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Fracture, mechanics and chemistry: Intermittency and avalanche statistics in thermally activated creeping crack fronts along disordered interfaces

T. Vincent-Dospital, R. Toussaint (Univ. Strasbourg, PoreLab Oslo), A. Cochard, (Univ. Strasbourg), S. Santucci (ENS de Lyon),

KJ Måløy, EG Flekkøy, (PoreLab Oslo)

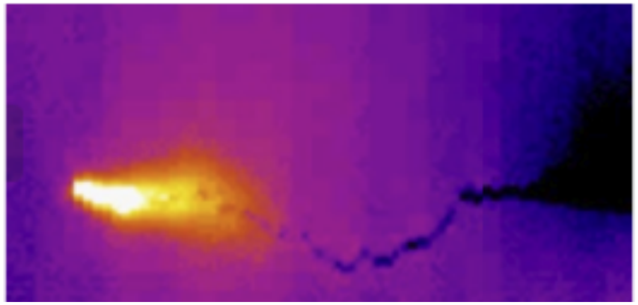
How to predict material failure by monitoring creep

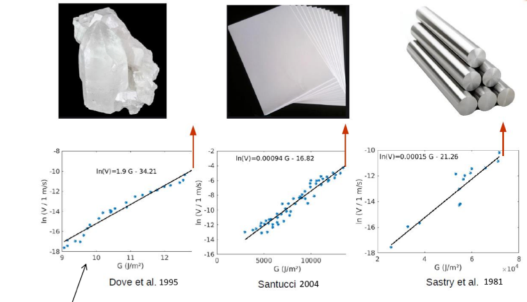
How local heating impacts fracture

Is breaking through matter a hot matter?

How fast can subcritical fracture be?

Eppur riscalda (and yet, it heats!)





Matter creeps… and snaps !

We can deduce α from the slope and G_c from the intercept.
We can then predict the rupture threshold from the thermal model.

ROYAL SOCIETY OF CHEMISTRY

Soft Matter

PAPER

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Thermal dissipation as both the strength and weakness of matter. A material failure prediction by monitoring creep†

Tom Vincent-Dospital,[ab] Renaud Toussaint,[ab] Alain Cochard,[a] Eirik G. Flekkøy[b] and Knut Jørgen Måløy[b]

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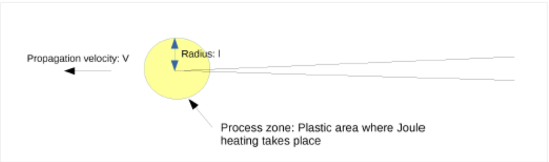
In any domain involving some stressed solids, that is, from seismology to general engineering, the strength of matter is a paramount feature to understand. We here discuss the ability of a simple thermally activated sub-critical model, which includes the auto-induced thermal evolution of cracks tips, to predict the catastrophic failure of a vast range of materials. It is in particular shown that the intrinsic surface energy barrier, for breaking the atomic bonds of many solids, can be easily deduced from the slow creeping dynamics of a crack. This intrinsic barrier is however higher than the macroscopic load threshold at which brittle matter brutally fails, possibly as a result of thermal activation and of a thermal weakening mechanism. We propose a novel method to compute this macroscopic energy release rate of rupture, G_a, solely from monitoring slow creep, and we show that this reproduces the experimental values within 50% accuracy over twenty different materials, and over more than four decades of fracture energy.

The heat diffusion equation



$$\Delta T = T - T_{room}$$
$$\partial_t \Delta T = D\nabla^2 \Delta T - \frac{\Delta T}{\tau} + \frac{\phi G V}{\rho c \pi l^2}$$

Diffusion equation for the temperature elevation

Loss in the surrounding air

Source term in the process zone, Notably depending on:

- A proportion of the fracture energy: ϕG
- The crack velocity: V
- The zone area: πl^2

Evolution law

$$v = v_0 \exp\left(\frac{\alpha^2 \Delta G}{k_B T}\right)$$

Arrhenius relation

Ex : water
(from Rockyview school)

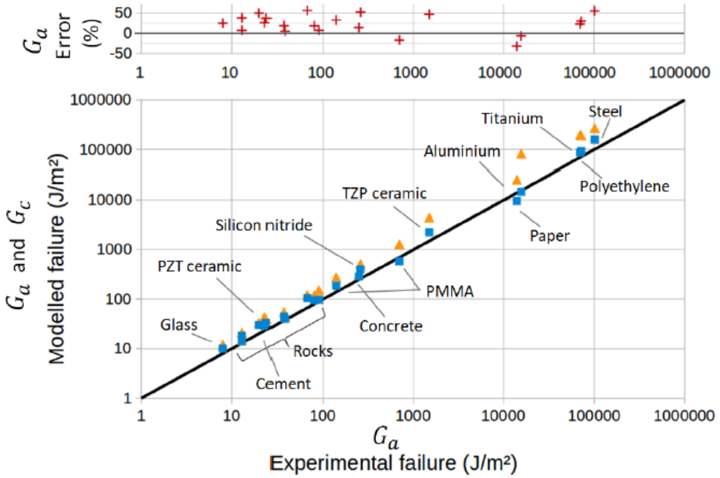
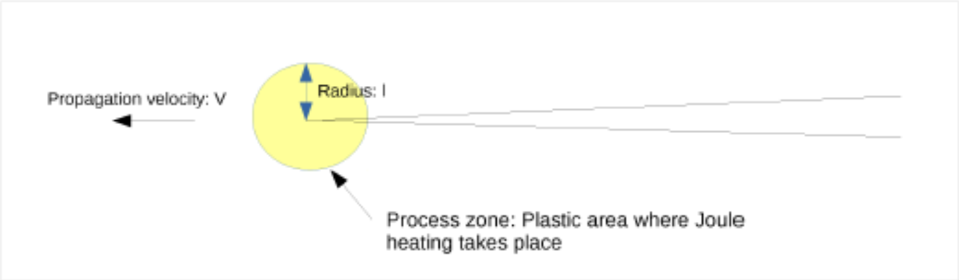


FIG. 3. (Bottom): Modelled G_a thresholds (squares) compared to the experimental ones from the literature. The black line is the identity. The energy barriers G_c (triangles), modelled from Eq. (3), are also shown for comparison. The labels locate different materials. See the supplementary material for the exhaustive list. (Top): Relative error on the avalanche threshold.

The heat diffusion equation



$$\Delta T = T - T_{room}$$

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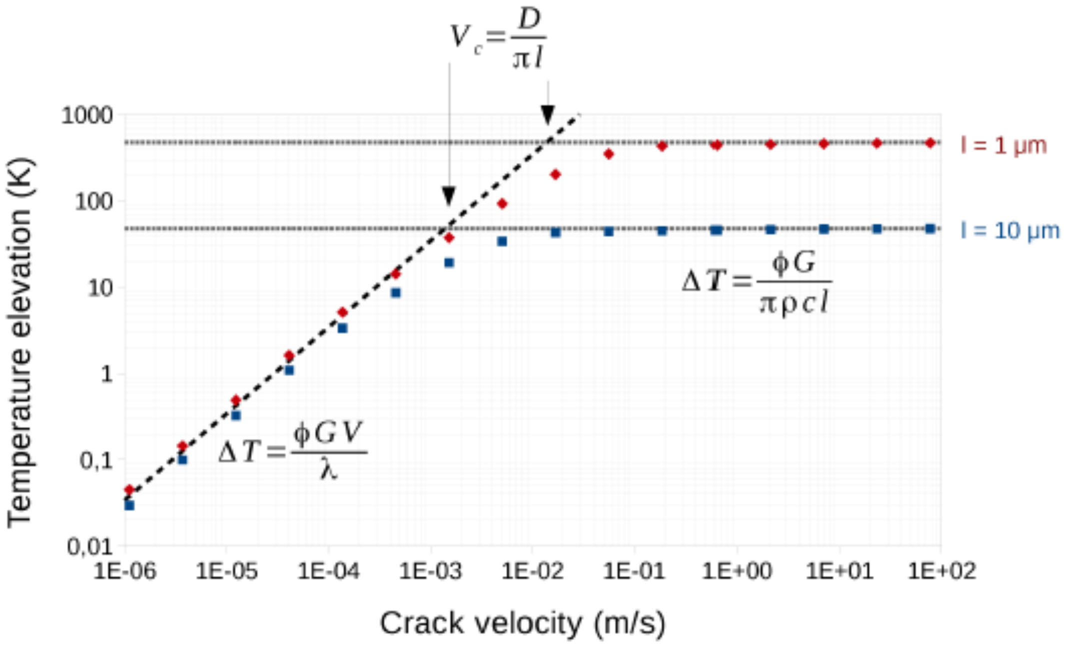
Diffusion equation for the temperature elevation

Loss in the surrounding air

Source term in the process zone, Notably depending on:

- **A proportion of the fracture energy:** ϕG
- **The crack velocity:** V
- **The zone area:** πl^2

Temperature elevation, velocity and process zone size



At high speed: $\delta = \sqrt{\frac{Dl}{\pi V}} < l \qquad \Delta T = \frac{\phi G l h}{\rho c (\pi h l^2)} = \frac{\phi G}{\pi \rho c l}$

At low speed: $\delta = \sqrt{\frac{Dl}{\pi V}} > l \qquad \Delta T = \frac{\phi G l h}{\rho c (\pi h \delta^2)} = \frac{\phi G V}{\lambda}$

G: energy release rate (J/m^2)

ρ: mass density

c: heat capacity

h: paper thickness

λ: heat conductivity

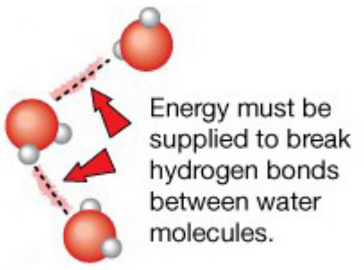
- Taking into account **effect of thermal bath on fracture**: Arrhenius
- Modeling – depinning problem and activation energy:

Subcritical crack growth model

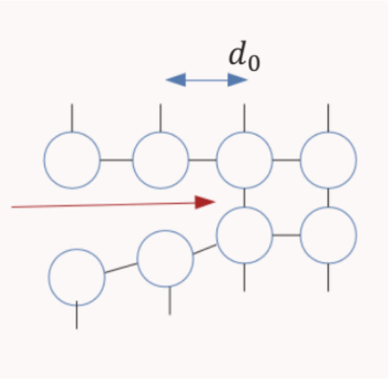
Evolution law

$$v = v_0 \exp\left(\frac{\alpha^2 \Delta G}{k_B T}\right)$$

Arrhenius relation



Ex : water
(from Rockyview school)

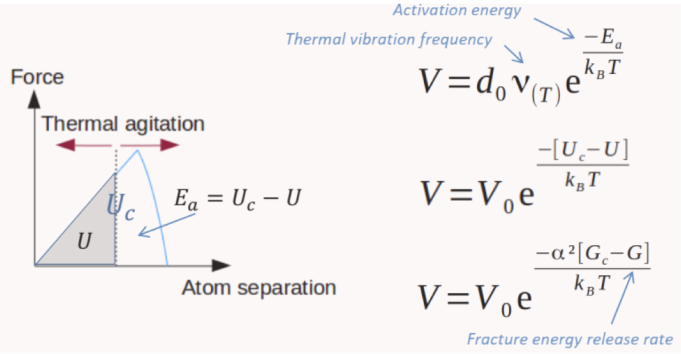


$\Delta G = G_c - G$ Fracture (Activation) energy – energy release rate

T : Temperature

α : Length scale associated with individual degrees of freedom of the microscopic fracturing process

kB : Boltzmann constant



Comparison**: stick-slip** in **tape peeling** (polymer flow/fracture)
(Santucci et al. Data), modeling Vincent-Dospital et al.

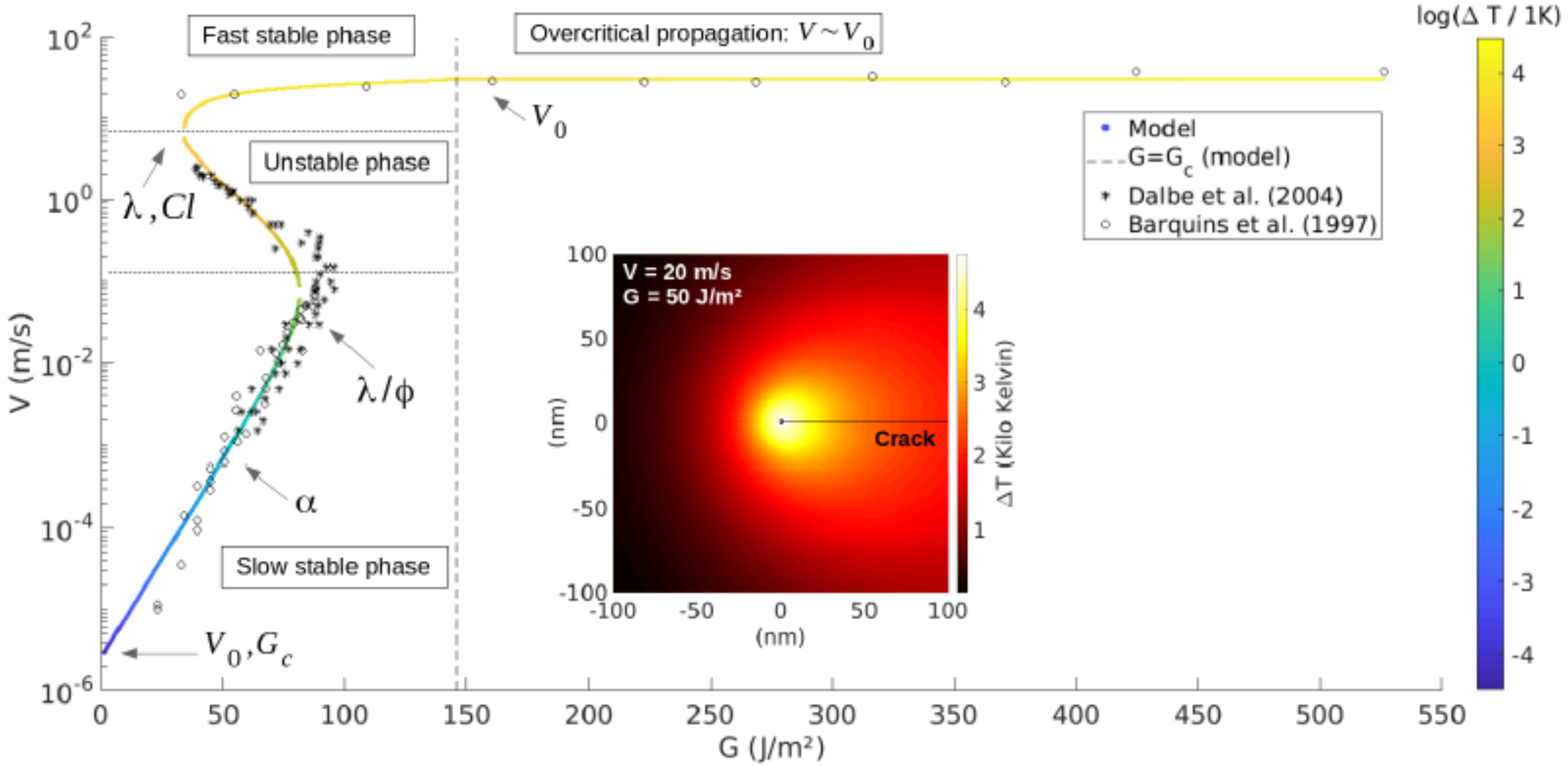
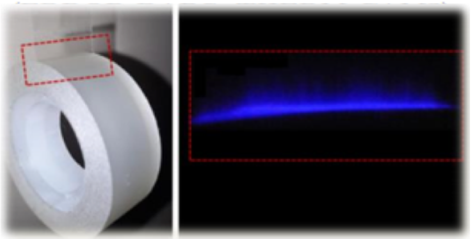
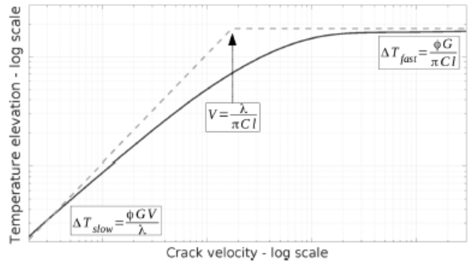


FIG. 2. Propagation velocity as a function of G as predicted by Eq. (1) and (2) and fitted to the tape experimental data[10,11]. The unstable branch cannot be measured and the data points, there, are only averaged V versus G for a crack that stick-slips, in the given set-up, between the slow and the fast phase. The Arrows indicate which model parameters each part of the curve is mainly sensitive to. The insert shows the modeled temperature field around the crack front, at the onset of the fast to slow phase shift ($V = 20$ m s^{-1}).

Associated with fractoluminescence: Black body radiation?

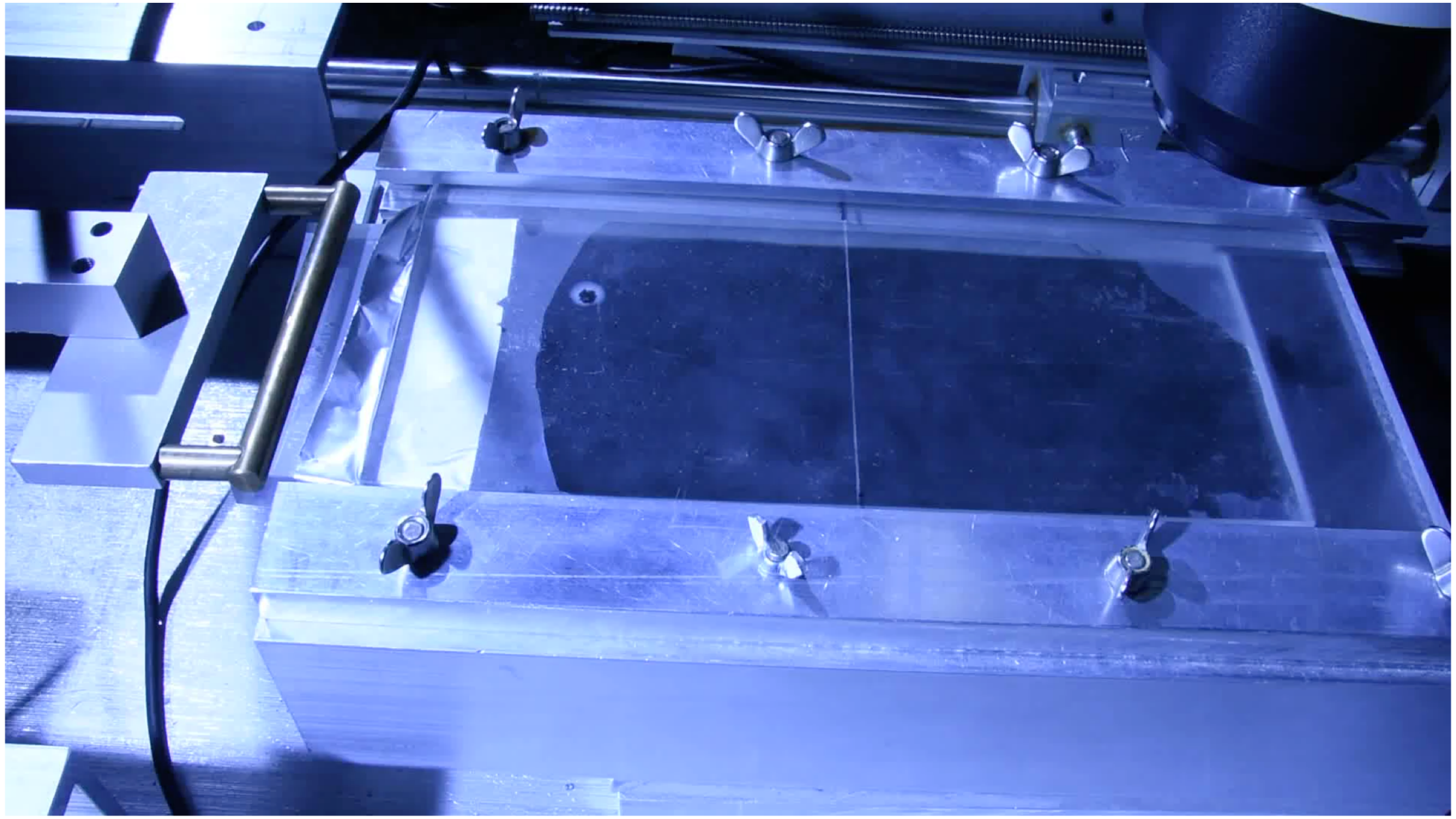


$$V = V_0\, e^{\frac{\alpha^2(G - G_c)}{k_b T}},$$

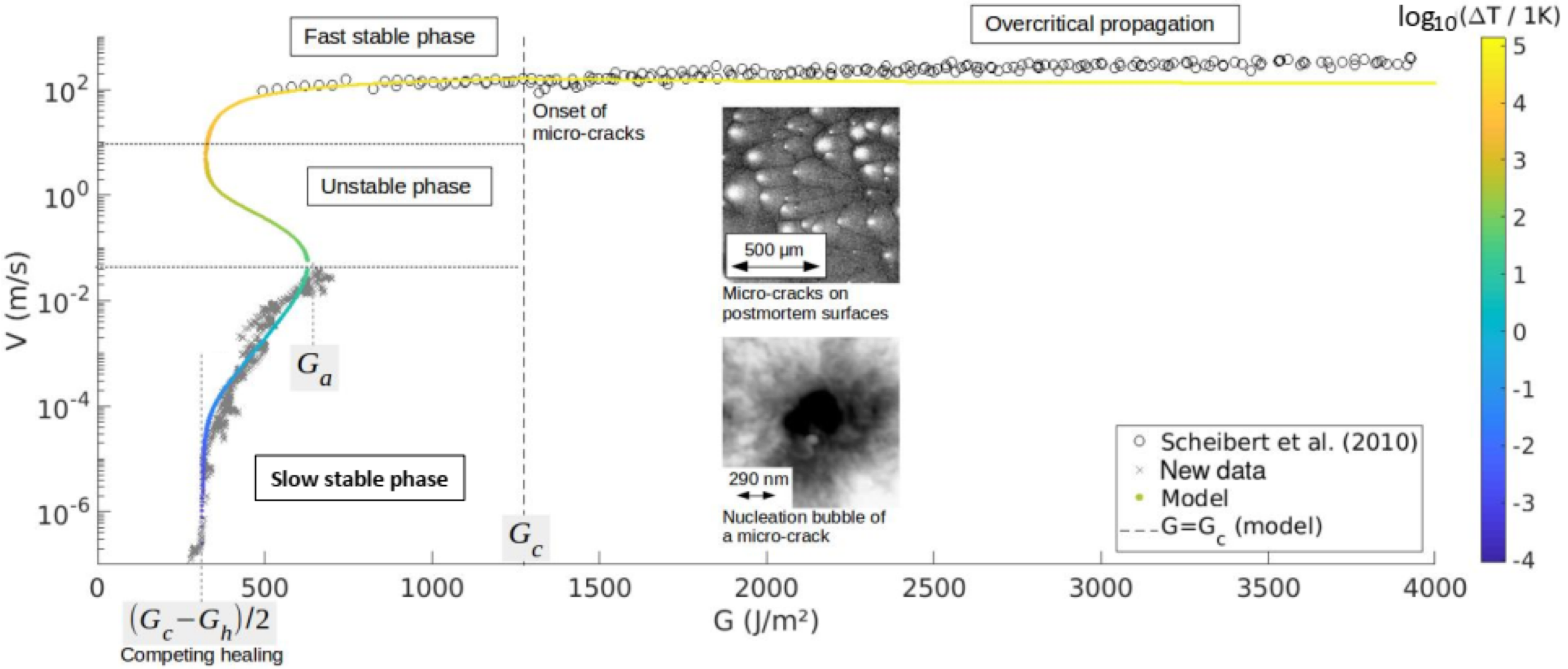


Comparison: **Fast fracture in PMMA, nucleation of damage** (Bonamy et al. Data)

Interfacial fracture in PMMA, PoreLab, Oslo:
Creep and Fast rupture

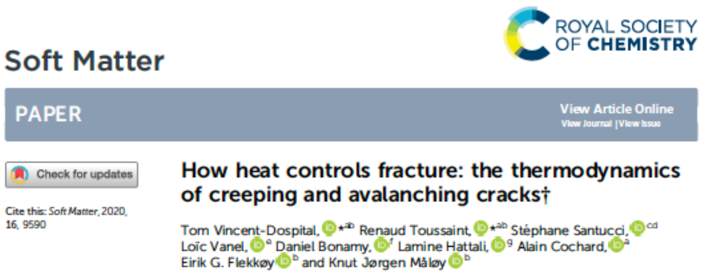


Comparison: **Fast fracture in PMMA, nucleation of damage** (Bonamy et al. Data)



$$V = v_0 e^{\frac{-\alpha^2[G_c - G]}{k_b[T_0 + \Delta T(\phi G, V)]}} - v_0 e^{\frac{-\alpha^2[G + G_h]}{k_b[T_0 + \Delta T(\phi G, V)]}}$$

Breaking **Healing**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Soft Matter

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How heat controls fracture: the thermodynamics of creeping and avalanching cracks†

Tom Vincent-Dospital, Renaud Toussaint, Stéphane Santucci, Loïc Vanel, Daniel Bonamy, Lamine Hattali, Alain Cochard, Eirik G. Flekkøy and Knut Jørgen Måløy

Vincent-Dospital, Toussaint, Santucci, Vanel, Bonamy, Hattali, Cochard, Flekkøy and Måløy, *Soft Matter*, 2020

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Research

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http://dx.doi.org/10.1098/rsta.2017.0399

Accepted: 26 September 2018

One contribution of 15 to a theme issue 'Statistical physics of fracture and earthquakes'.

Subject Areas:
geophysics, mathematical physics, mechanics, statistical physics, thermodynamics

Thermally activated crack fronts propagating in pinning disorder: simultaneous brittle/creep behaviour depending on scale

A. Cochard[1], O. Lengliné[1], K. J. Måløy[2] and R. Toussaint[1,2]

[1]Institut de Physique du Globe de Strasbourg, UMR 7516 CNRS, Université de Strasbourg/EOST, Strasbourg, France
[2]PoreLab, The Njord Center, Department of Physics, University of Oslo, Blindern, Oslo, Norway

RT, 0000-0002-3698-1934

We study theoretically the propagation of a crack front in mode I along an interface in a disordered elastic medium, with a numerical model considering a thermally activated rheology, toughness disorder and long-range elastic interactions. This model reproduces not only the large-scale dynamics of the crack front position in fast or creep loading regimes, but also the small-scale self-affine behaviour of the front.

scientific reports

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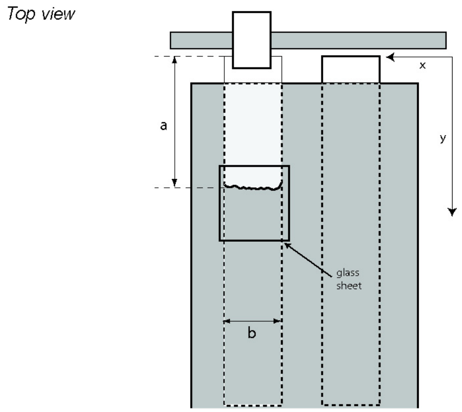
Thermally activated intermittent dynamics of creeping crack fronts along disordered interfaces

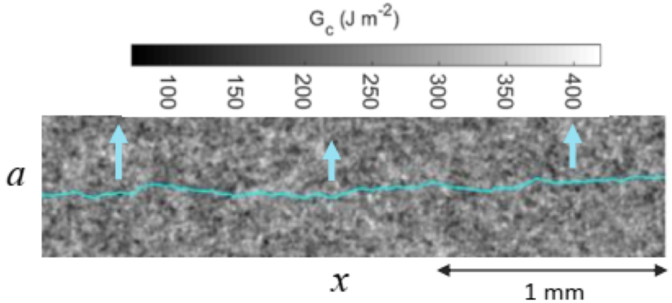
Tom Vincent-Dospital[1,2], Alain Cochard[1], Stéphane Santucci[3,4], Knut Jørgen Måløy[2] & Renaud Toussaint[1,2]

Avalanches and comparison to experiments, at fixed T

- Experimental setup (PMMA, Oslo group, Tallakstad, Maloy, Santucci et al.) to study intermittent crack front propagation in transparent material



Mode I; fixed temperature, non linear law (Arrhenius) for v(G), quenched disorder+elastic interactions



Load redistribution from front roughness

Average load

Medium toughness

$$V = V_0 e^{\frac{\alpha^2[\bar{G} + G_e - G_c]}{k_B T}}$$

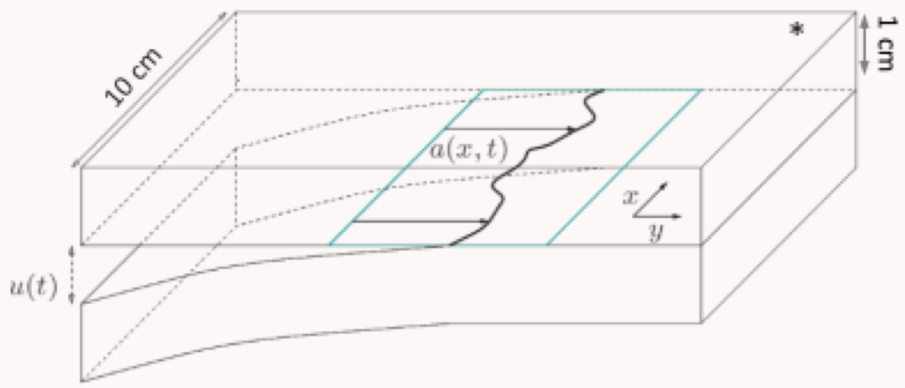
Environment

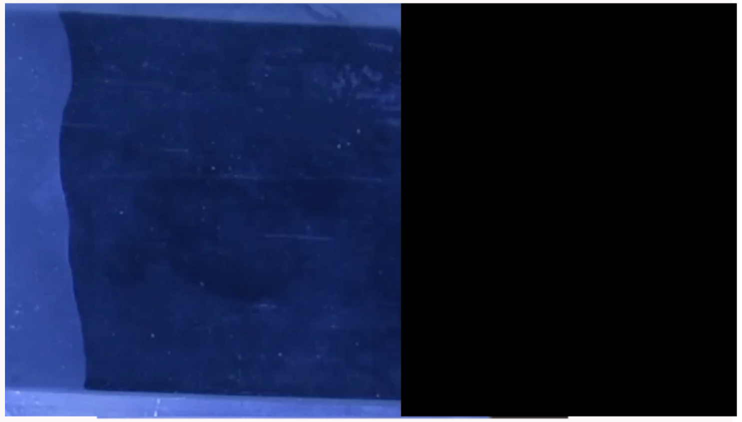
$$G_e(x,t) = -\frac{1}{\pi}\mathrm{PV}\int_{-\infty}^{+\infty} \frac{\partial a(x',t)/\partial x'}{x - x'}\mathrm{d}x'.$$

Gao and Rice, 1989

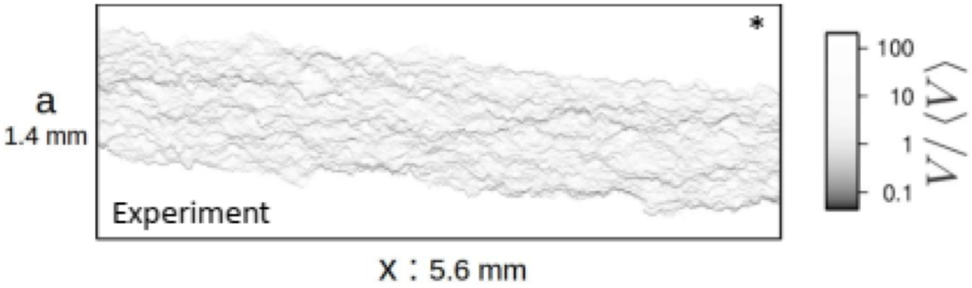
Cochard et al., 2018

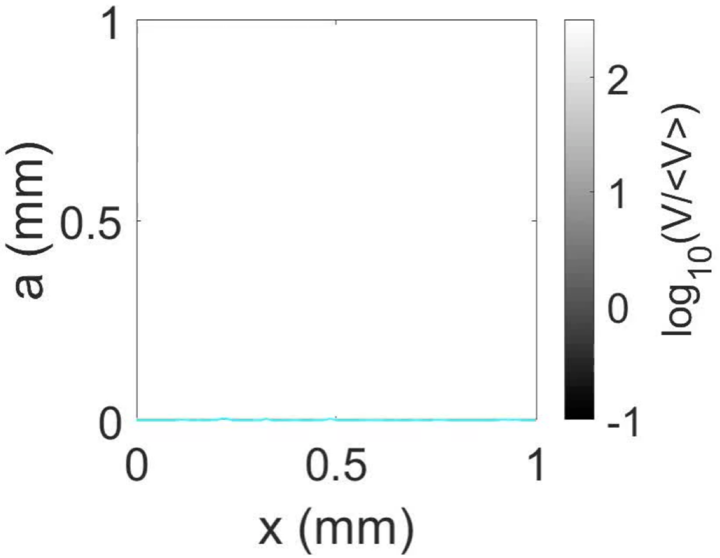
Global view:





Through a microscope:





* Cochard et al., 2018, Experiments from Tallakstad et al., 2011

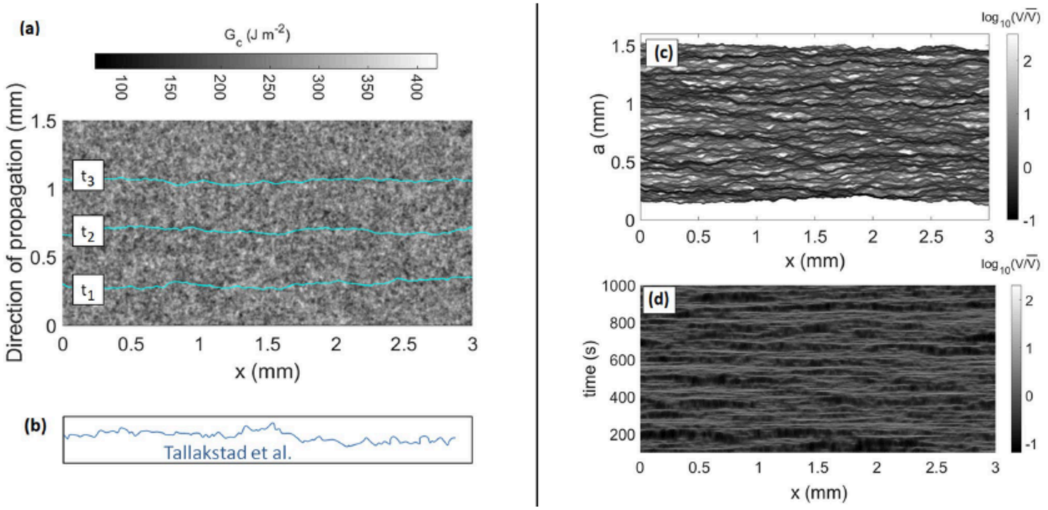
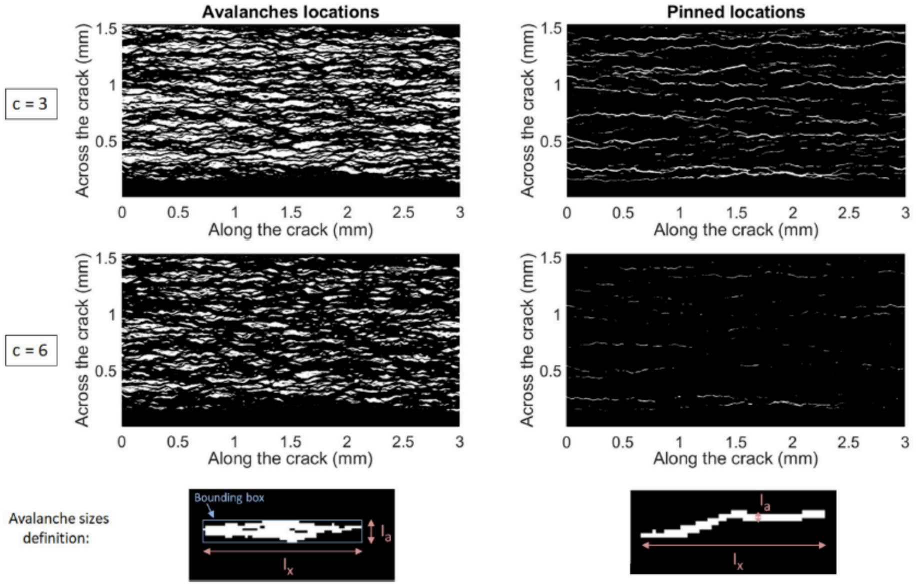
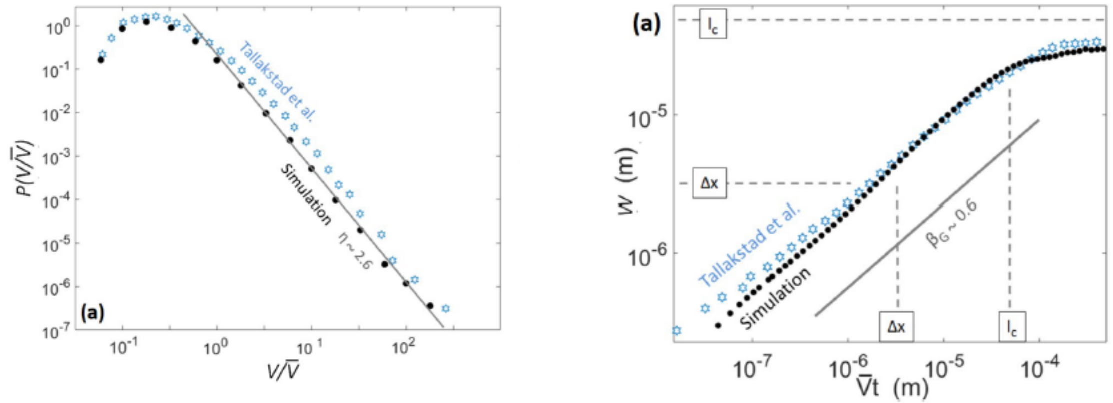


Figure 3. (a) Normal distribution of the fracture energy G_c considered for the simulations. The average value is $\overline{G_c} = 250\,\mathrm{J\,m^{-2}}$, with a standard deviation $\delta G_c = 35\,\mathrm{J\,m^{-2}}$ and a correlation length $l_c = 50\,\mu\mathrm{m}$. The three lines are the modelled propagating front at three different times $t_1 < t_2 < t_3$, using Eqs. (1) and (2). (b) A crack front reported by Tallakstad et al.[28] (Fig. 3 of the experimental paper), plotted on the same spatial scales. (c,d) Local velocity maps $V(x, a)$ in the space–space domain (c) and $V(x, t)$ in the space-time domain (d) for a modelled crack propagating in this G_c landscape. Both maps are shown with the same color scale and they are computed on a resolution similar to that of the experiments by Tallakstad et al.[28], using the waiting time matrix (see text for details). The velocity are plotted related to the average crack velocity $\overline{V} = 1.5\,\mu\mathrm{m\,s^{-1}}$. All parameters used run the corresponding simulation are summarised in Table 1.





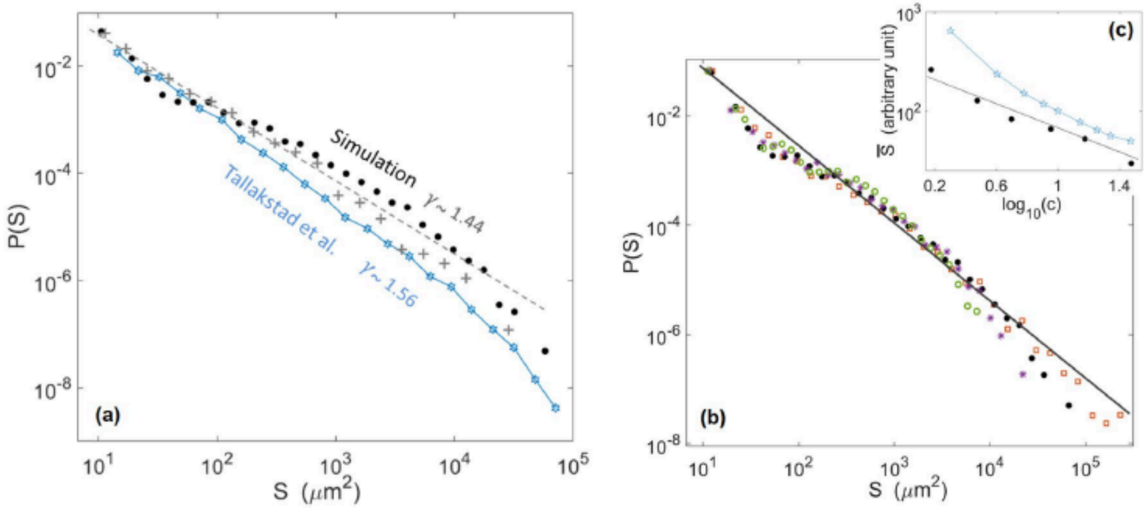
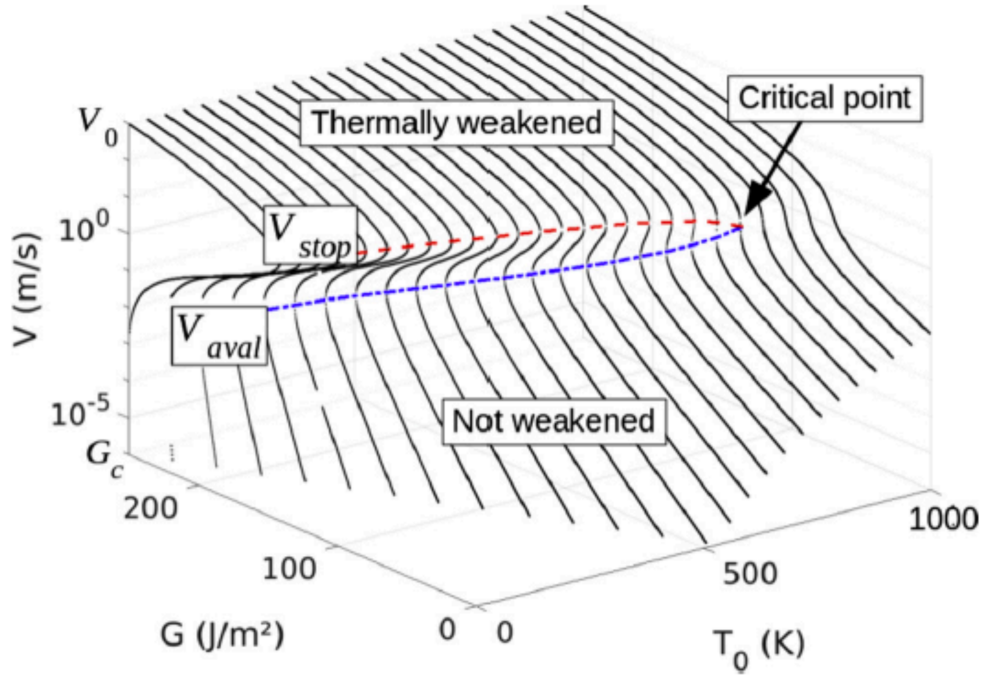


Figure 8. (a) Probability density function of the surface of the modelled avalanche clusters (plain points) and of the modelled pinning clusters (crosses), for a threshold $c = 3$. The straight dashed line has a slope $\gamma = 1.44$, as per Eq. (12). For comparison, the hollow stars show the experimental probability density function obtained by Tallakstad et al.[28] for the avalanche and pinning clusters (both are overlapping, see Fig. 10 of their manuscript). (b) Same probability density function for various c values: $c = 1.5$ (squares), $c = 3$ (plain points), $c = 6$ (stars), $c = 12$ (circles). The straight line has a slope $\gamma = 1.4$, as per Eq. (12). (c) Variation of the mean avalanche size $\overline{S}$ as a function of the threshold c for the simulation (plain points) and the experiments (hollow stars). The

This framework also leads to the description of brittleness as a first order phase transition, and brittle/ductile transition as a second order phase transition (a critical point)

PHYSICAL REVIEW MATERIALS 4, 023604 (2020)

V : rupture velocity
T_0 : ambient temperature
G: loading (applied energy release rate)



PHYSICAL REVIEW MATERIALS 4, 023604 (2020)

Thermal weakening of cracks and brittle-ductile transition of matter: A phase model

Tom Vincent-Dospital,[1,2,*] Renaud Toussaint,[1,2,†] Alain Cochard,[1] Knut Jørgen Måløy,[2] and Eirik G. Flekkøy[2]
[1]*Université de Strasbourg, CNRS, Institut de Physique du Globe de Strasbourg, UMR 7516, 5 rue René Descartes, F-67000 Strasbourg, France*
[2]*SFF Porelab, The Njord Centre, Department of Physics, University of Oslo, P. O. Box 1048, Blindern, N-0316 Oslo, Norway*