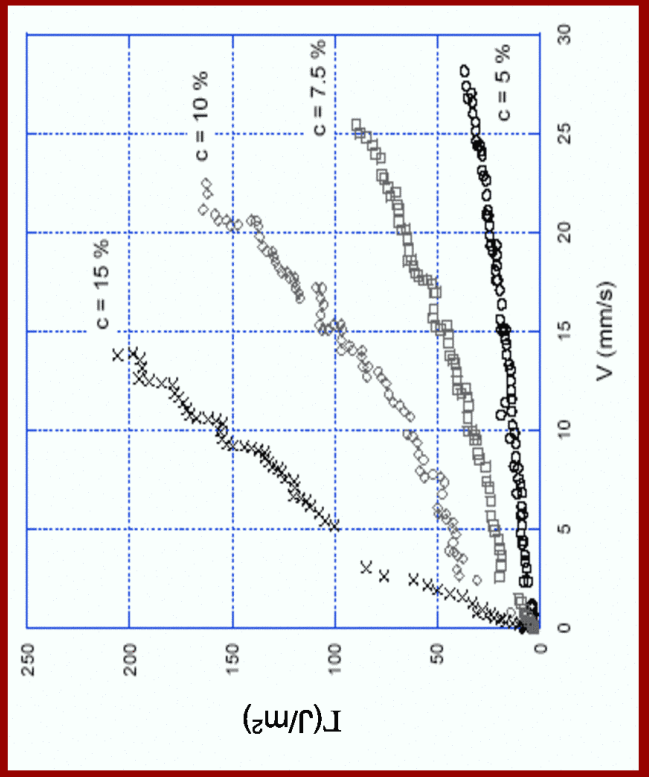
[Unpublished material]



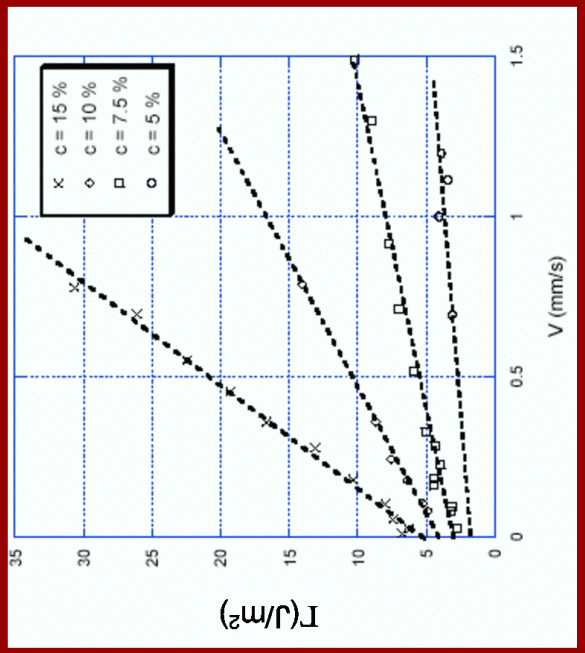


Single notch
Fixed grip
« semi- infinite » slab
Fracture energy :
$\Gamma_\infty = 1/2\ E^*(\Delta h)^2/h_0$
$\Gamma = -1/2\ \Delta h/e\ dF/dx$
tip velocity $V = dx/dt$

$\Gamma(V\ ;\ c_{gelatin},\ \eta_{solvent},\ \ldots)$?



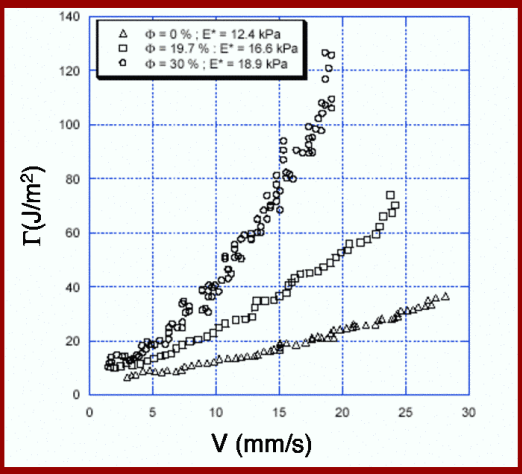
Γ and E increase with c ⇒ the stiffer the tougher

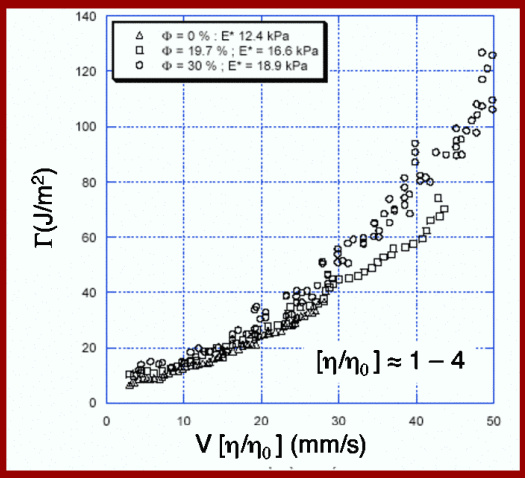


$\Gamma_0 >> 2\gamma_{water/air}$

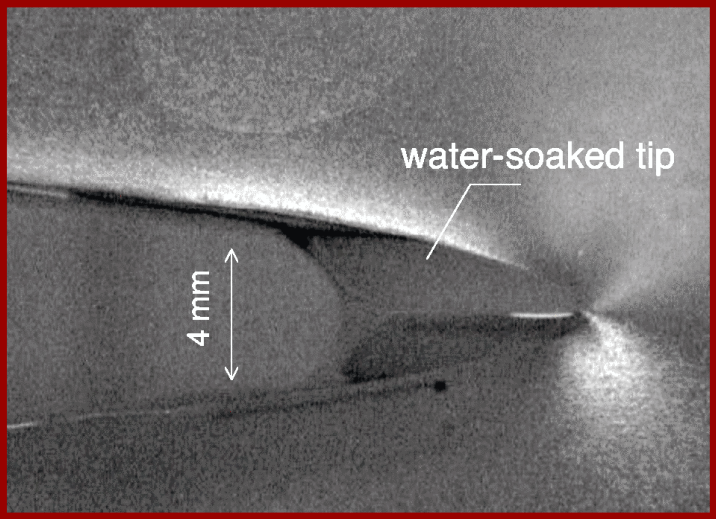
$\Gamma_0 \xi^2 \sim 10^3$ eV

Role of solvent (1)

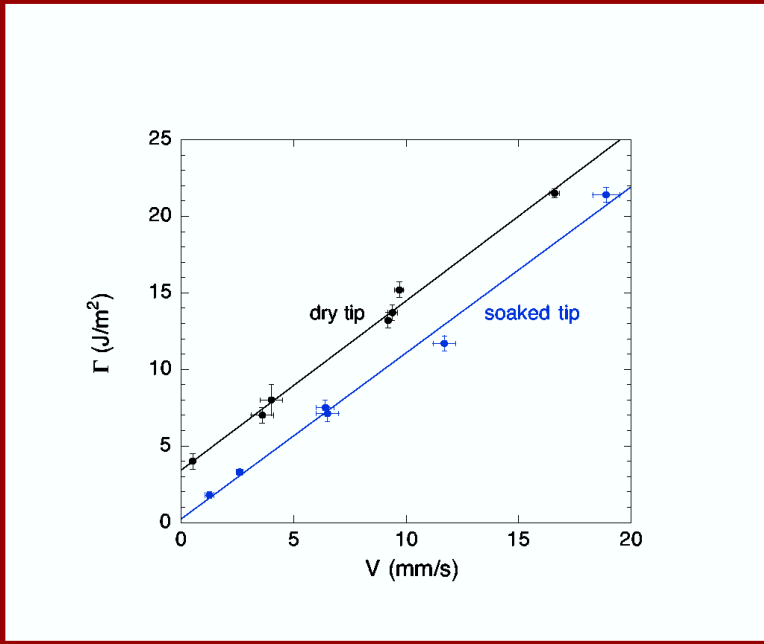




Role of solvent (2)



NB. $\Delta P_{Laplace} = \gamma/r << \sigma_\infty$



NB. for viscoelastic fracture (cf.e.g.Persson & Brenner, PRE 71 (2005) 036123) one would expect $\Gamma(V) = \Gamma_0[1+f(V)]$… seems to be ruled out here.

Possible routes to interpretation of $\Gamma(V)$…

1. Keep in mind…

- $\Gamma_0 \sim$ a few J/m^2
- $\Gamma_0 >> 2\gamma_{water/air}$
- $\Gamma_0 \xi^2 \sim 10^3$ eV >> sission energy for a chain (U ~ a few eV)

2. Lake & Thomas argument

- Breaking a chain of n elements requires stocking nU >> U, ultimately released

  [Lake & Thomas, Proc. Roy. Soc. A 300 (1967) 108]

  → $\Gamma_0 \sim nU\Sigma$

  → ideal, semi-dilute, gel : $S \sim \xi^{-2} \sim 1/(na^2) \Rightarrow \Gamma_0 \sim U/a^2 \sim$ a few J/m^2

  → OK but … incompatible with the weakness of the crosslinks

3. Poroelasticity

→ if the process zone extends over L,

drained/undrained transition (Ruina) at $V \sim D_{coll}/L$

→ In PAAm gels Y.Tanaka see a change in fracture profile for $V \sim D_{coll}/\xi$

→ $L \sim \xi$ in PAAm (strong chemical gels) ?

→ at first sight nothing happens here (cf. point 5 below) : $L \gg \xi$?

4. Viscoelasticity

→ Essentially ruled out by soaked-tip experiment

→ $\Gamma(V)$ should then be attributed to rate-dependent dissipation within the process zone…

5. Crazing

[see e.g. Rottler & Robbins PRE 68 (2003) 011820]

→ Could it occur here ?

→ hint : the fracture profile is not mirror-like (Ra ~ μm), whatever the velocity

→ The gel network can be plastically deformed, probably by unwinding (?) the crosslinks : favorable to drawing fibrils ?

→ A highly speculative issue !!