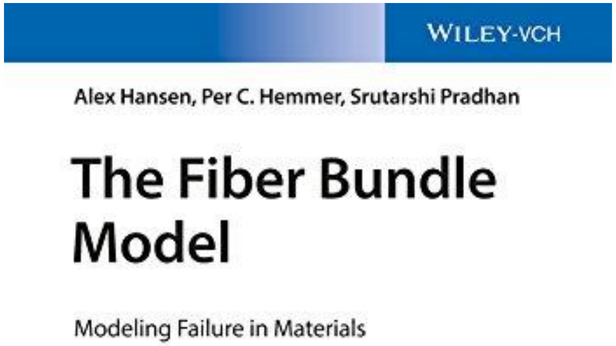
Fiber-Bundle models in fracture

A tentative overview

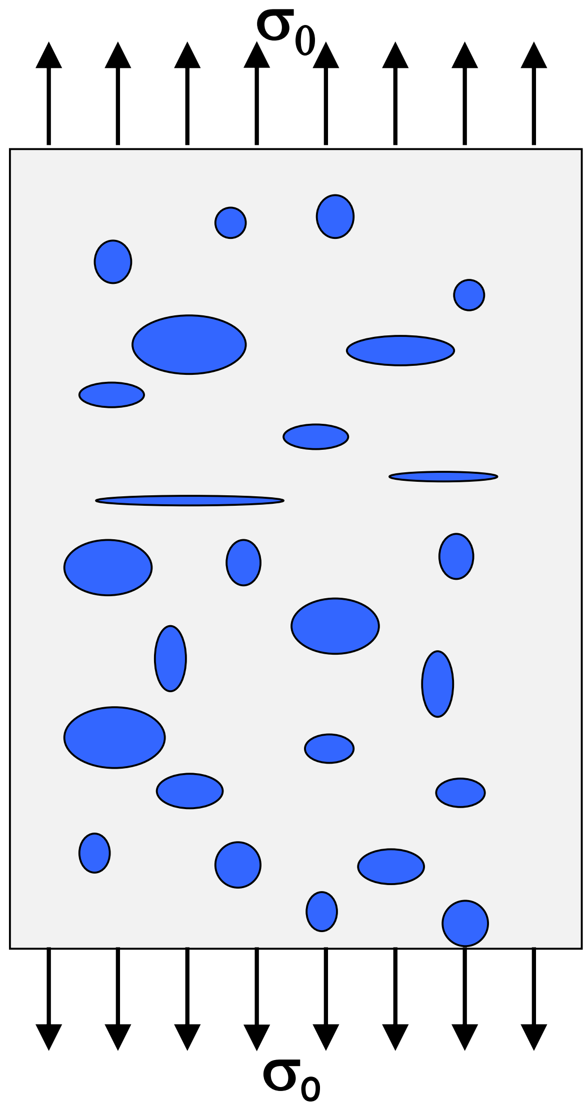
Daniel Bonamy

Service de Physique de l'Etat condensé -- SPEC

CEA Saclay -- Orme des Merisiers



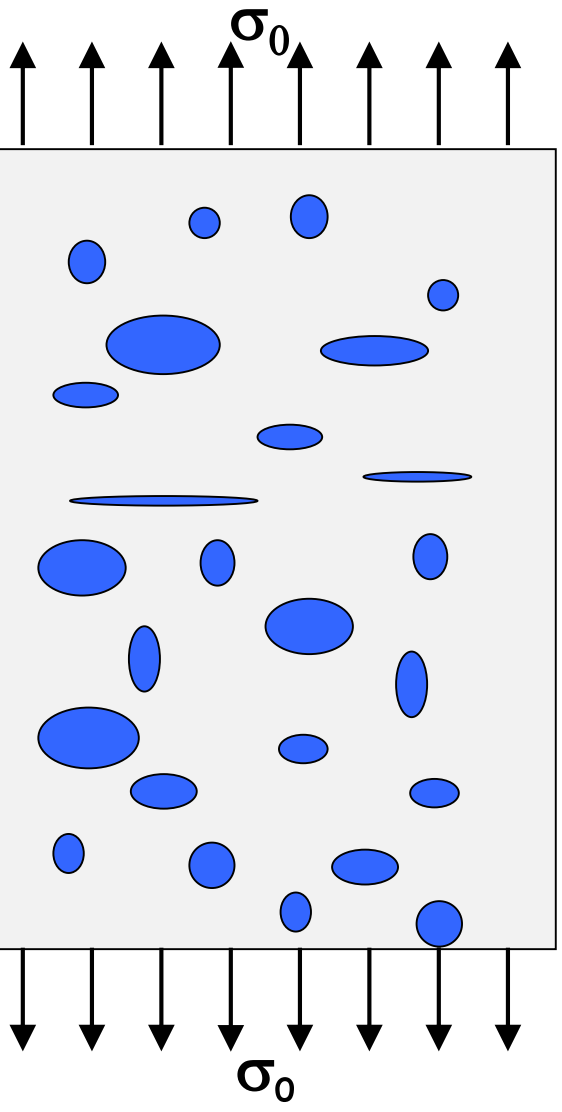
Complexity in fracture



Elastic response, elastic properties

$$E_{global} \cong mean(E_{local})$$

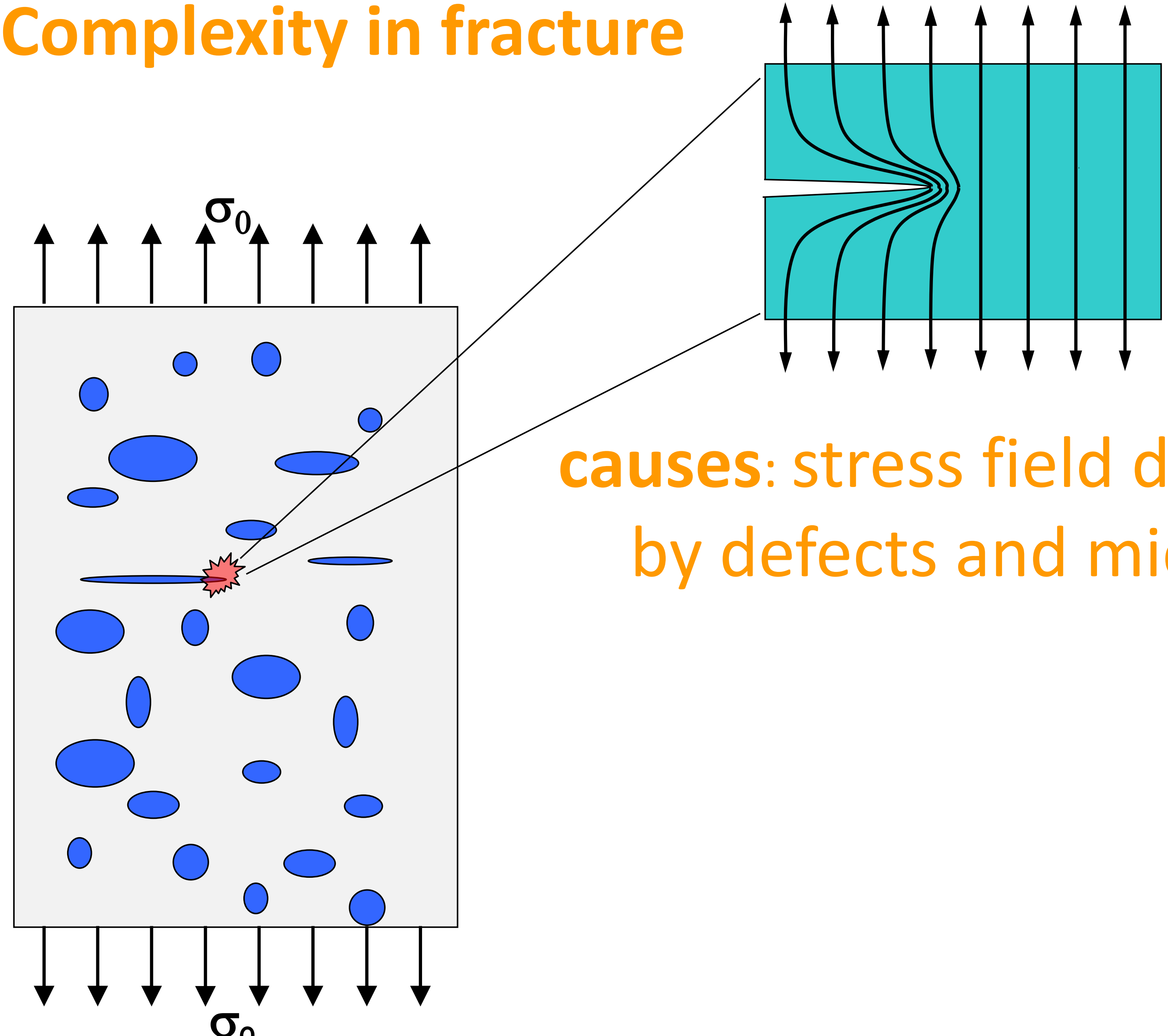
Complexity in fracture



Failure, strength in materials

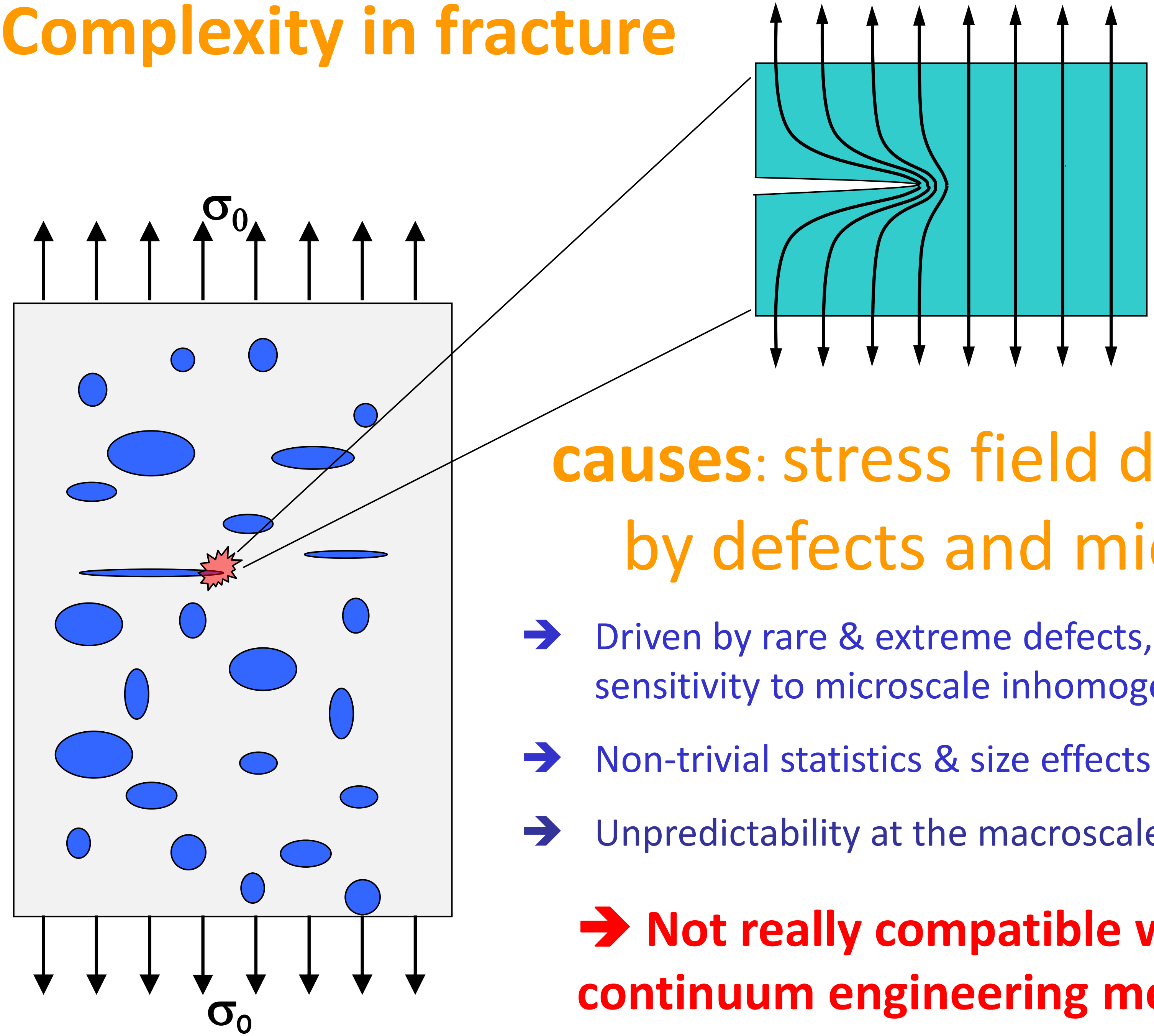
$$\sigma^f{}_{global} \cong mean(\sigma^f{}_{local})$$

Complexity in fracture



causes: stress field distortion by defects and microcracks

Complexity in fracture



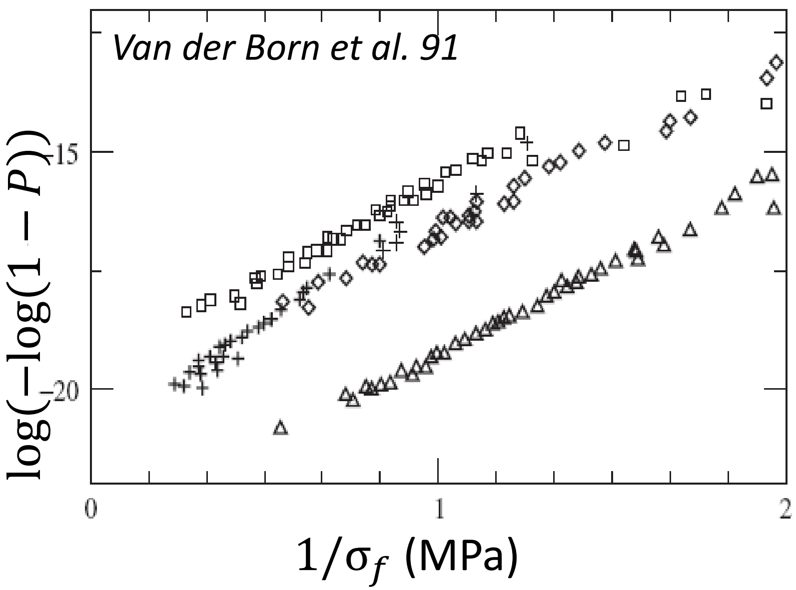
causes: stress field distortion by defects and microcracks

- ➔ Driven by rare & extreme defects, macroscale sensitivity to microscale inhomogeneities,
- ➔ Non-trivial statistics & size effects for strength
- ➔ Unpredictability at the macroscale

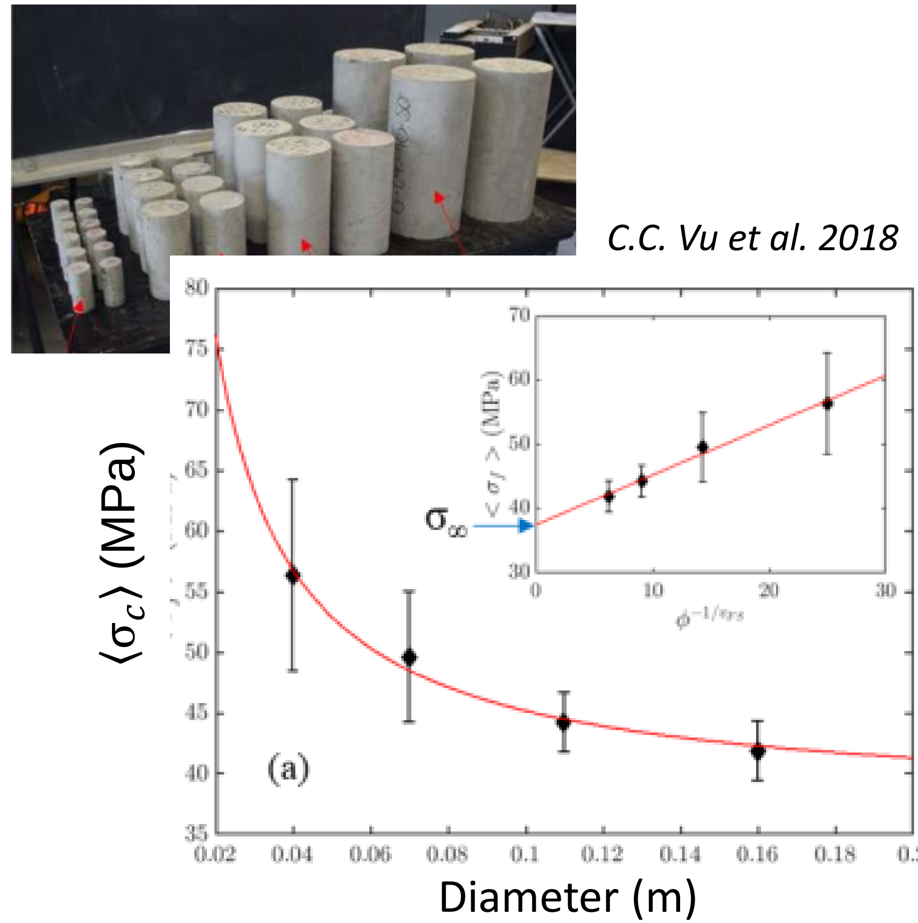
➔ Not really compatible with continuum engineering mechanics

Complexity in fracture : illustrations (1/2)

Extreme event statistics on strength
[Here Duxbury-Leath law on ceramics components]

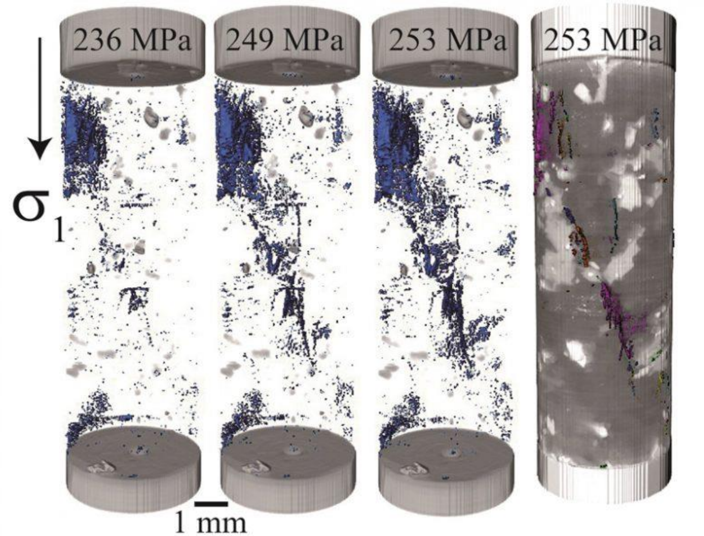


Non-trivial size dependency on strength [Here on concrete]



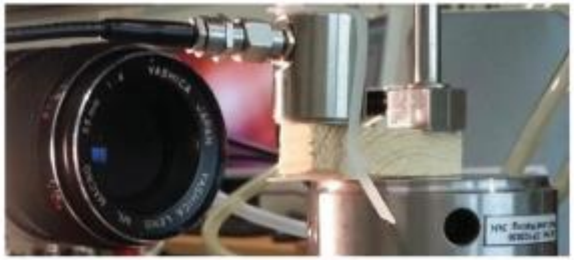
Complexity in fracture : illustrations (2/2)

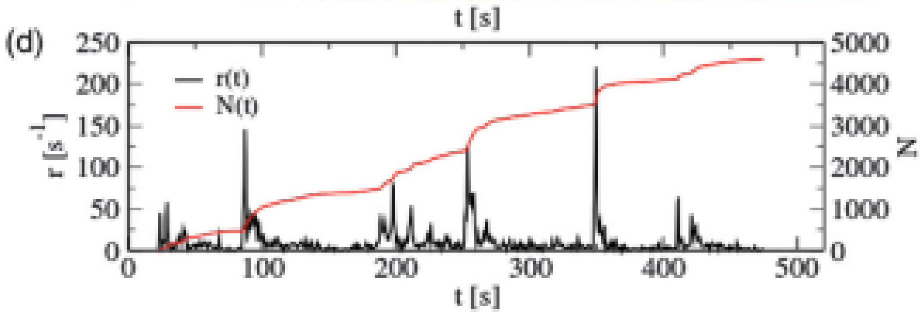
X-ray tomography imaging of damage in rocks *Renard et al. 2018*

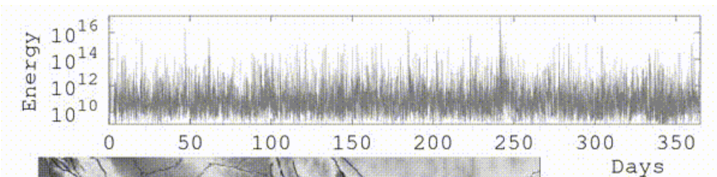


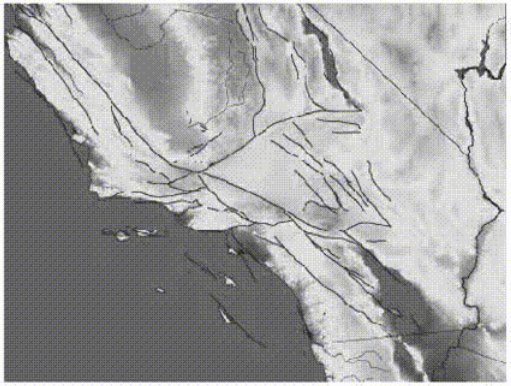
Acoustic emission in compressed wood

Makinen et al. 2015









Sismicity in California, 2012

Bares. 2013

Highly intermittent dynamics
Damage localization in space

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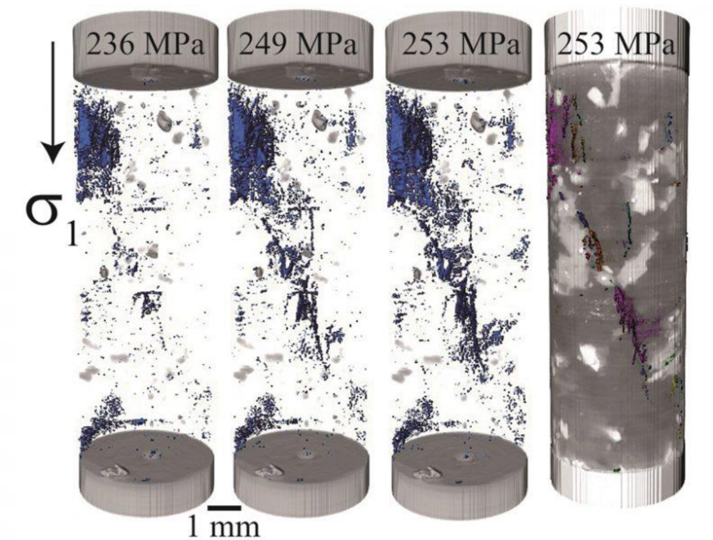

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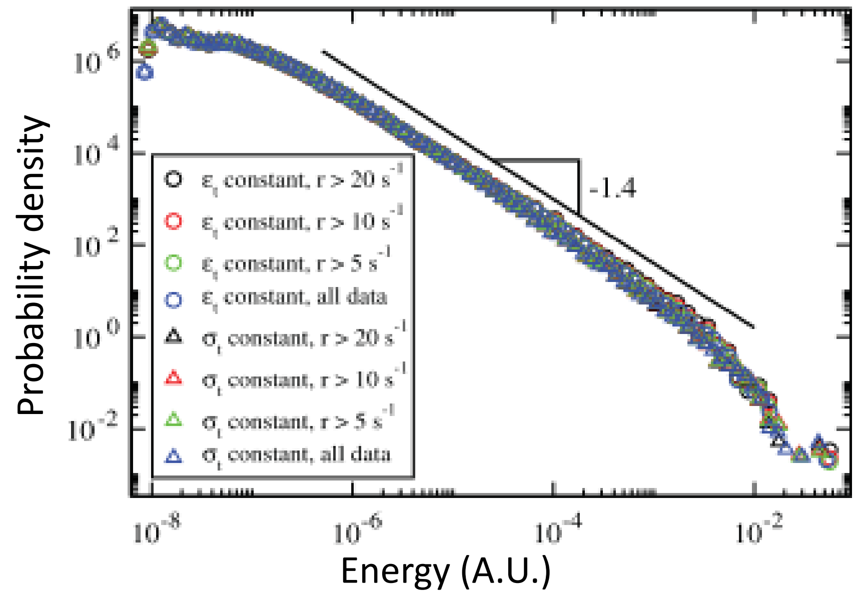

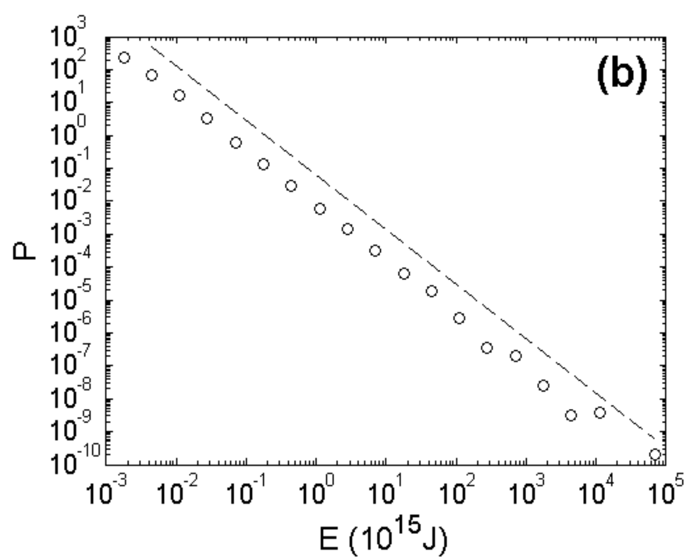

Highly intermittent dynamics
Damage localization in space

Scale-free avalanches of damage
Power-law distributed size/energy

Fiber Bundle Models (FBM): the approach

Material simplified to:

N parallel brittle fibers
Same stiffness $\kappa = 1$

Random failure threshold

Prescribed rules for load redistribution


F.T. Pierce, 1926


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Equal load Sharing (ELS)
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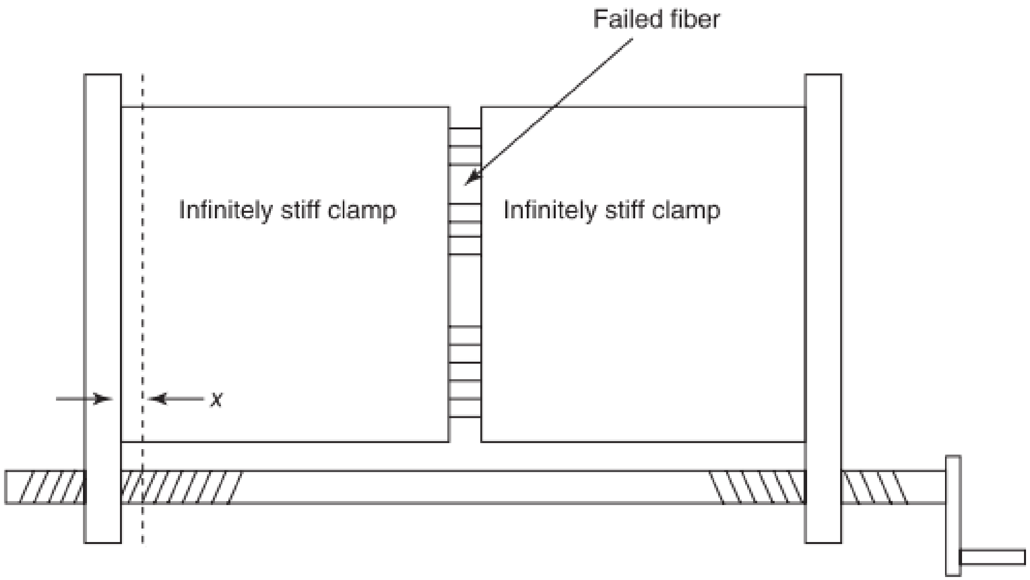

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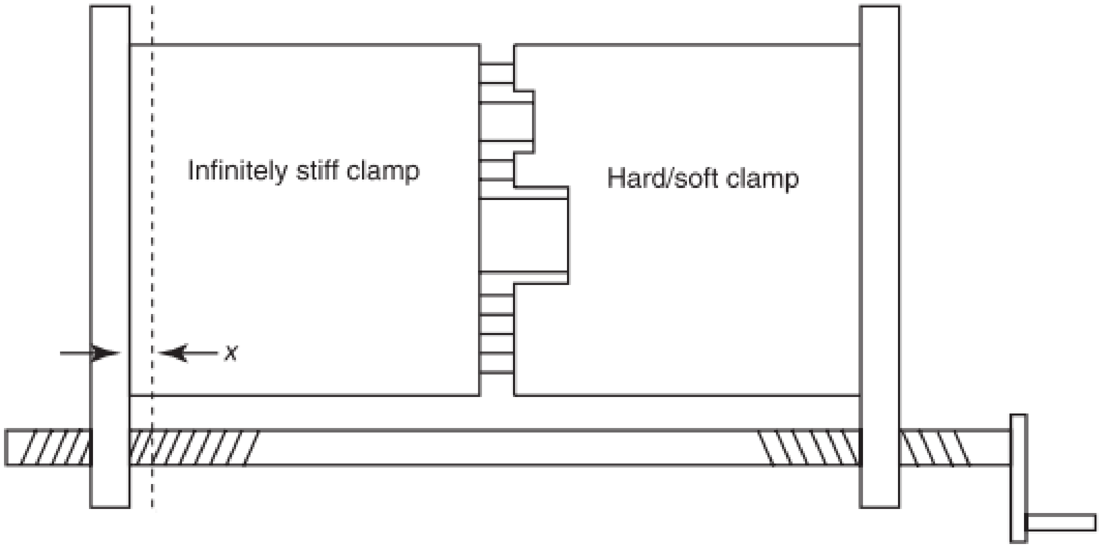

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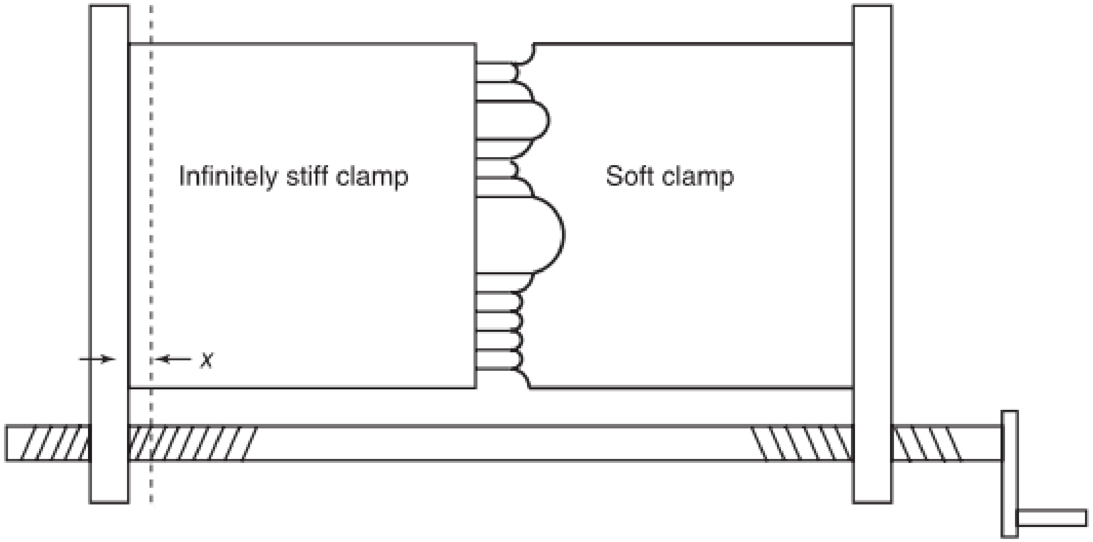
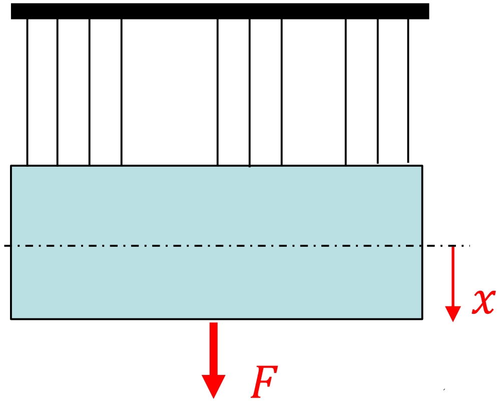
Intermediate load Sharing (ILS)
Load transfer decreases with distance from failed fiber



ELS -- FBM: continuum (average) behavior



- $N \to \infty$ parallel brittle fibers
- Overall stretching force F, => stress $\sigma = F/N$
- Same stiffness $\kappa = 1$
- Same fiber extension : x
- Random critical loads x_i with distribution $p(x)$ [cumulative $P(x)$]

Fully tractable analytically

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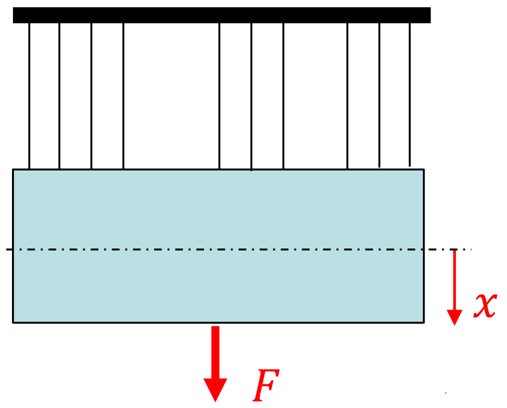

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Displacement-driven “experiment”, at displacement x:

Number of intact fibers: $\mathrm{n}(x) = N\big(1 - P(x)\big)$

➔ Density: $\rho = n/N$: $\rho(x) = 1 - P(x)$

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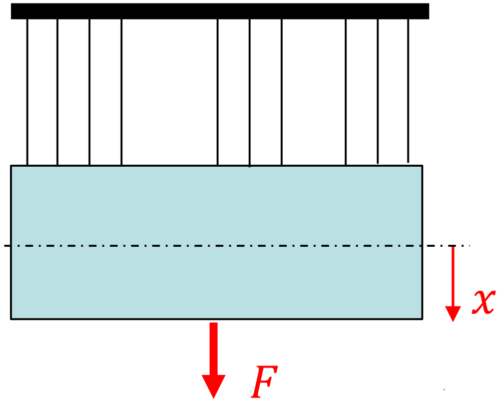

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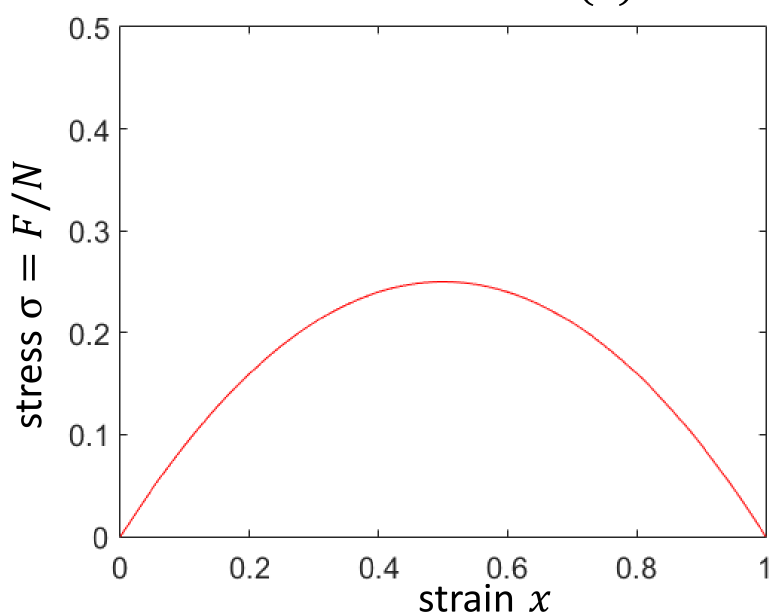
➔ Applied stress $\sigma(x) = x\,\big(1 - P(x)\big)$

Uniform distribution $P(x) = x$



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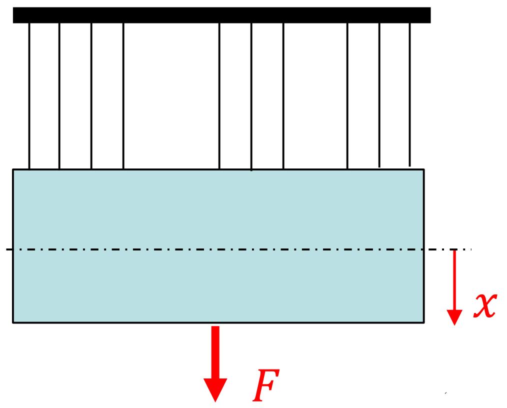

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➔ Density: $\rho = n/N$: $\rho(x) = 1 - P(x)$

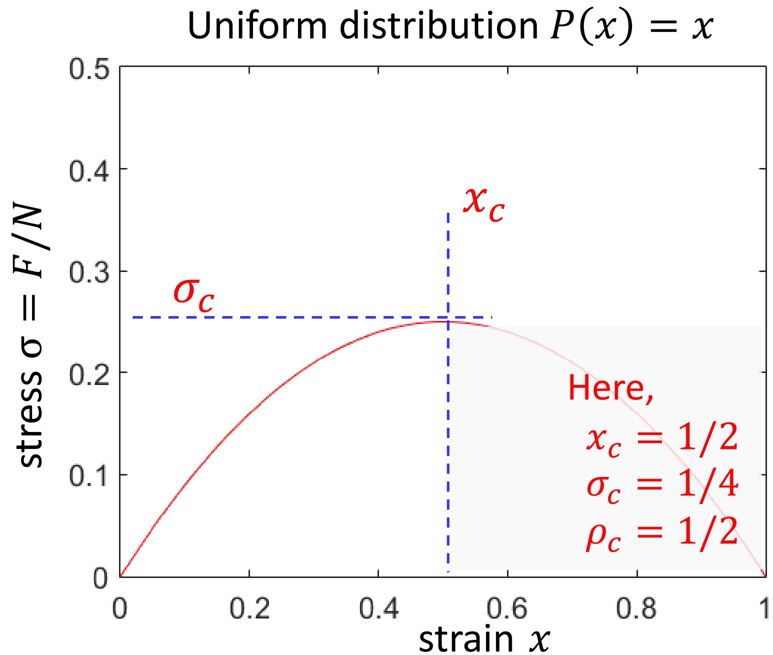
Stretching force $\mathrm{F}(x) = xn(x)$

➔ Applied stress $\sigma(x) = x\,(1 - P(x))$

Failure at the maximum point:

➔ Strength $\sigma_c = \sigma(x_c)$, so that $\sigma'(x_c) = 0$

➔ Critical damage: $\rho_c = \rho(x_c)$



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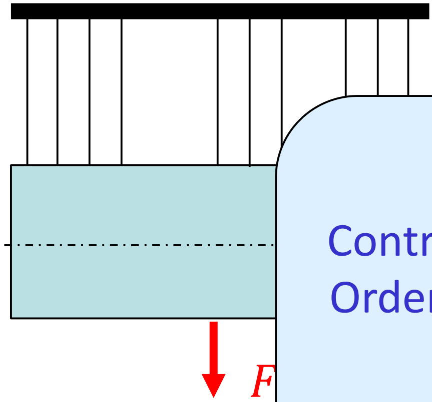

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- ss $\sigma = F/N$
- bution $p(x)$
- ulative $P(x)$]

Critical behavior at failure

Control parameter : σ
Order parameter : $\rho - \rho_c$

$$\rho - \rho_c \sim (\sigma_c - \sigma)^{1/2}$$
$$\frac{\mathrm{d}\rho}{\mathrm{d}\sigma} \sim (\sigma_c - \sigma)^{-1/2}$$

Universal, independent of $P(x)$

Fully tractable ana

Displacement-drive

Number of intact fibers: $\mathrm{n}(x) = N\big(1 - P(x)\big)$
➔ Density: $\rho = n/N$: $\rho(x) = 1 - P(x)$

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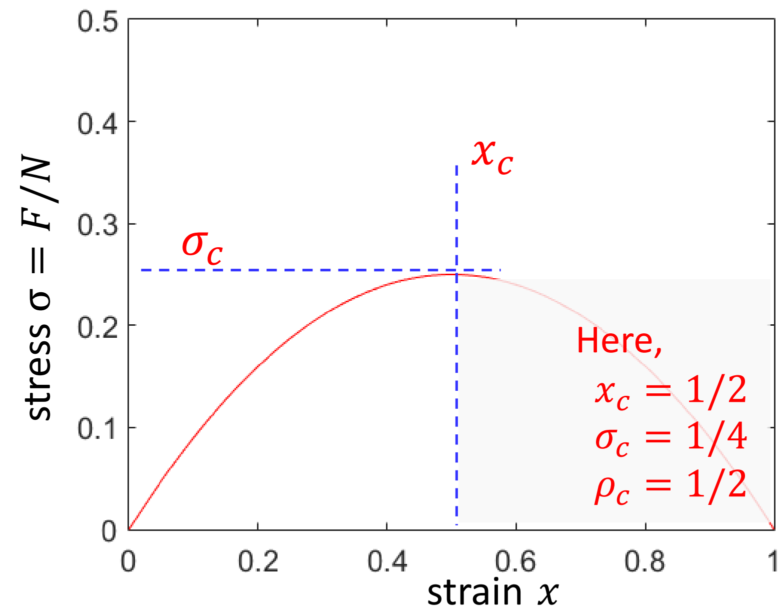
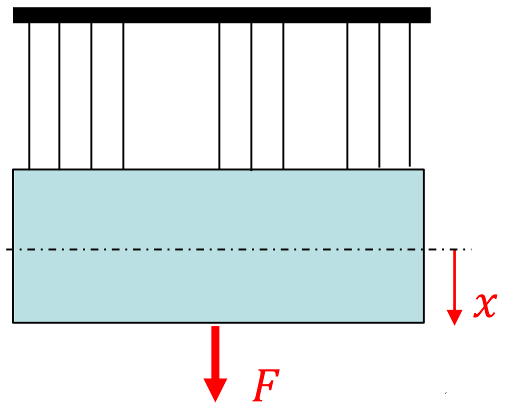


ELS -- FBM: size effect and fluctuations



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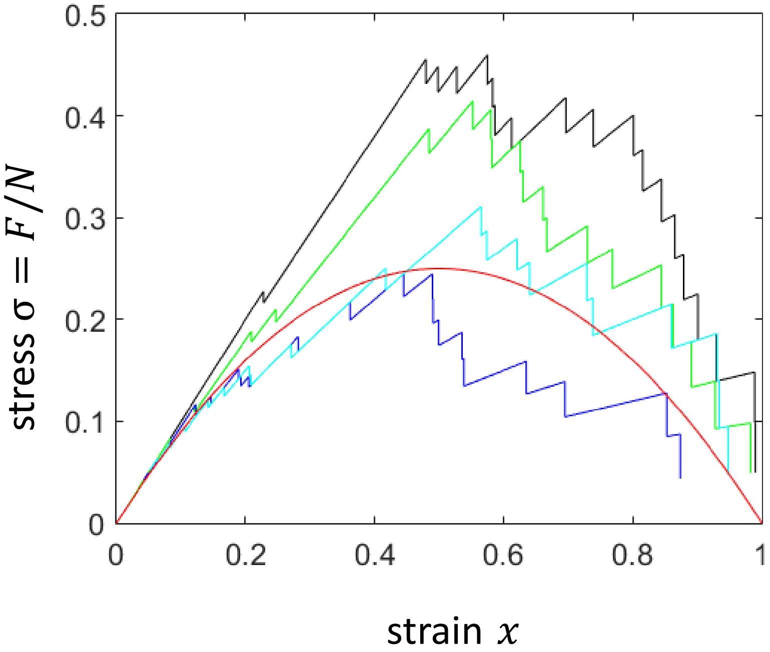
Uniform distribution $P(x) = x, N = 20$

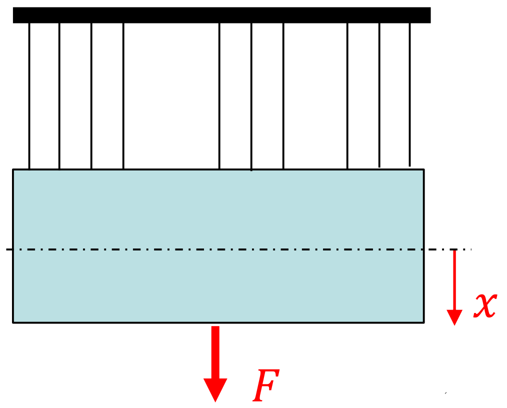


$pdf(\sigma|x, N)$ known analytically (roughly Gaussian)

Daniels, Prc. R. Soc. London A, 1945

- :$\langle\sigma_N\rangle(x) = x\big(1 - P(x)\big)$
- $\langle(\sigma_N - \langle\sigma_N\rangle)^2\rangle(x) = x^2 P(x)\big(1 - P(x)\big)$/N

ELS -- FBM: size effect and fluctuations



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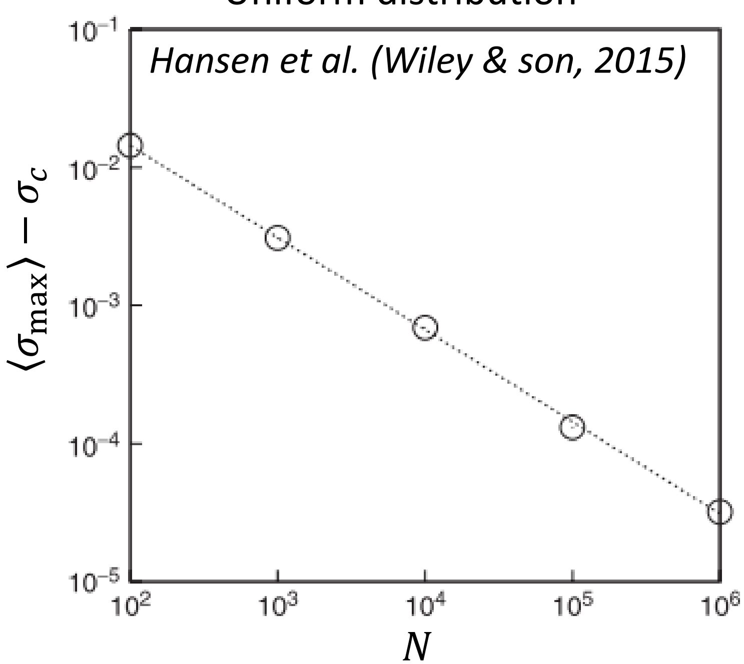
Uniform distribution



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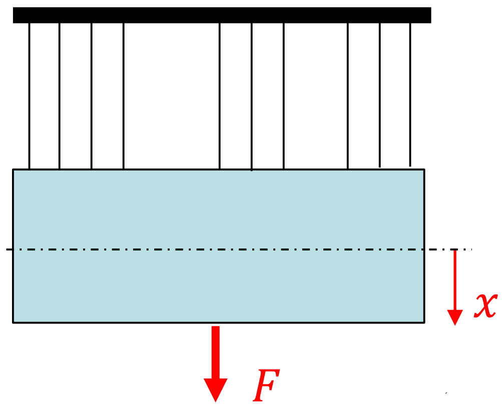
(Tiny) size effect on strength

$$\langle \sigma_{\max\,|N} \rangle = \sigma_c + K/N^{2/3}$$

ELS -- FBM: avalanches precursors



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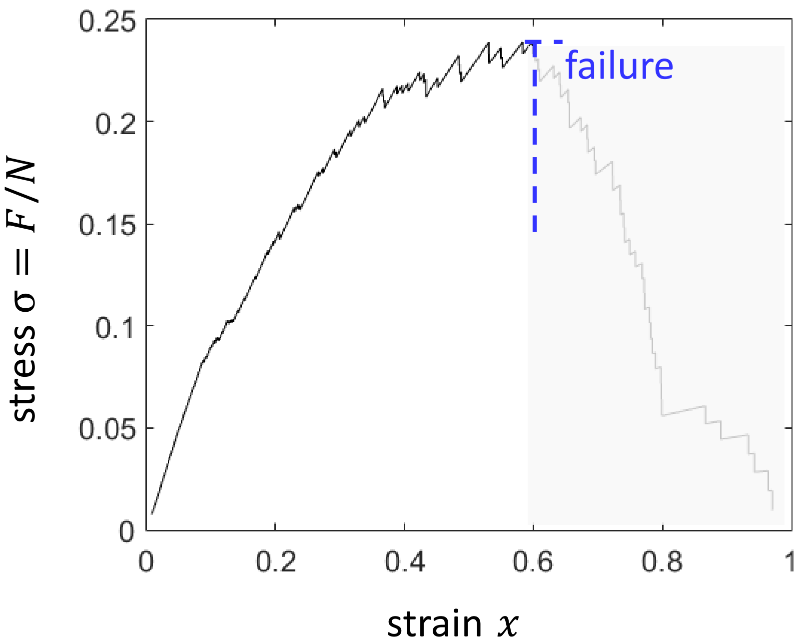
Uniform distribution $P(x) = x, N = 100$



Displacement imposed experiment

➔ monotonic $\sigma(x)$

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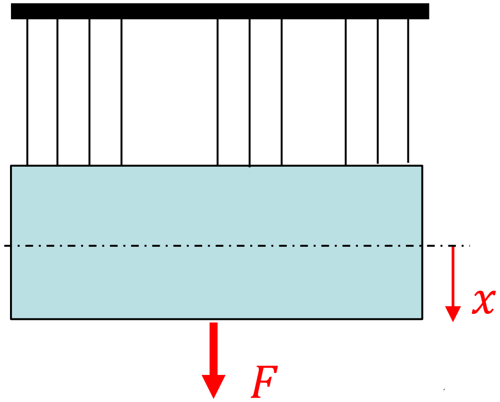

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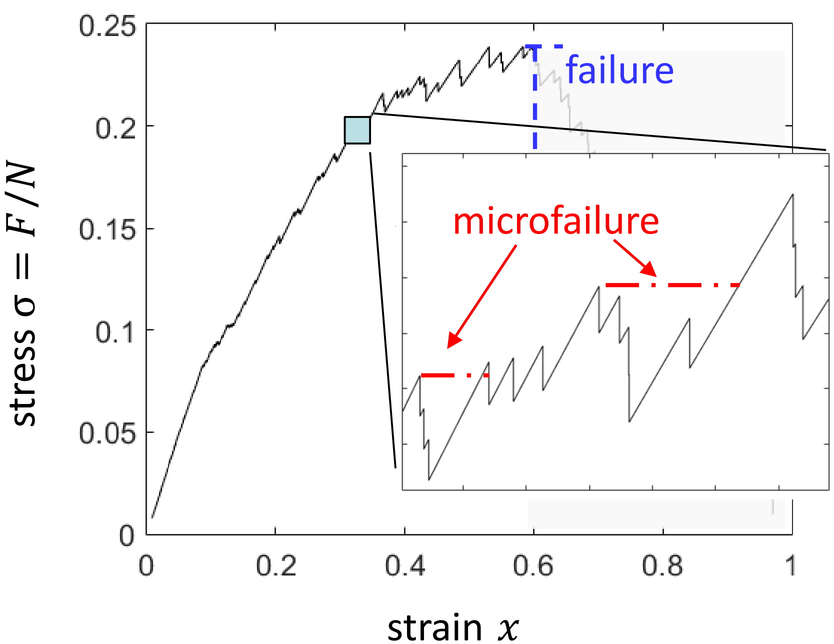

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Avalanche size S = number of fibers involved in microfailure

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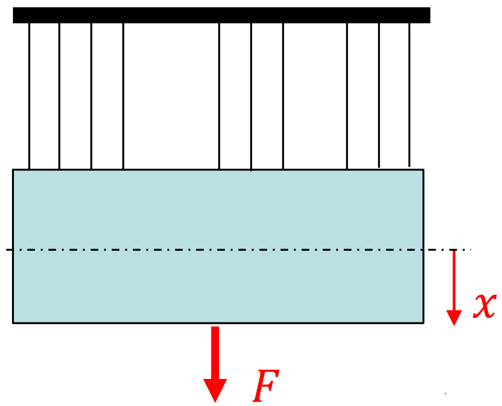

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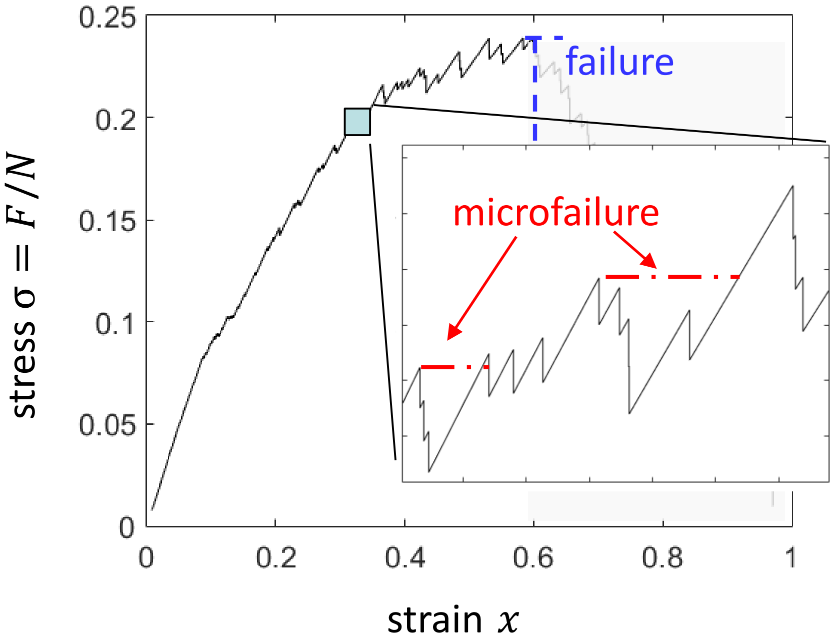

Displacement imposed experiment
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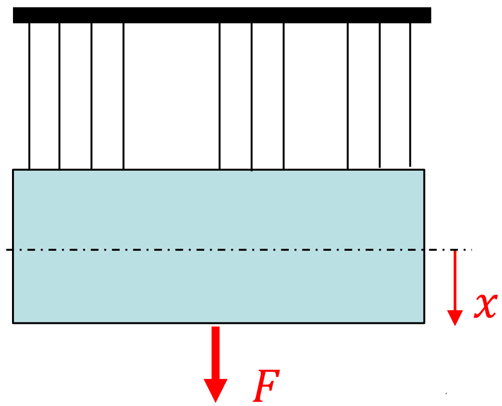
Size distribution fully computable analytically
Hansen & Hemmer 1992, 1994

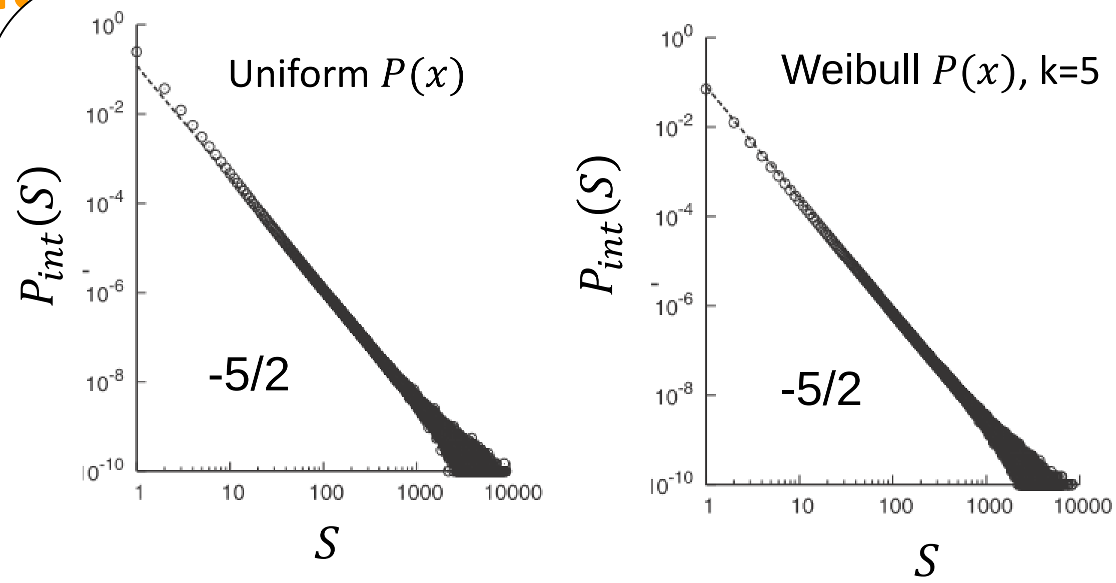
at failure: $P(S|\sigma_c) \sim S^{-3/2}$
before failure: $P(S|\sigma) \sim S^{-3/2} \exp(-S(\sigma - \sigma_c))$

integrated $P_{int}(S) \sim S^{-5/2}$

Interpretable via random walk

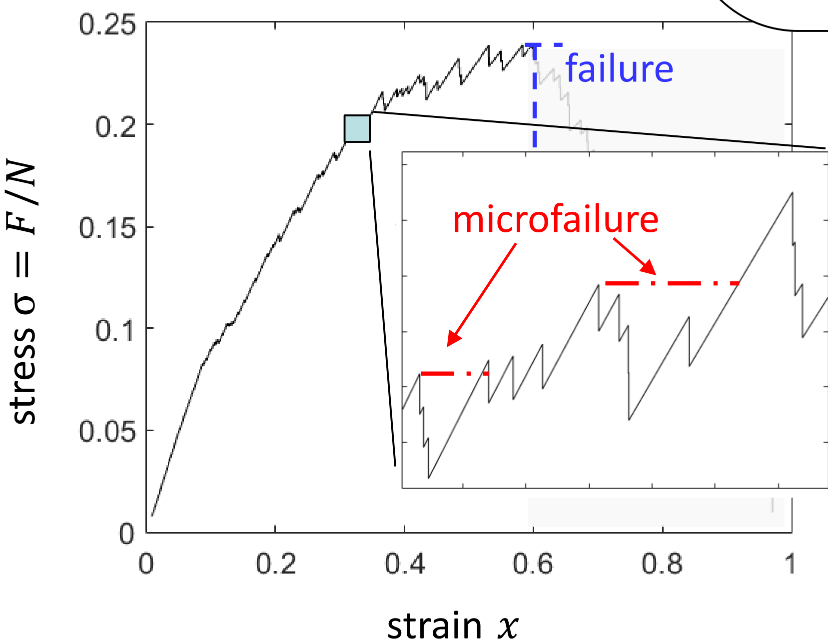
ELS -- FBM: avalanches precursors





20000 sample, N=10^6, from Pradhan et al. 2010

Uniform distribution $P(x) = x$, $N =$



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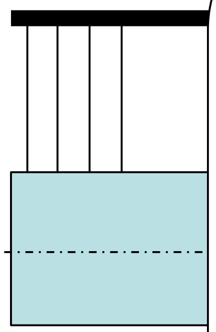
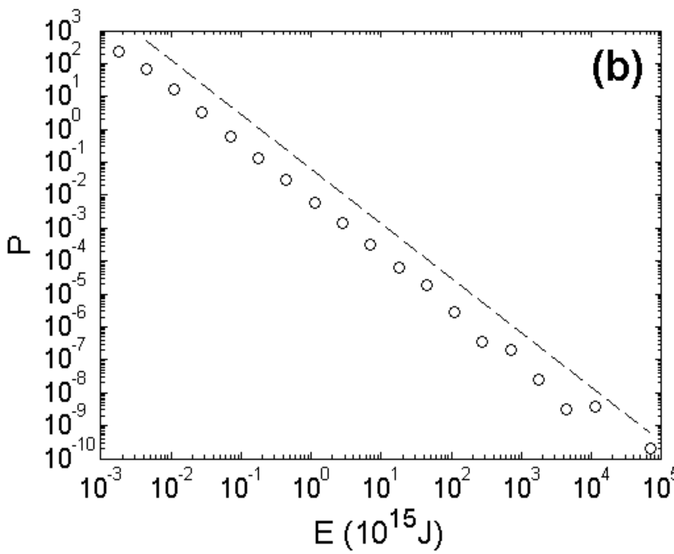


Qualitatively compatible with experiments

Energy distribution of Earhquakes



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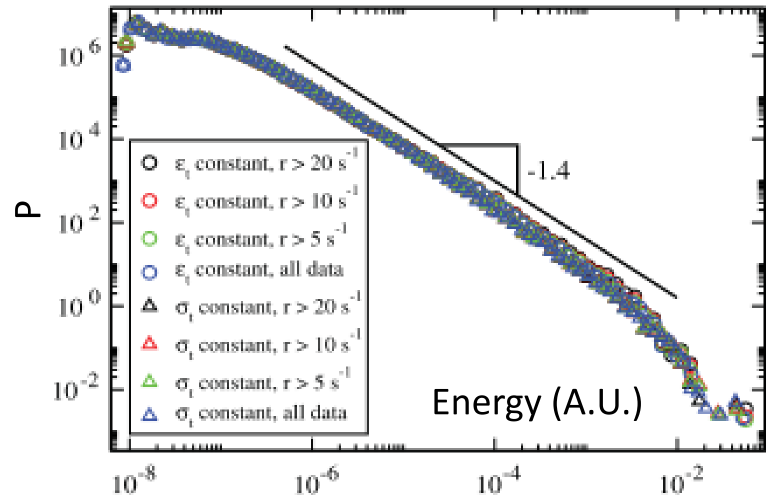
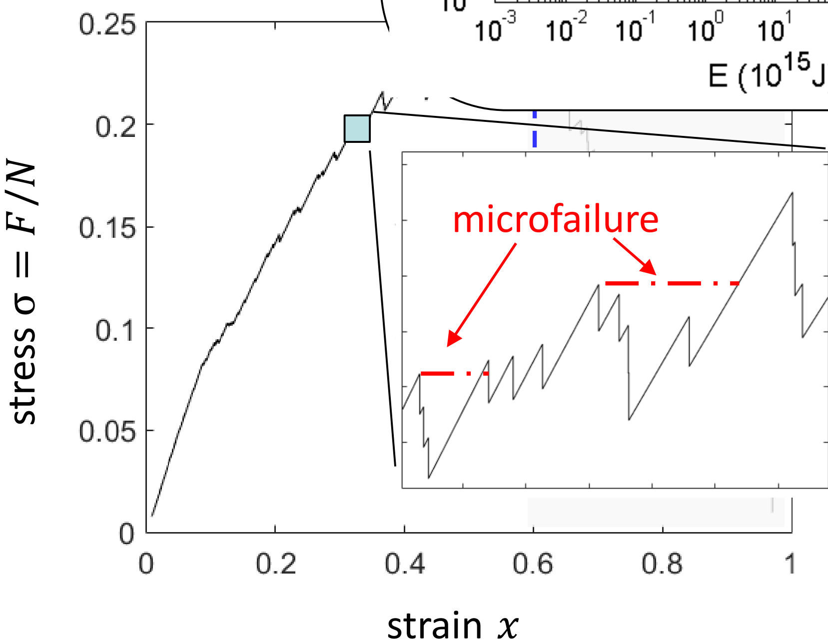


Uniform distribut



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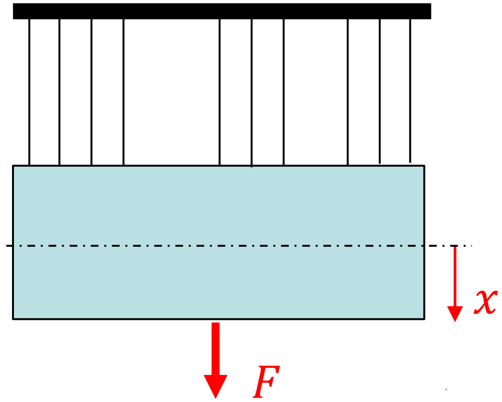
ELS -- FBM: more on avalanches precursors



Experimental observable,
energy release by avalanche

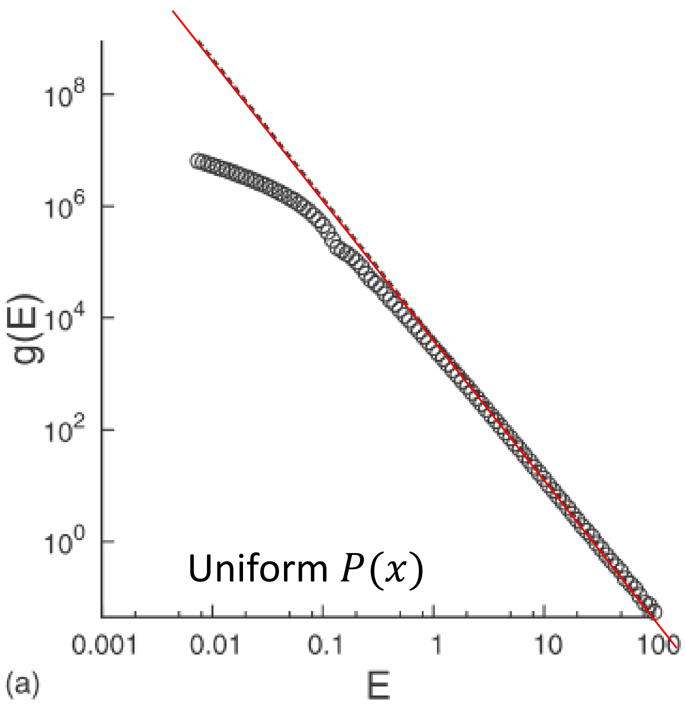
$E = \frac{1}{2} S x^2$

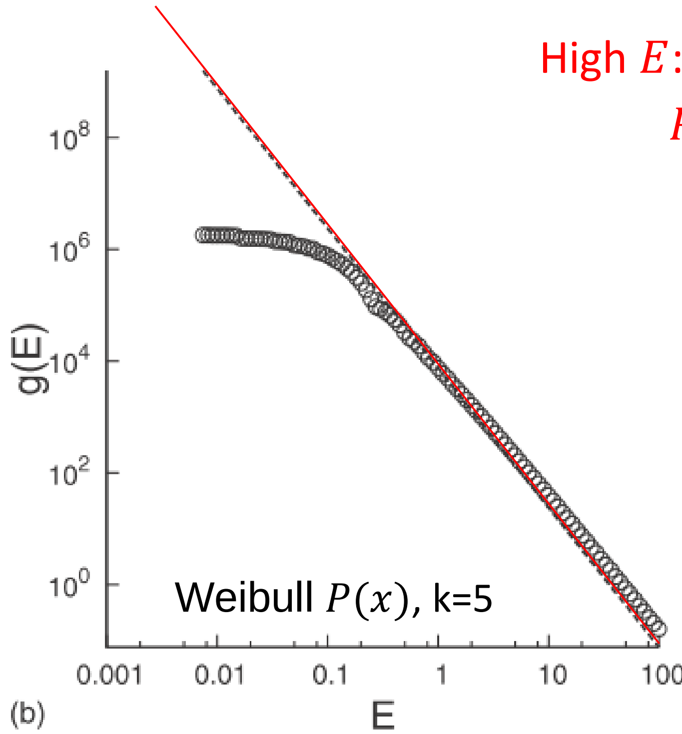
Energy distribution fully determined analytically

Pradhan et al, Rev. Mod. Phys. 2010

High E: universal

$P_{int}(E) \sim E^{-5/2}$





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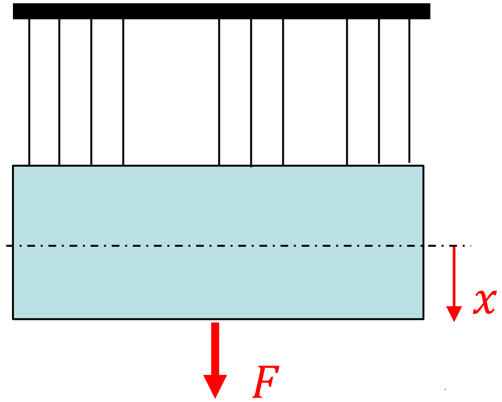

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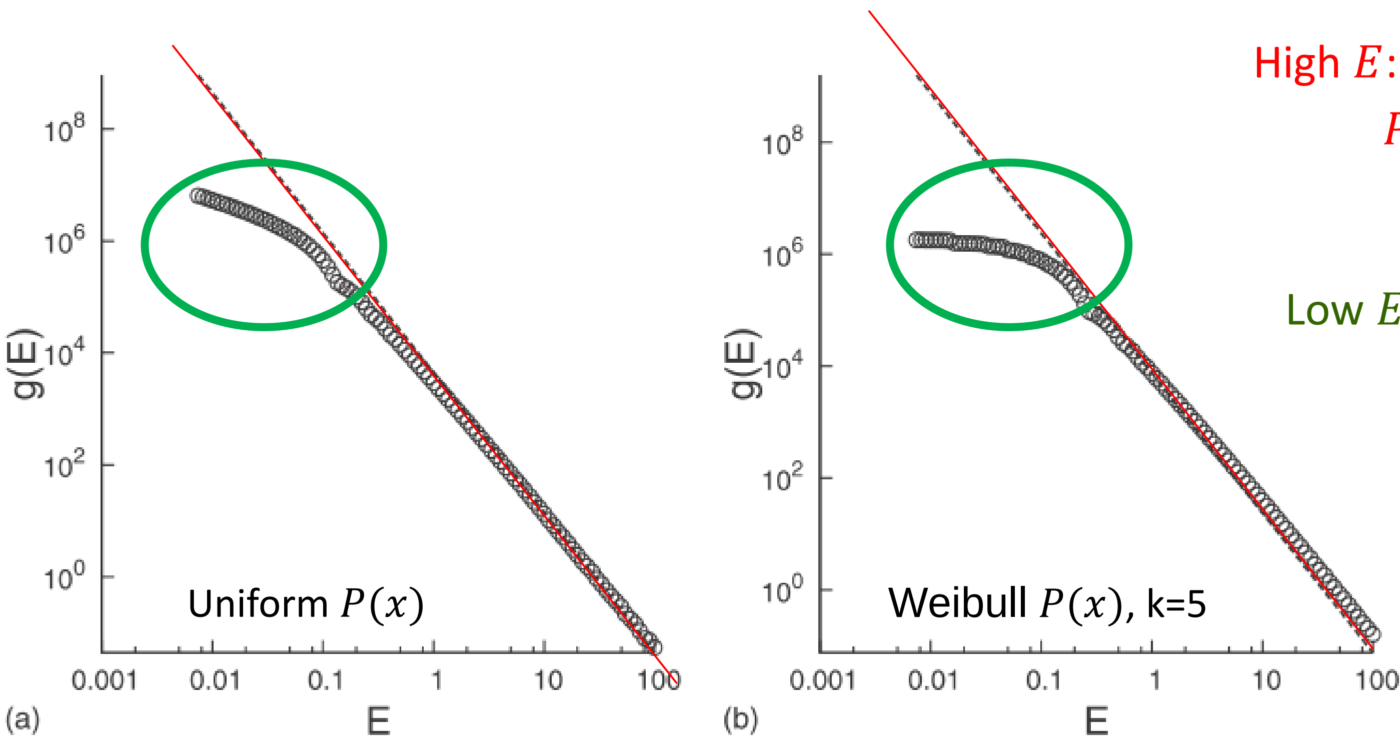
Energy distribution fully determined analytically

Pradhan et al, Rev. Mod. Phys. 2010



High E: universal

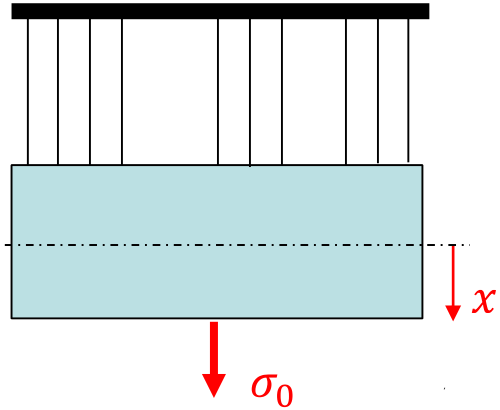
$$P_{int}(E) \sim E^{-5/2}$$

Low E: non-universal

$$P_{int}(E) \approx \frac{Np\left(\sqrt{2E}\right)}{\sqrt{2E}}$$

20000 sample, N=10^6, from Pradhan et al. 2010

ELS -- FBM: thermal noise & creep



N Mallick, PhD, ENS Lyon, 2010, M. Stojanova, PhD, ENS Lyon, 2015

- N parallel brittle fibers
- Overall constant stress $\sigma_0 = F_0/N < \sigma_c$
- Same stiffness $\kappa = 1$
- Same fiber extension : x
- Random critical loads x_i, pdfGaussian pdf, variance T_d
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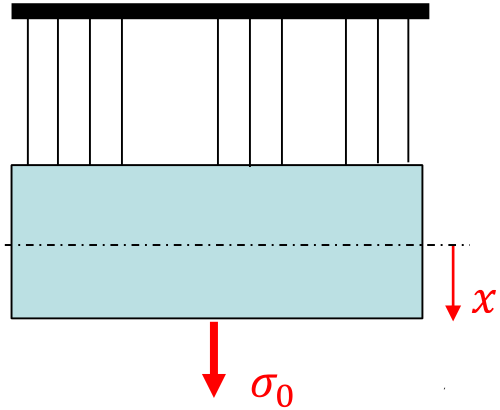

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➔ Analytical determination of failure rate during creep due the constant stress loading

Omori law
$$\frac{dn}{dt} \approx \frac{A\sqrt{T/T_d}}{t^p}$$

… with temperature/stress dependent Omori exponent

$$p \approx 1 + \frac{T}{T_d} - K(\sigma_c - \sigma_0)\,\frac{\sqrt{T}}{2T_d}$$

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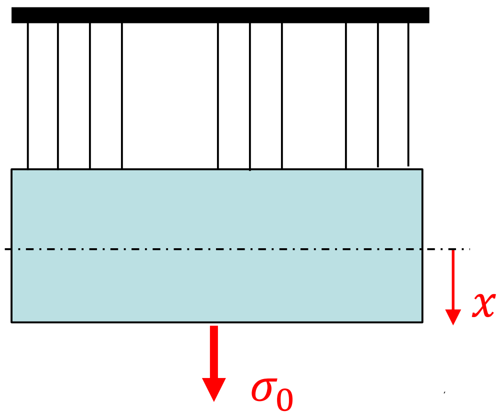

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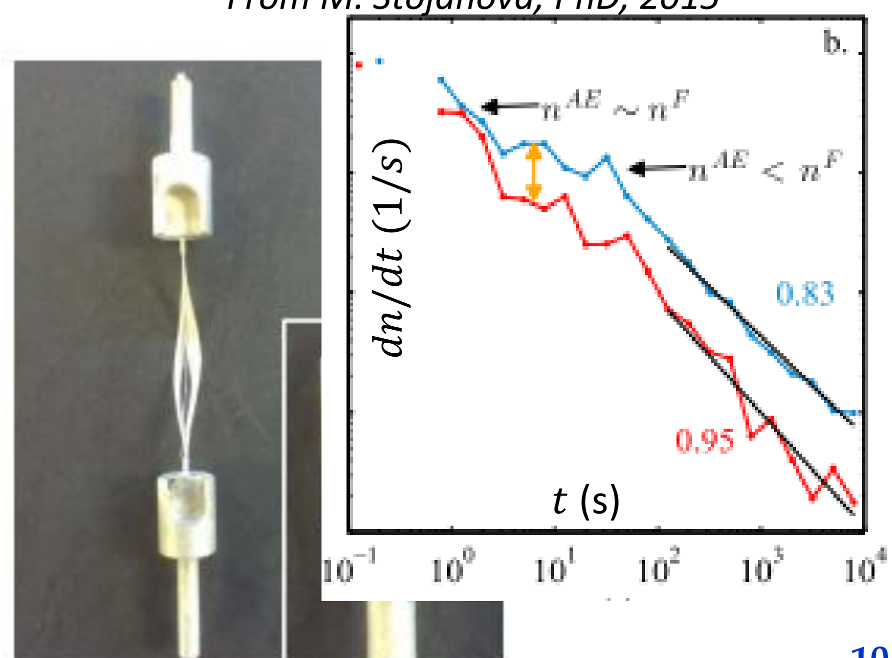
Used to interpret creep experiments in e-glass bundle instrumented in acoustic

From M. Stojanova, PhD, 2015



Fiber Bundle Models (FBM): the approach

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Same stiffness $\kappa = 1$

Random failure threshold

Prescribed rules for load redistribution

F.T. Pierce, 1926

H.E. Daniels, 1945

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Load of failed fiber redistributed
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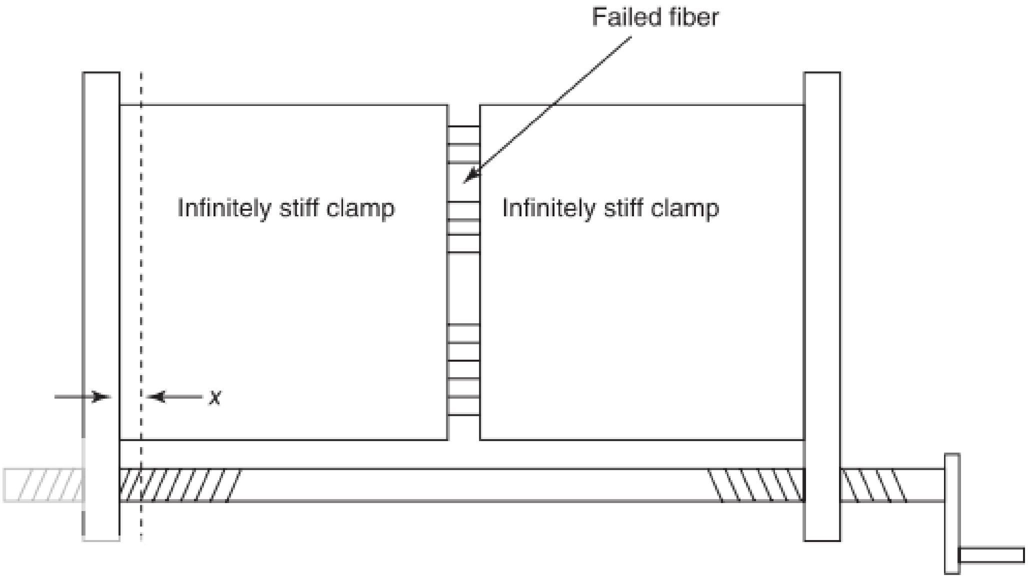

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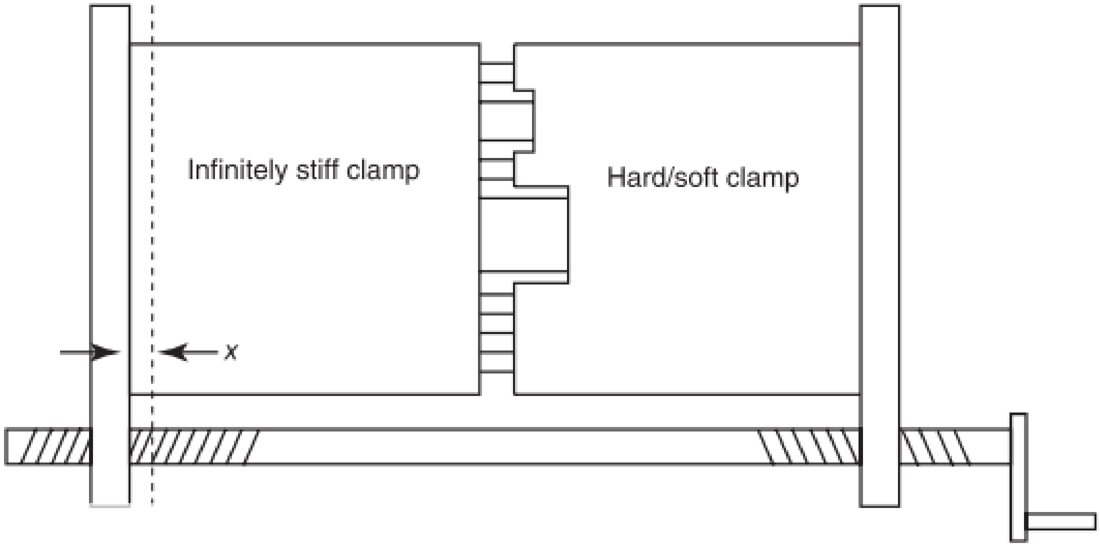

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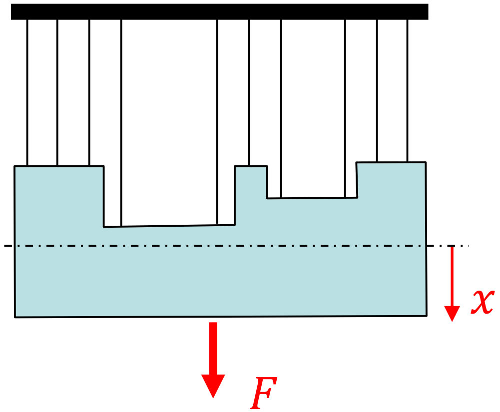
LLS -- FBM: 1D models



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Full analytical solutions not available anymore

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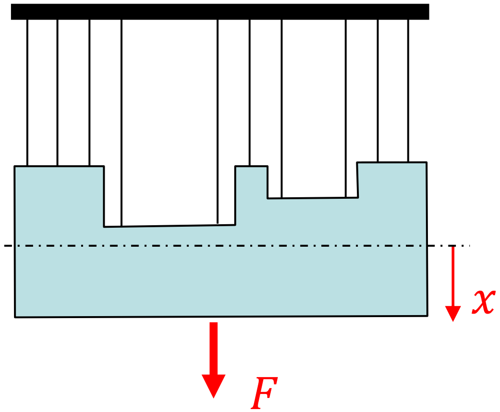

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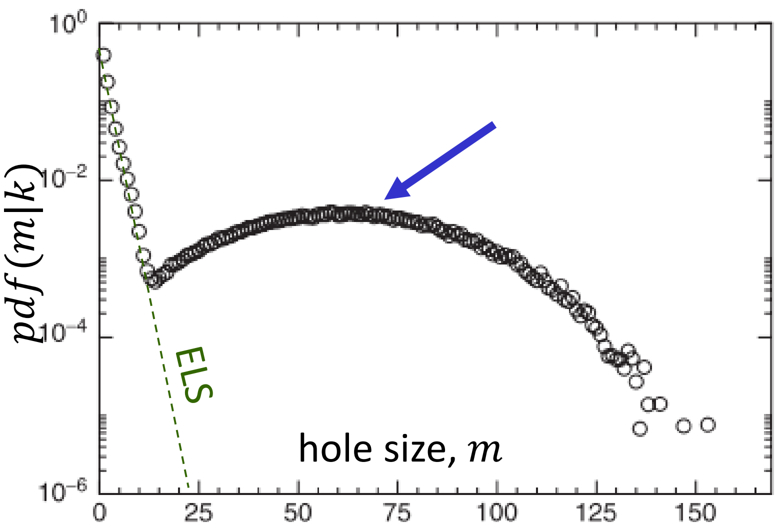
Pdf of hole size after k breaking

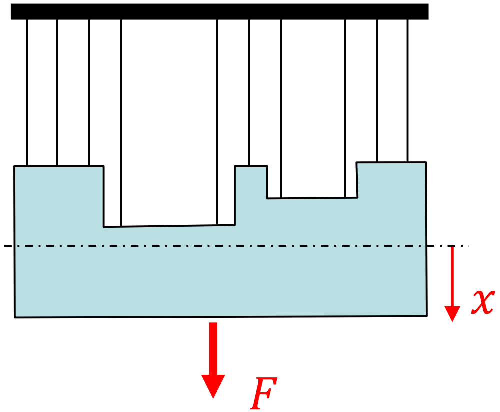
Uniform: $P(x)$=x $N = 1000, \mathrm{k} = 200$

Hansen et al. (Wiley & son, 2015)



Localization captured

LLS -- FBM: 1D models



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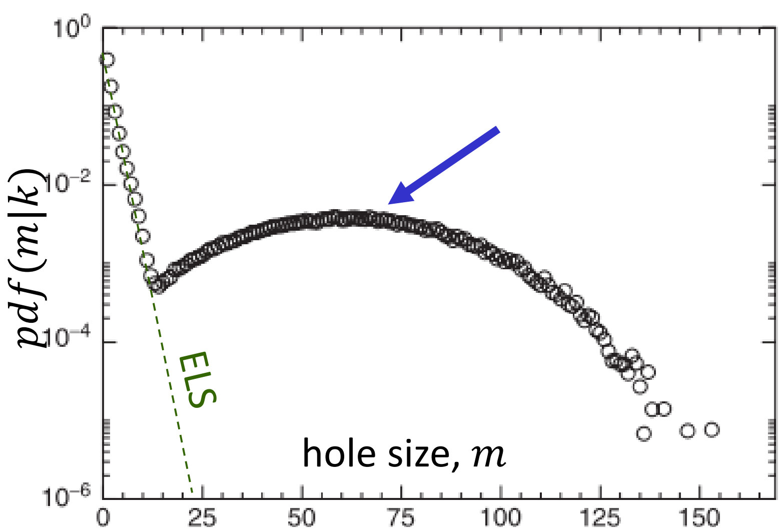


Localization captured

highly dependent of $P(x)$...

... importance: x_{min}^c and $P(x \approx x_{min}^c)$

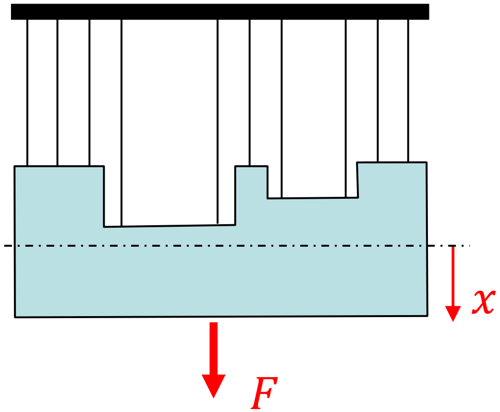
- $x_{min}^c = 0, P(x) = x^\beta, \beta \to \infty$

  infinite disorder, no localization, ELS

- $x_{min}^c = 2/3$, uniform above,

  fully localized, single crack growth

LLS -- FBM: 1D models, size effect on strength



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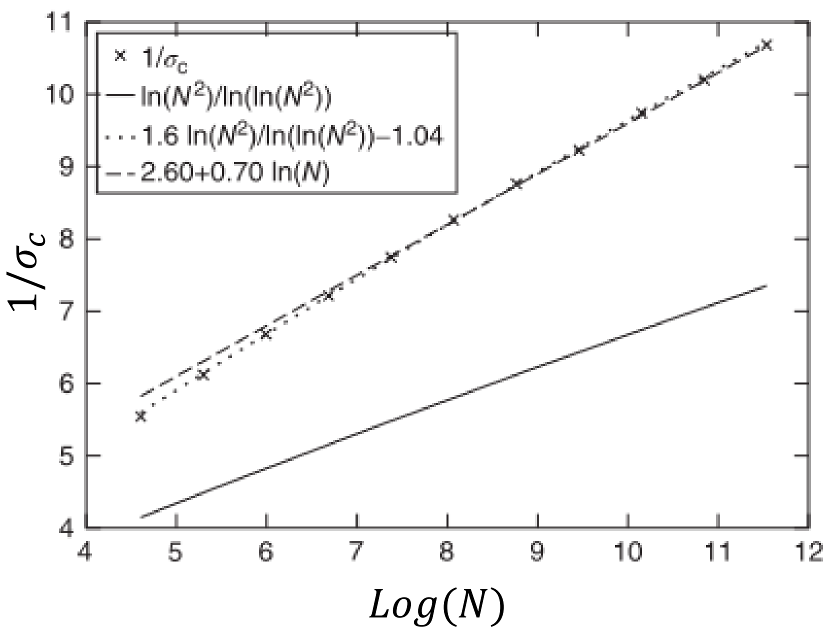
  [cumulative $P(x^c)$]

Size effect can be reproduced

But depend of $P(x)$, x_{min}^c and $P(x \approx x_{min}^c)$

Uniform distribution

Hansen et al. (Wiley & son, 2015)



Case of uniform distribution, $P(x) = x$

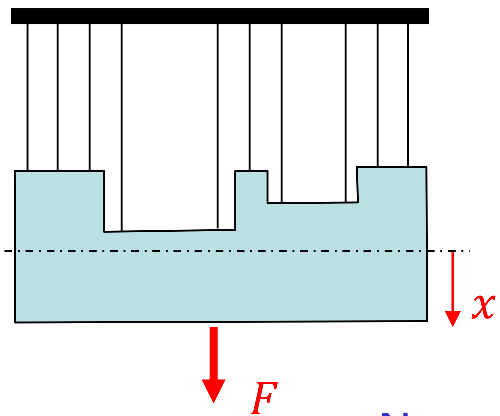
Numerics, simple estimates: $\sigma_c \approx 1/\log(N)$

Zhang & Ding, Phys. Lett. A 1994, PRB &995

More refined: $\sigma_c \approx \log(\log(N^2))/\log(N^2)$

Hansen et al (Wiley & son, 2015)

LLS -- FBM: 1D models, avalanche distribution



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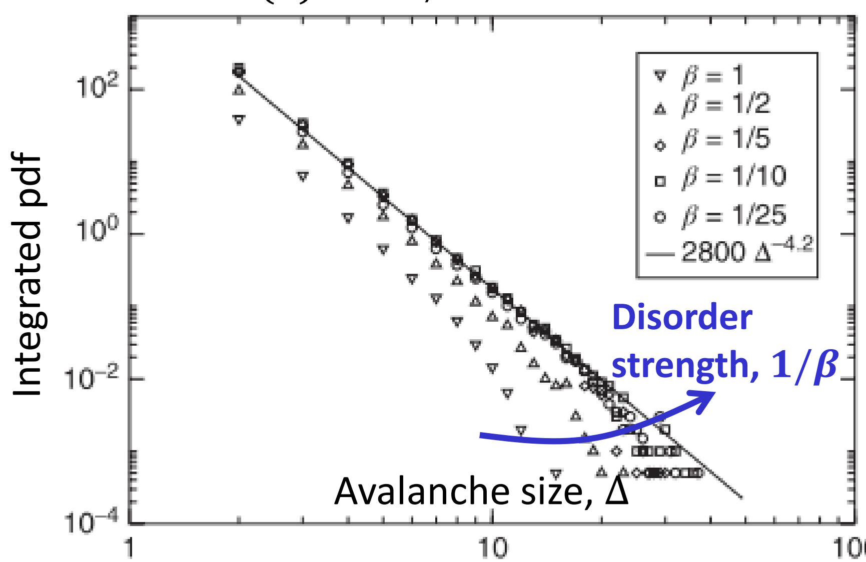
  [cumulative $P(x^c)$]

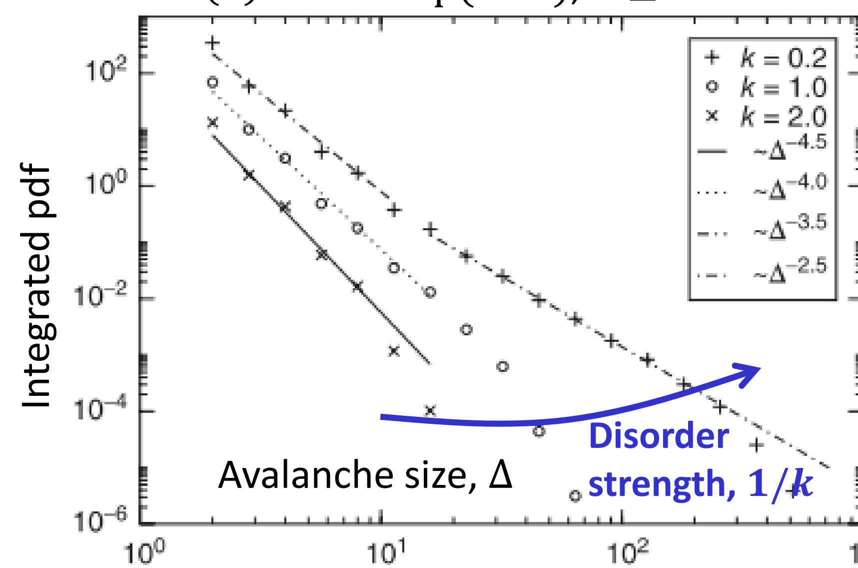
Non-universal size-distributions,
Depend on critical load distribution, $P(x)$

Zhang & Ding Phys. Lett. A 1994, Pradhan et al. RMP, 2010

$P(x) = x^{\beta}$, $0 \leq x \leq 1$



$P(x) = 1 - \exp(-x^k)$, $0 \leq x < \infty$

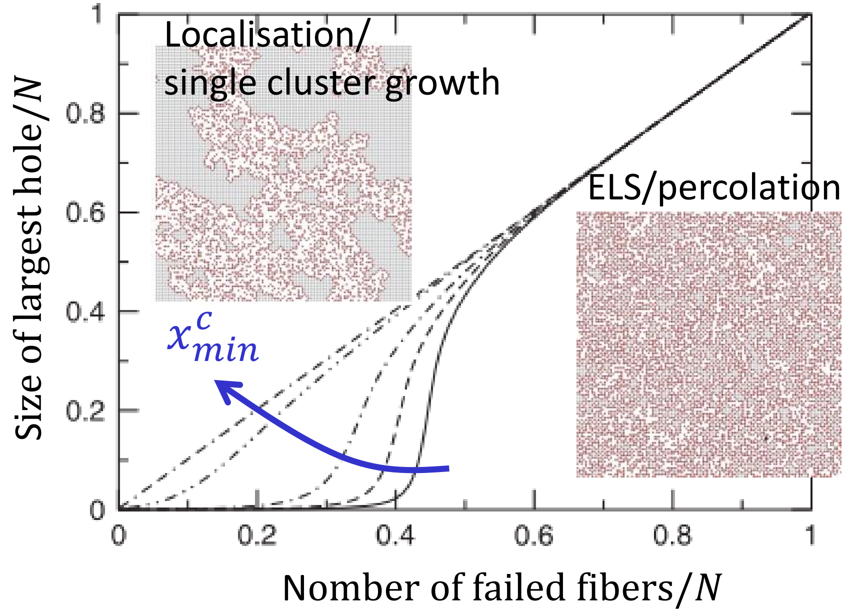


Hansen et al. (Wiley & son, 2015)

LLS – FBM in higher dimensions

Localization less important in 2d

➔ finite x_{min}^{c} now required to activate localization



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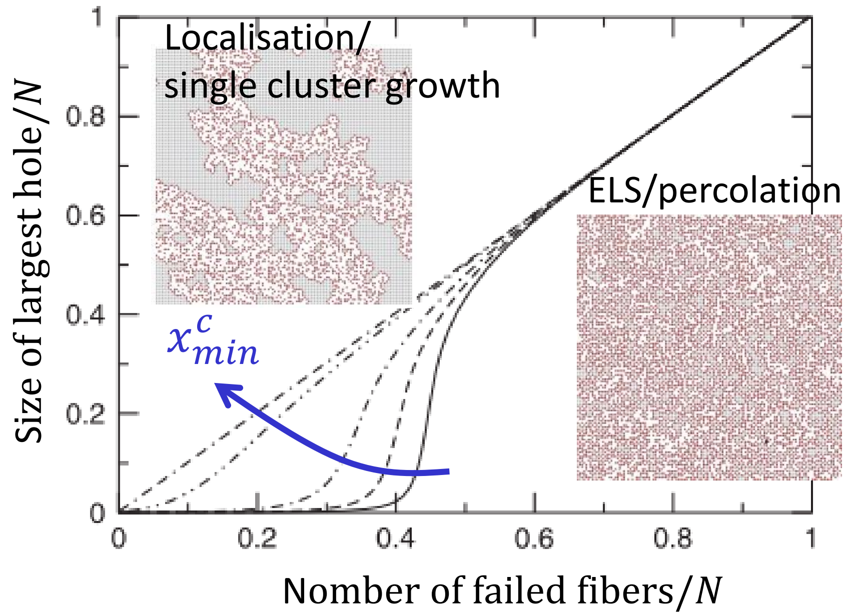
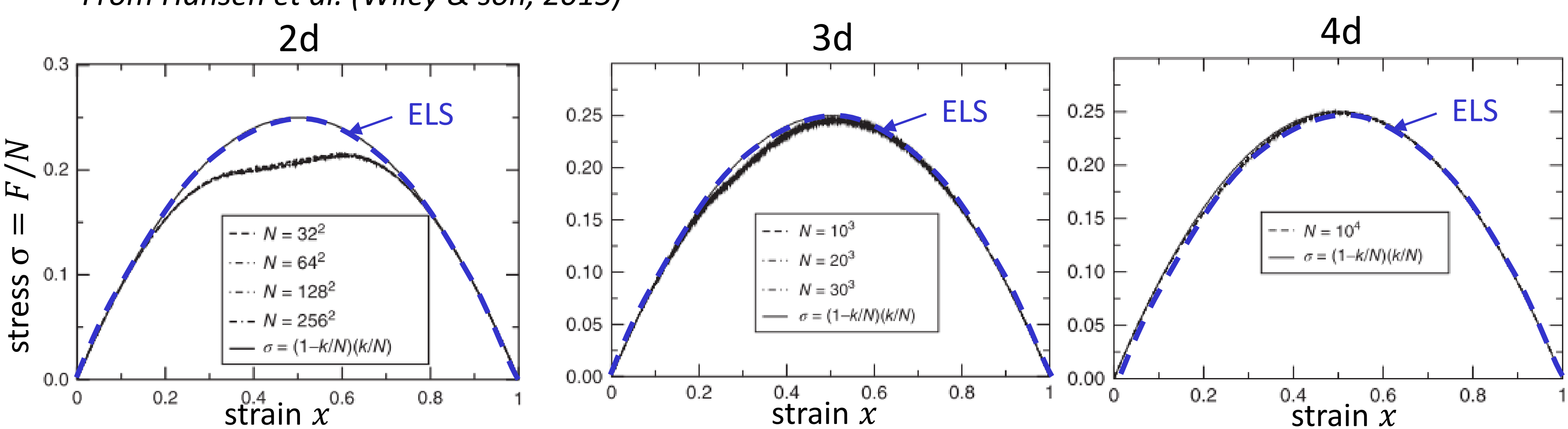


Stress-strain curve in LLS for uniform distribution, $P(x^c) = x^c$, over $[0,1]$

From Hansen et al. (Wiley & son, 2015)



When dimensionality increases, LLS-FBM looks more and more to ELS-FBM !

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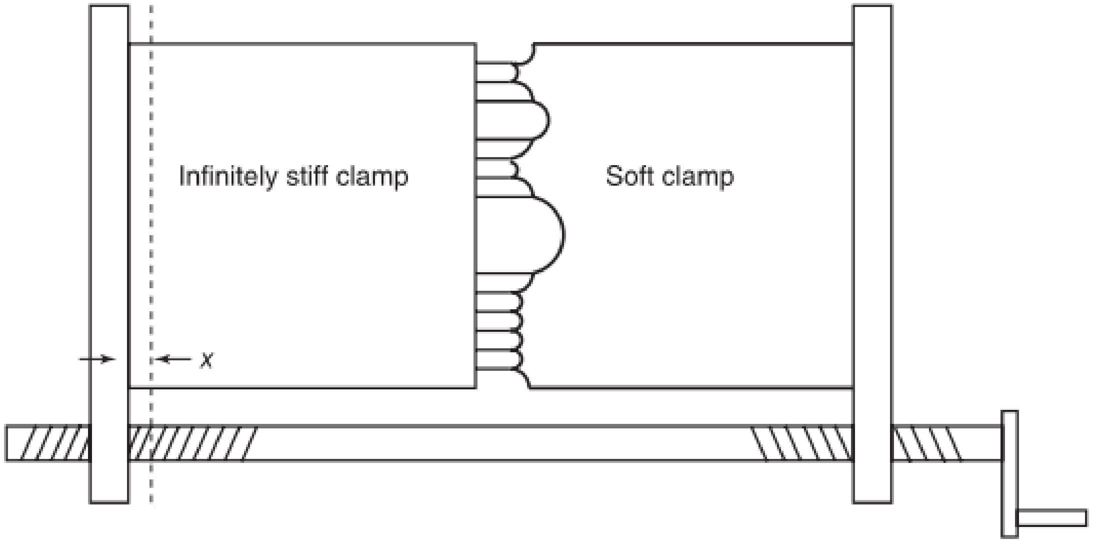
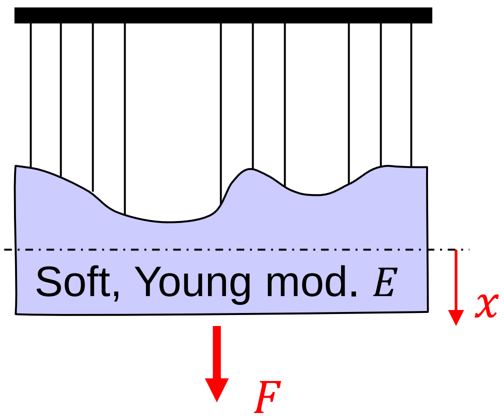


An example of FLS -- FBM: Soft-clamp model

Stormo, Gjerden, Hansen PRE, 2012



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: $\sigma_i = \kappa(x_i - x), x_i = \sum_j G_{ij}\sigma_j$,

G_{ij} = green function for 2D elastic infinite half space

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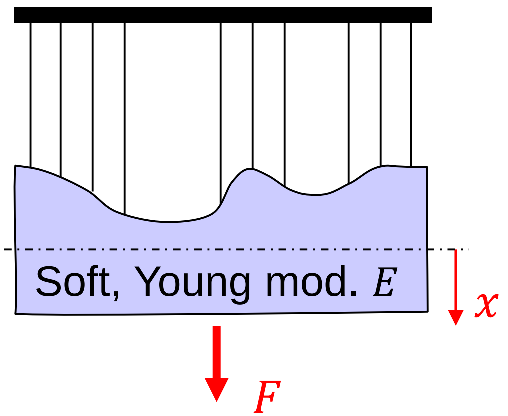

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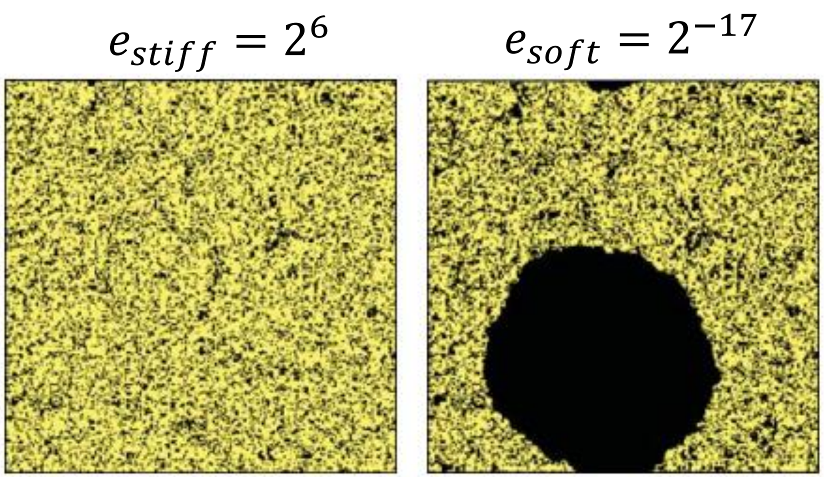
Control parameter for interaction: $e = E/N$

➔ Increasing size ≡ softer clamp

Transition from LLS (small e) to ELS (large e)



From Hansen et al. (Wiley & son, 2015)

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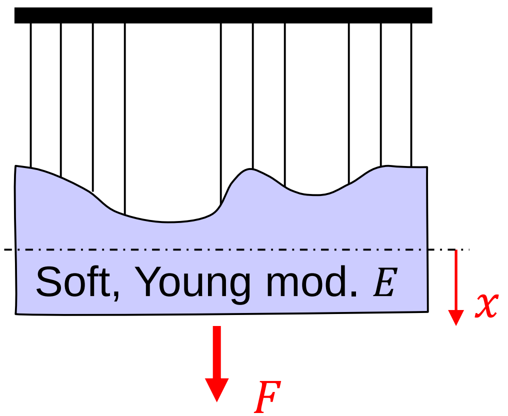

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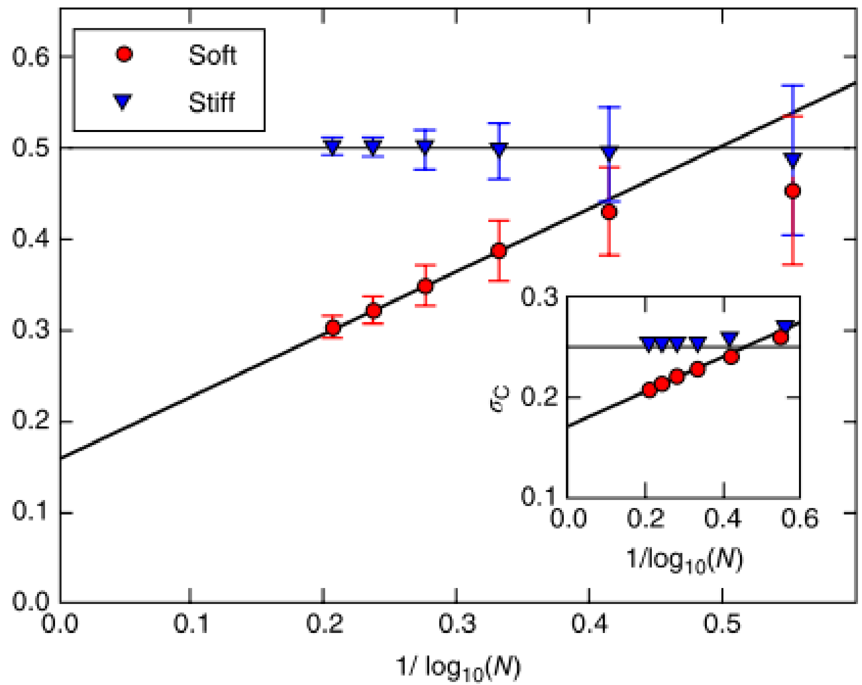
Size effect on strength at small e, absence of size effect at large e



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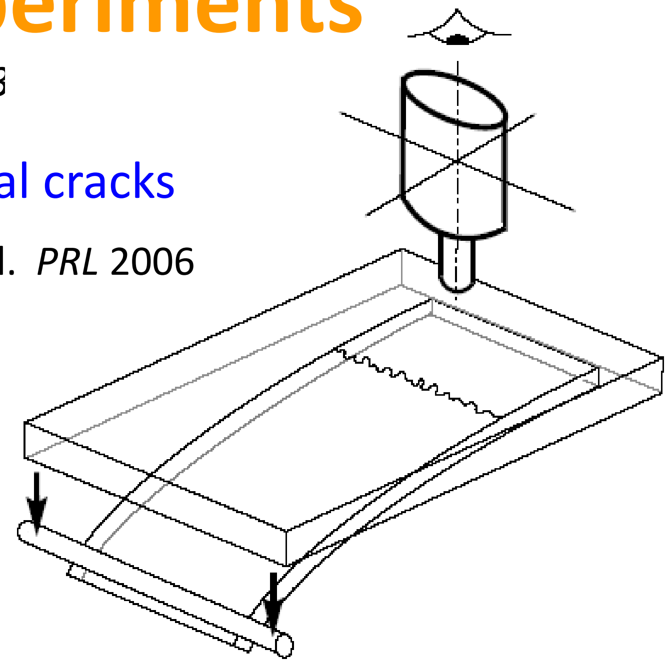
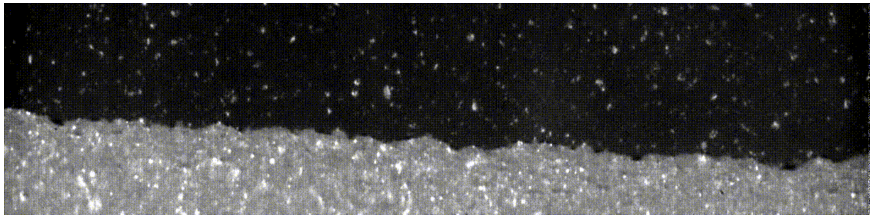
FBM: Soft-clamp model & experiments

Gjerden, Stormo, Hansen PRL, 2013

Interfacial cracks

Maloy et al. *PRL* 2006





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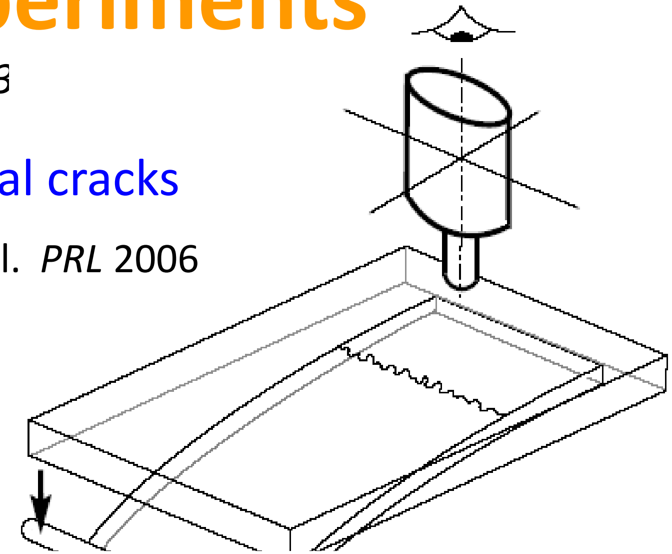

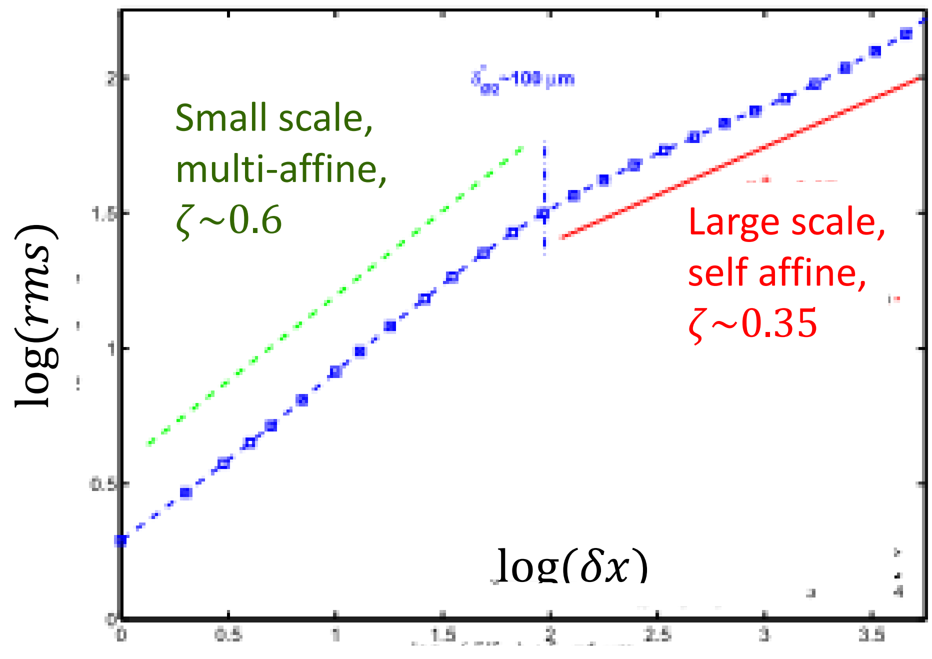

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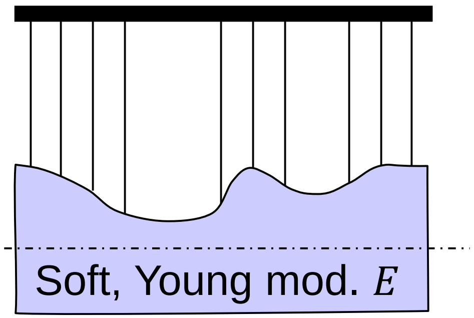

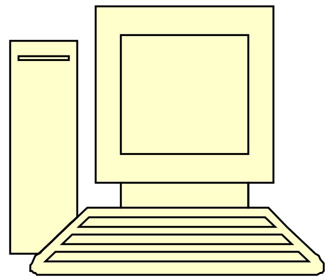

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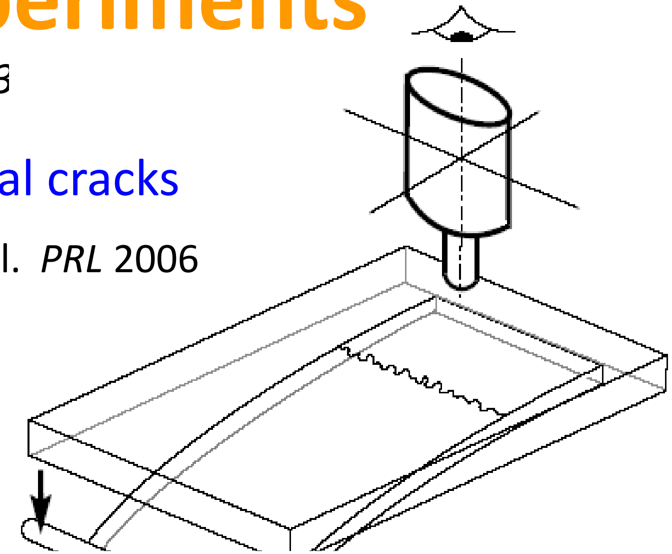
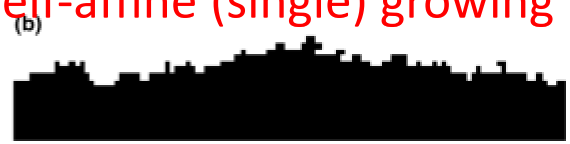


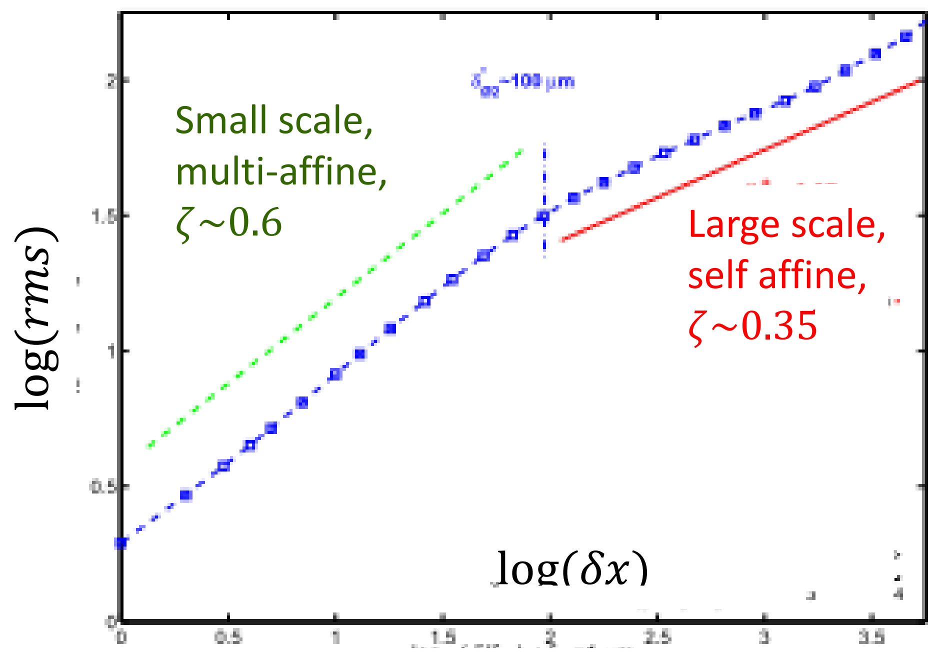
Large N (soft e)

Self-affine (single) growing front



Small N (stiff e)

Fractal percolated clusters



➔ In (experimental) fracture: ELS/percolation at small scales,
LLS/single crack growth at large scales

FBM: few take-home messages

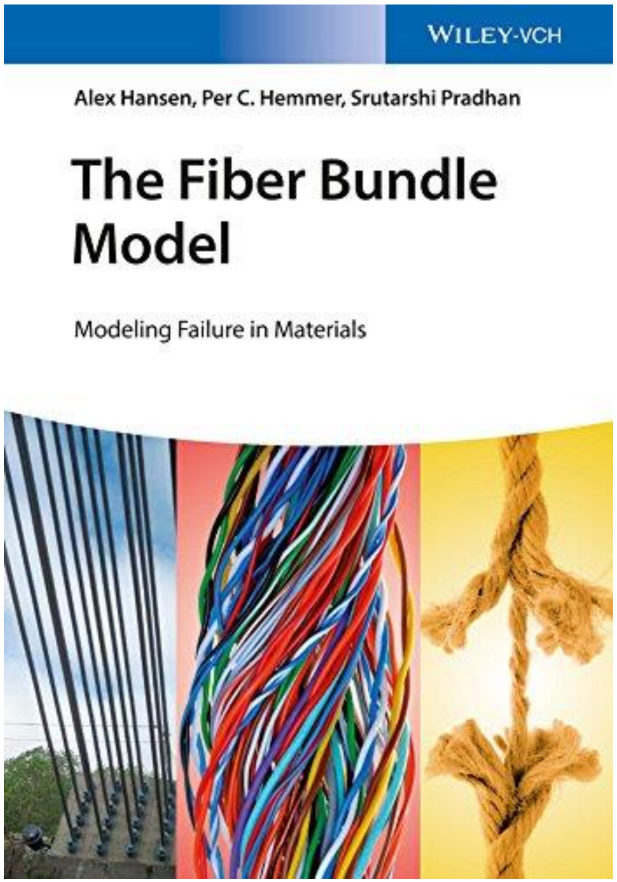
- FBMs address fracture problems via models of increasing complexity/description ability depending of the redistribution rules

- Simplest one: Equal-load-Sharing FBM :
  - fully tractable analytically, fracture ←→ critical phenomena
  - capture qualitatively gradual damaging before failure, scale-free precursor avalanches, response in creep,
  - ail capturing localization and size effects

- Local-load-Sharing FBM
  - Not tractable numerically anymore
  - Capture localization and size effects
  - No universality, very dependent on threshold distribution (and its minimum)
  - As dimension increases, looks more and more to ELS

- Soft-clamp FBM
  - LLS at large scales, ELS at small scales
  - Explain 2 scaling regimes in fracture depending on length-scales

Thank you for your attention



To know more

REVIEWS OF MODERN PHYSICS, VOLUME 82, JANUARY–MARCH 2010

Failure processes in elastic fiber bundles

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Alex Hansen†

Department of Physics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway

Bikas K. Chakrabarti‡

Theoretical Condensed Matter Physics Division and Centre for Applied Mathematics and Computational Science, Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Kolkata 700064, India

(Published 1 March 2010)

The fiber bundle model describes a collection of elastic fibers under load. The fibers fail successively and, for each failure, the load distribution among the surviving fibers changes. Even though very simple, this model captures the essentials of failure processes in a large number of materials and settings. A review of the fiber bundle model is presented with different load redistribution mechanisms from the point of view of statistics and statistical physics rather than materials science, with a focus on concepts such as criticality, universality, and fluctuations. The fiber bundle model is discussed as a tool for understanding phenomena such as creep and fatigue and how it is used to describe the behavior of fiber-reinforced composites as well as modeling, e.g., network failure, traffic jams, and earthquake dynamics.