Pattern formation and rupture transitions in semi-flexible fiber networks with mobile cross-linkers

P. B. Sunil Kumar
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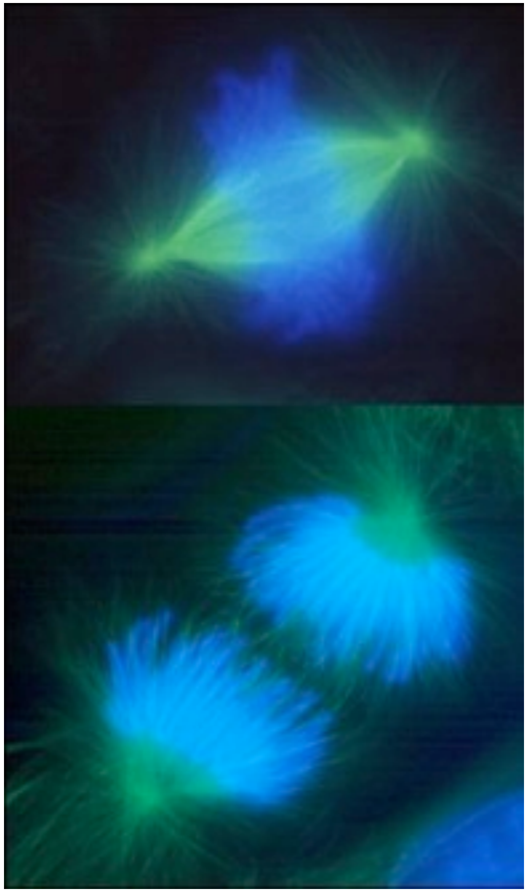
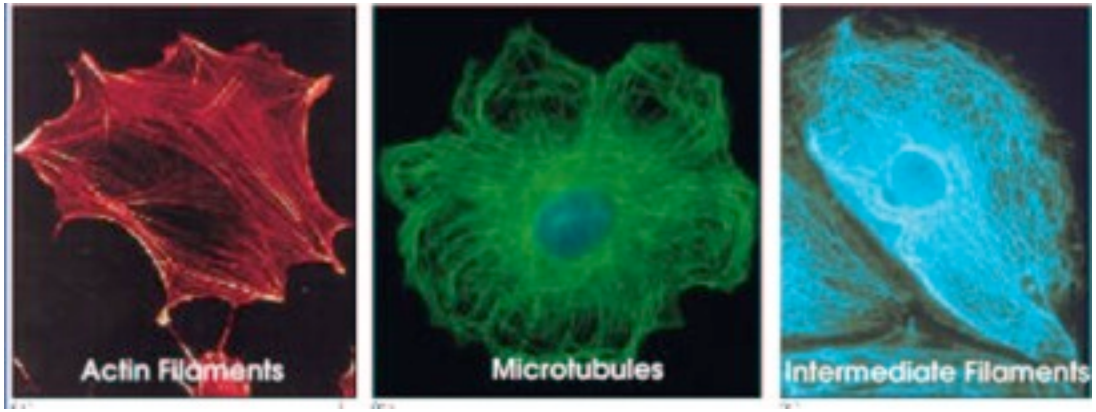
http://www.physics.iitm.ac.in/~sunil

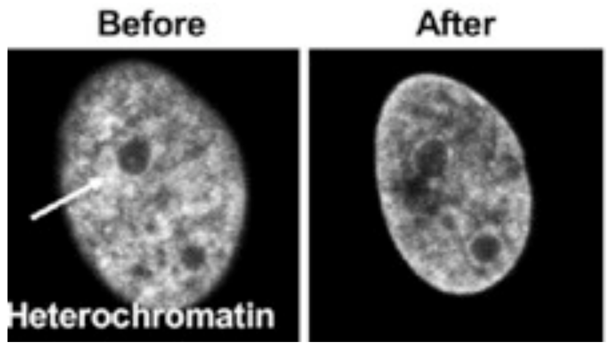


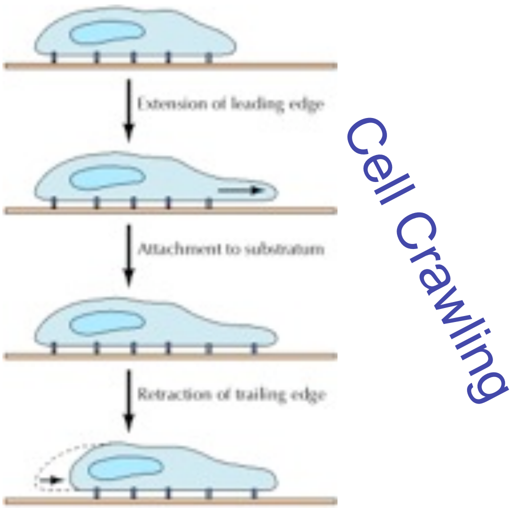


Spatial and temporal organization is important for function

Nucleus is held under tension

A. Mazumder and G. V. Shivashankar
Biophys. J. 93, 2209 , 2007



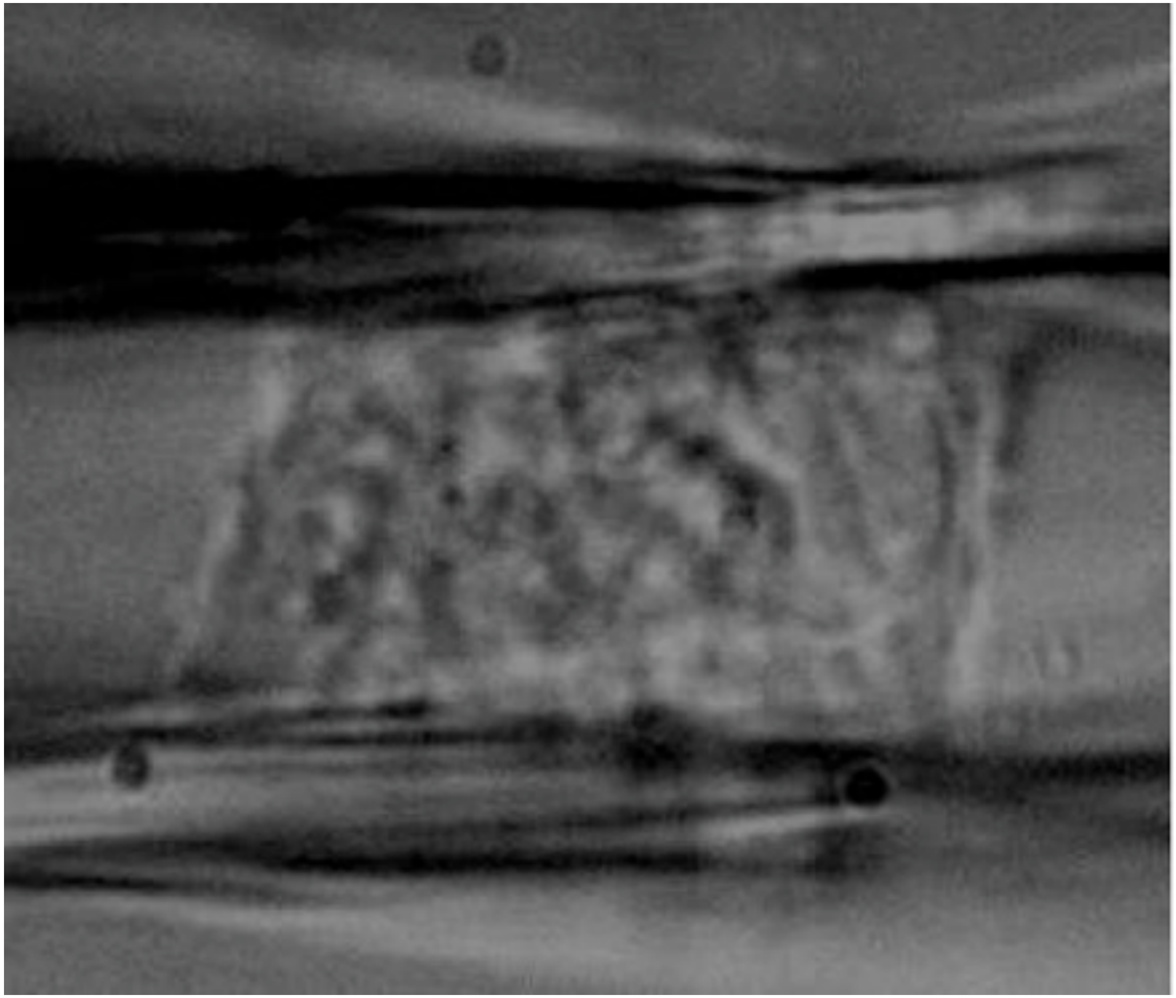


Mechanical cues are found to alter gene transcription, cellular differentiation in culture, and developmental programs in organisms, suggesting a strong link between cellular architecture and information control within living cells.

Formation of actin-ADF/cofilin rods transiently retards decline of mitochondrial potential and ATP in stressed neurons.
Bernstein B.W. et al *Am J* Physiol Cell Physiol 291: C828–C839, 2006.

Cell stretching experiments

P. Fernadez, P. Pullarkat and A. Ott: Biophysical Journal , March 2006



3T3 Fibroblasts stuck to two micro plates coated with fiberonectin from bovine plasma

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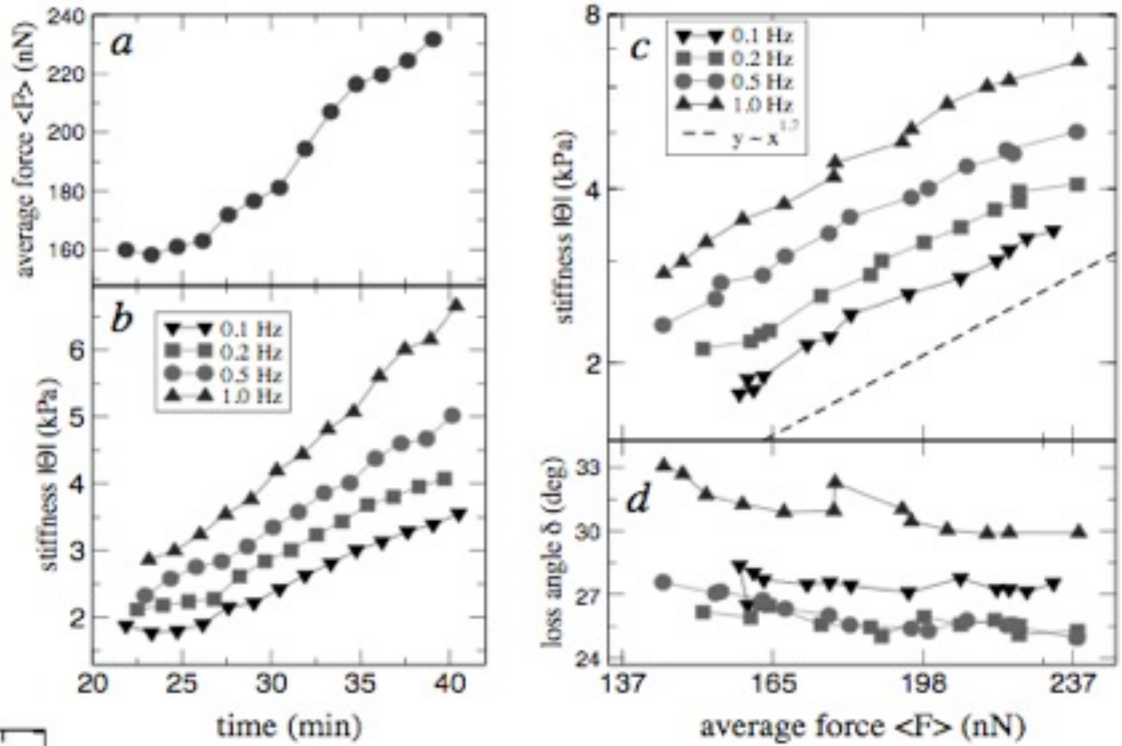
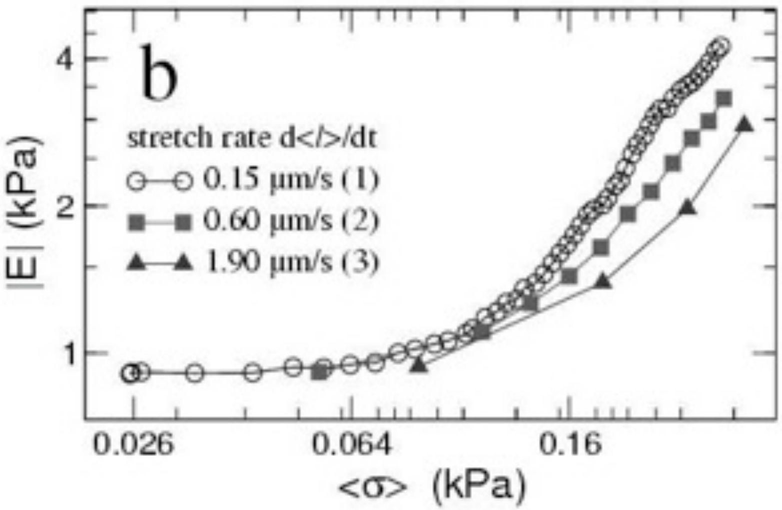
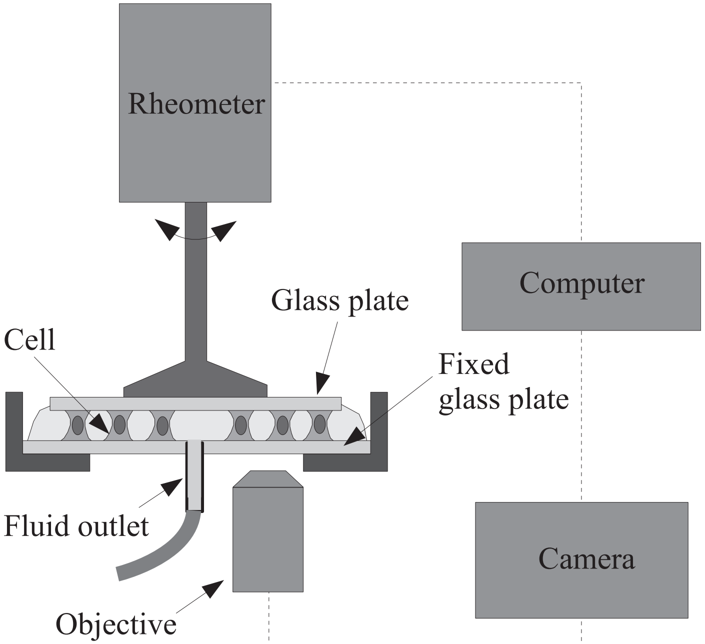
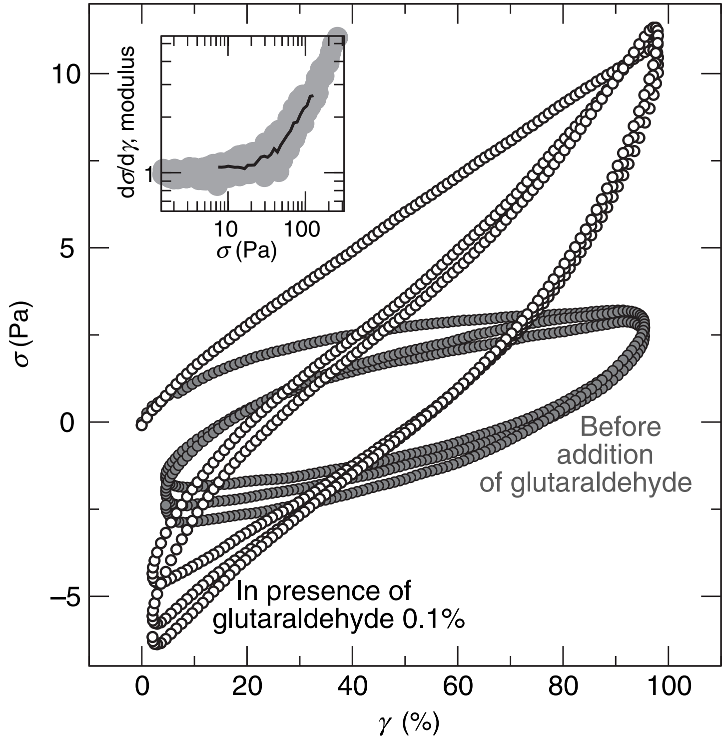
P. Fernadez, P. Pullarkat and A. Ott: Biophysical Journal , March 2006





Shearing a monolayer of Swiss 3T3 fibroblast cells



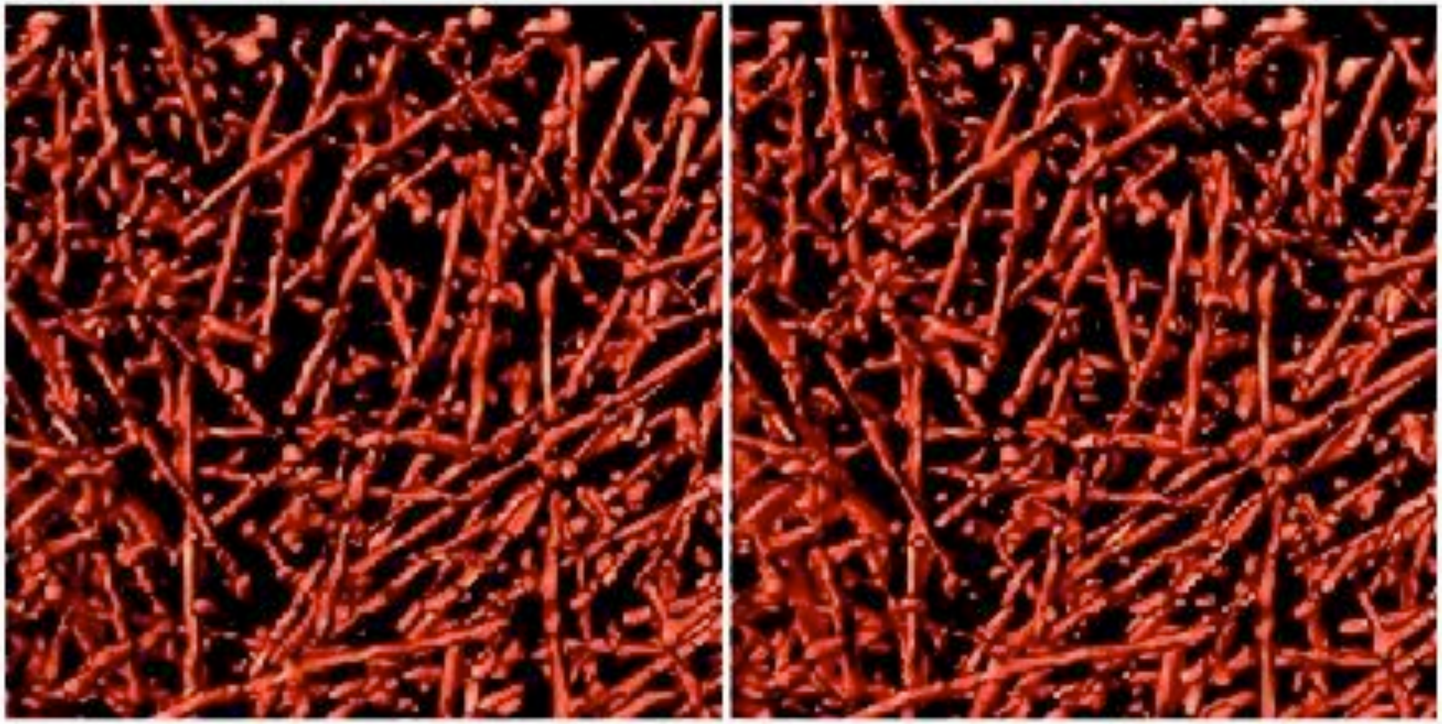


Shear rheology of a cell monolayer: P. Fernández,L. Heymann2 ,A. Ott, N. Aksel and P. A. Pullarkat
*New Journal of Physics **9** (2007)*

Cytoskeleton is a dense network of polymers !

The major constituent is the Actin filaments

Actin is a polymer having a persistence length of the order of 15 μm and thickness of about 7 nm.



Typical mesh size of the cytoskeletal network is about 100 nm

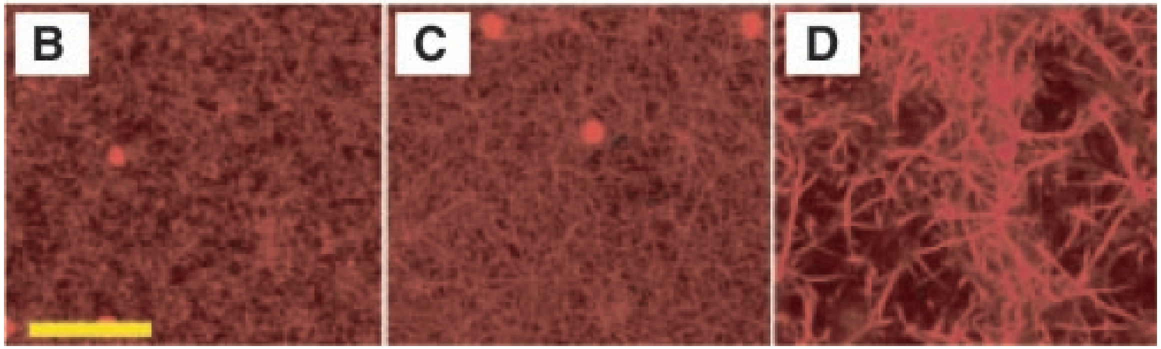
Medalia et.al Science ***298*** *1209 (2002)*

Building model systems : Actin networks

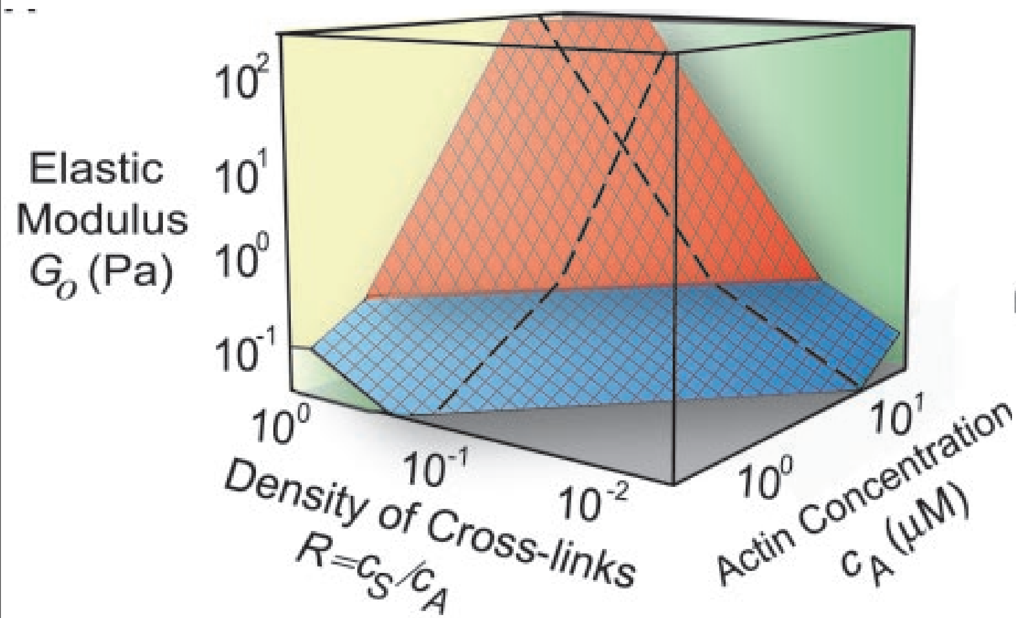
A state diagram for actin networks has been constructed by varying the density of cross links and the actin concentration, and showing how their changes affect the elastic modulus G_0 of the system. Gardel *et.al*. Science, **304,** 1301, (2004)

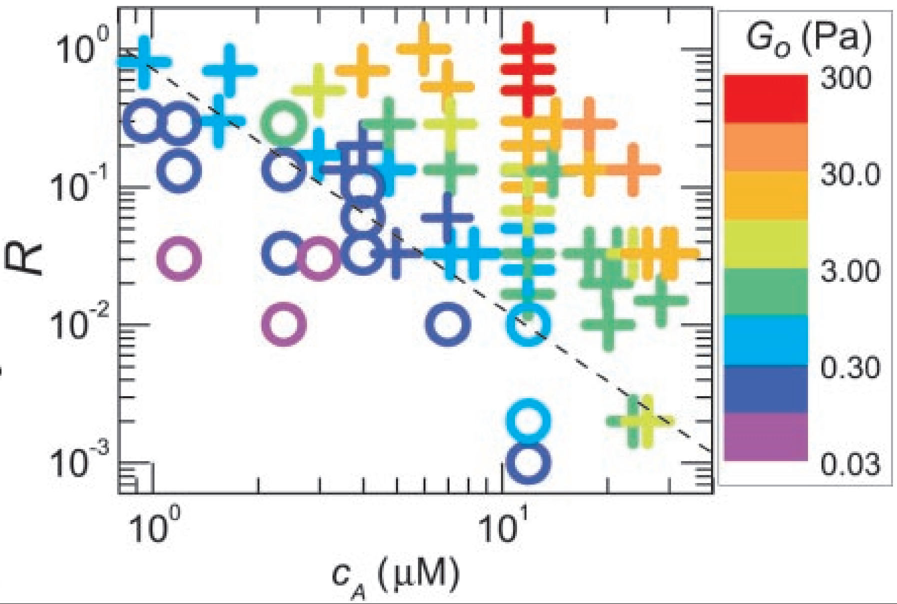
C_s - concentration of cross linker

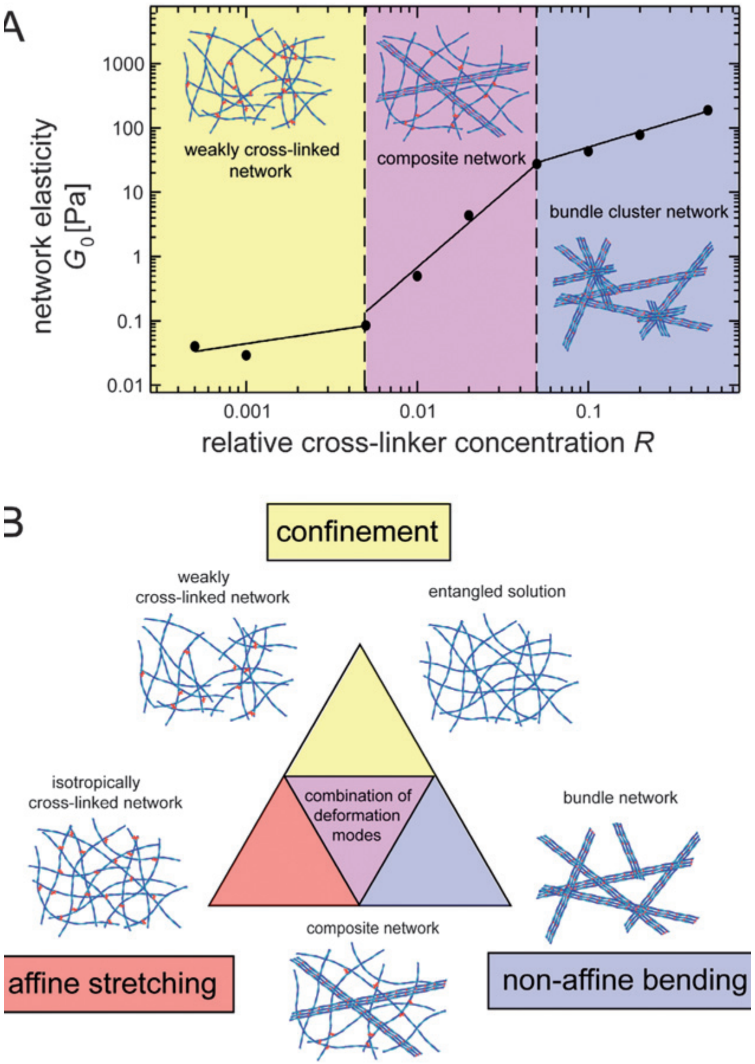
C_A - concentration of actin



(A) R=0.0, (B) 0.07, (C) 0.5, C_A =11.9 μM







In vitro experiments have established different structural regimes in actin networks depending on α-actinin (cross linker) concentration.

The transition between these regimes are accompanied by transitions in their mechanical behavior.

O. Lieleg, M. M. A. E. Claessens and A. R. Bausch : Soft Matter - 2009

Two views on strain hardening

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P. R. Onck, T. Koeman, T. van Dillen, and E. van der Giessen, Phys. Rev. Lett. **95**, 178192 (2005)

A model that allow for structural changes.

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J. Astrom, P.B. S. K., M. Karttunen and I. Vattulainen Phys. Rev. E **77**, 051913 (2008)

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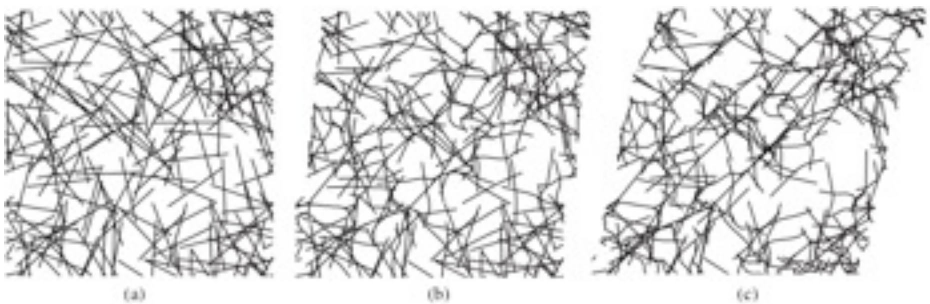

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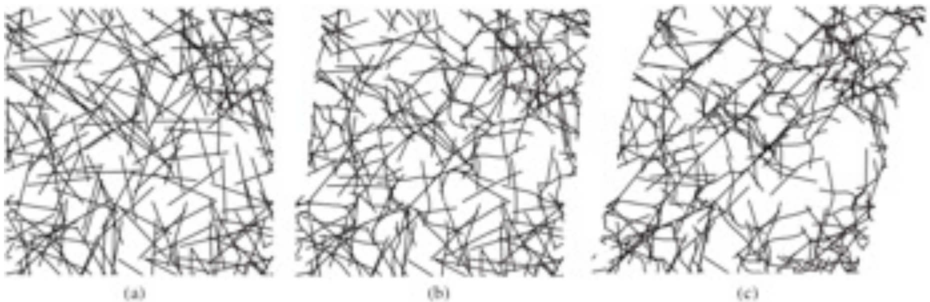
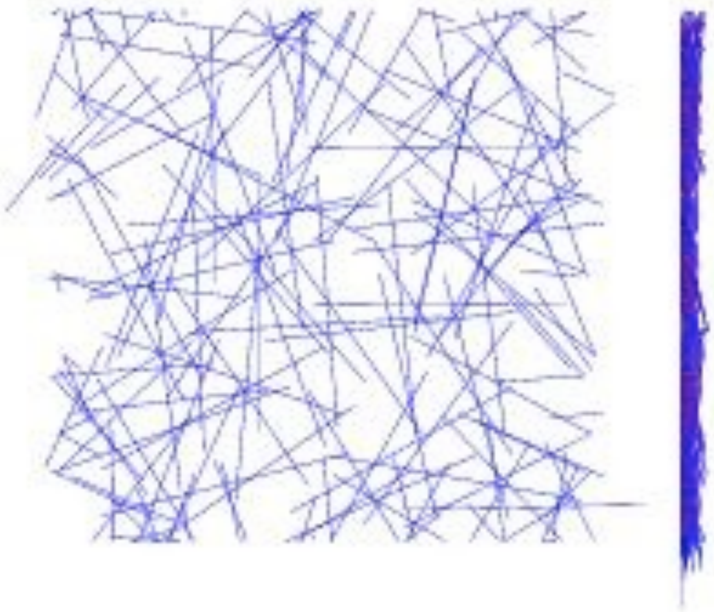
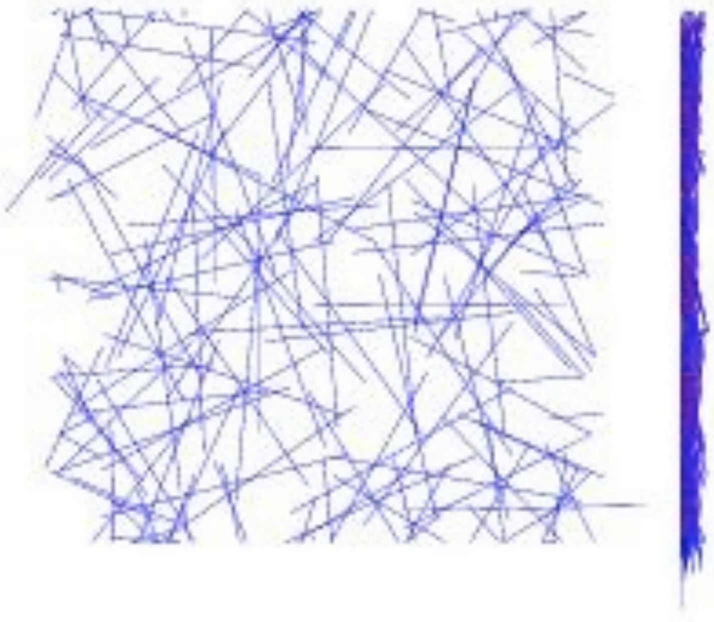


*Onck et. al PRL **95** 178102 (2005)*



Boundary conditions are chosen such that the boundary is free in the z-direction (thickness of the network), while the in-plane directions are periodic in the y-direction and fixed in the x-direction.

The mesh obtained through this deposition process is taken as the (initial) equilibrium configuration.



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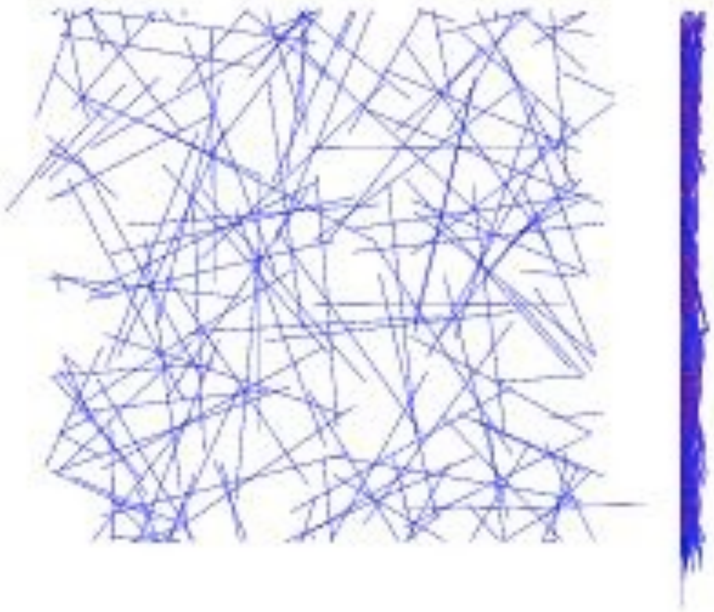
The mass of the fiber is modeled by a set of points (of equal mass “m”) placed at equal distances along the fiber



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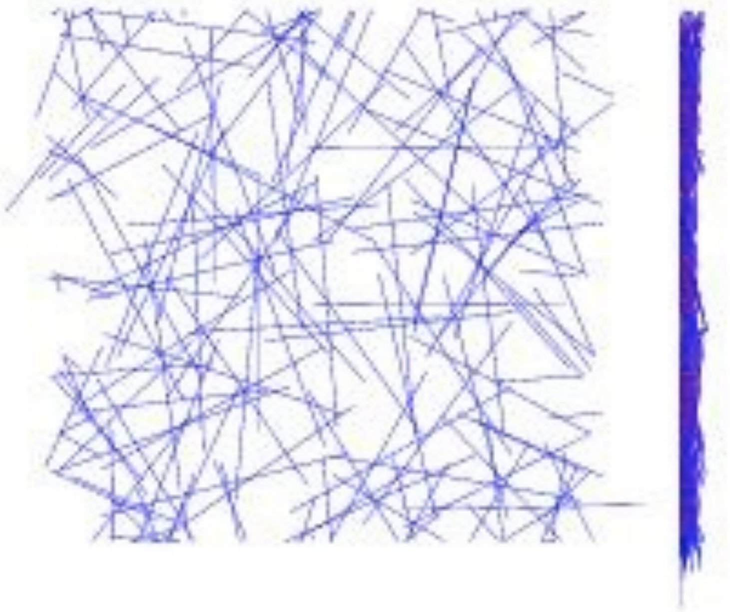

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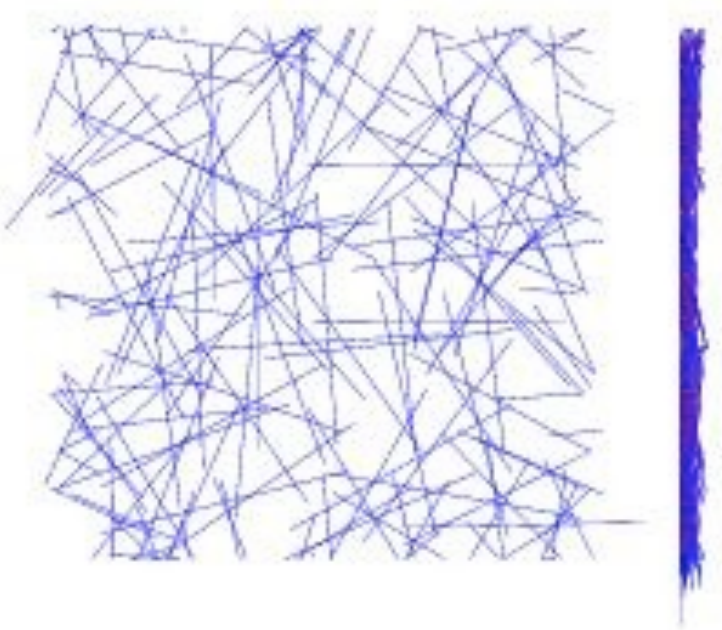

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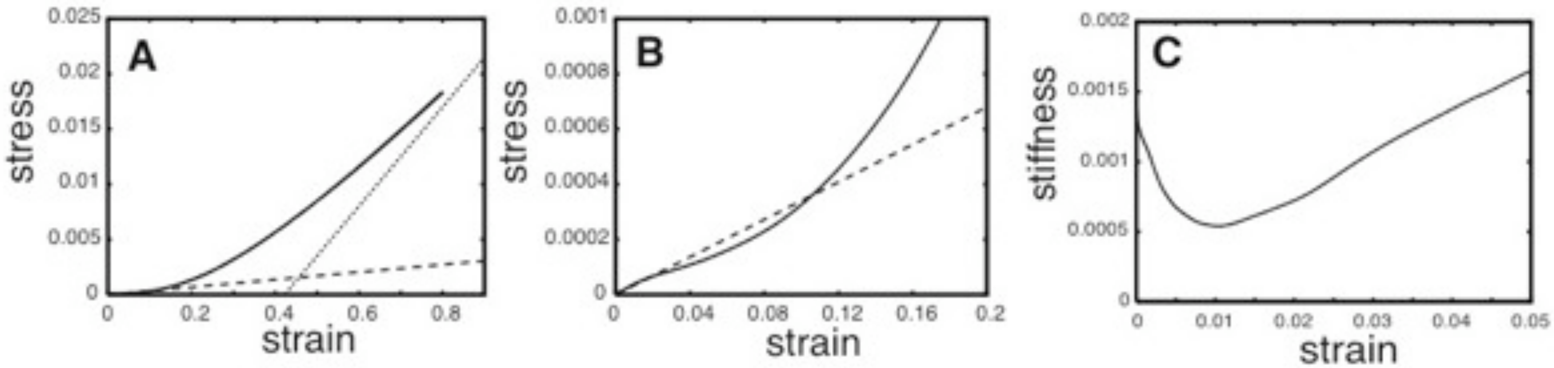
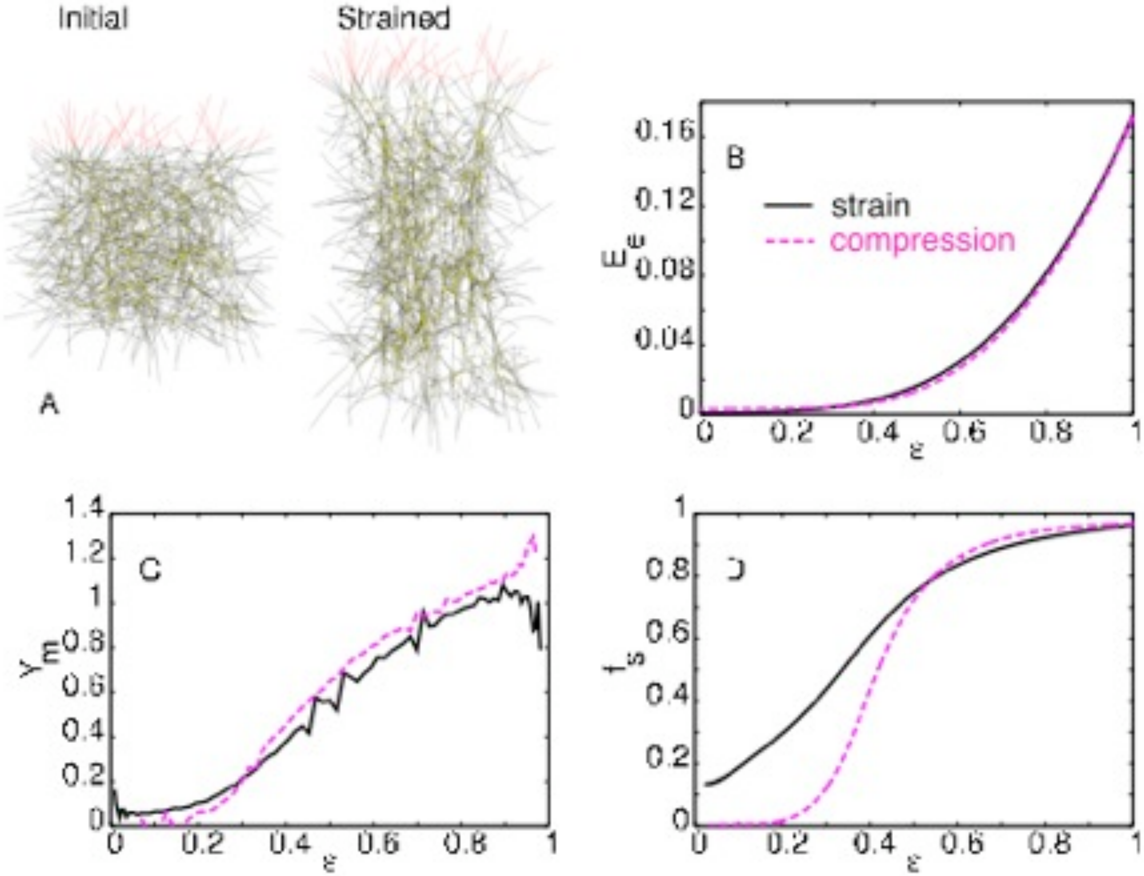
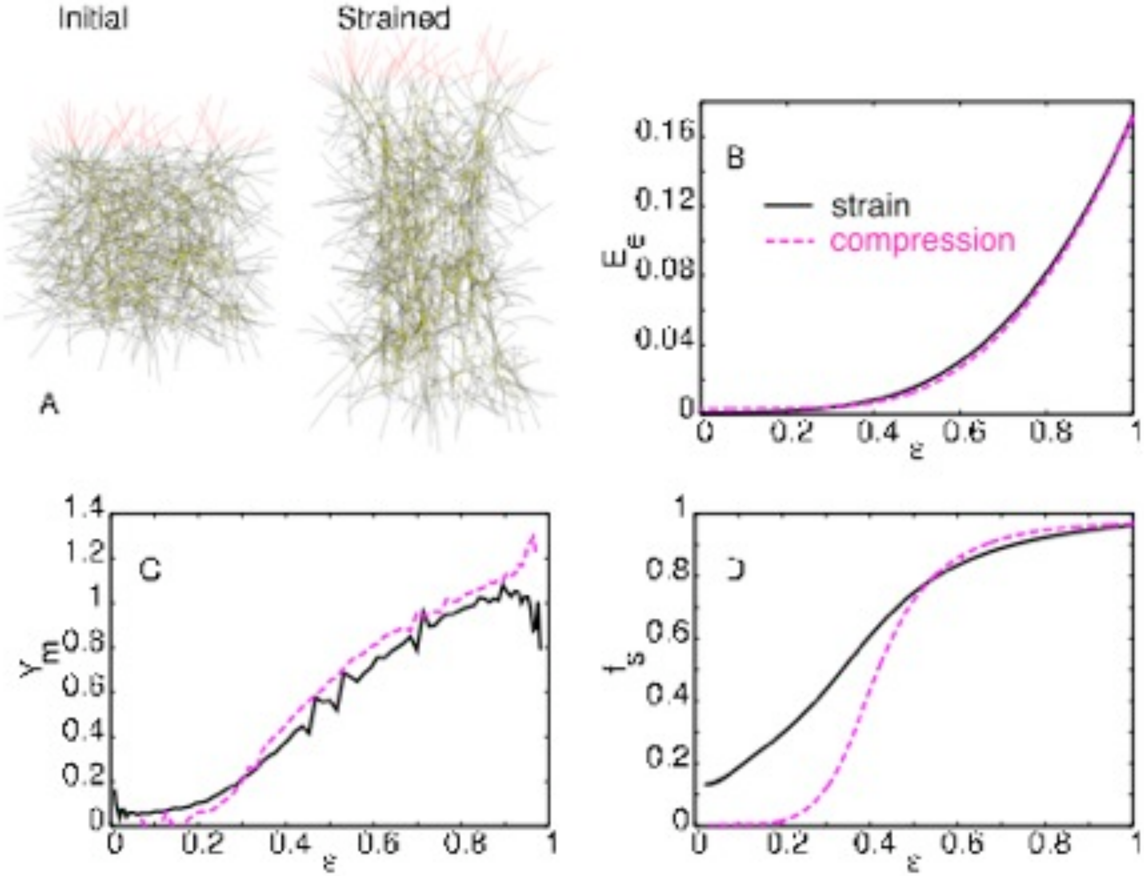
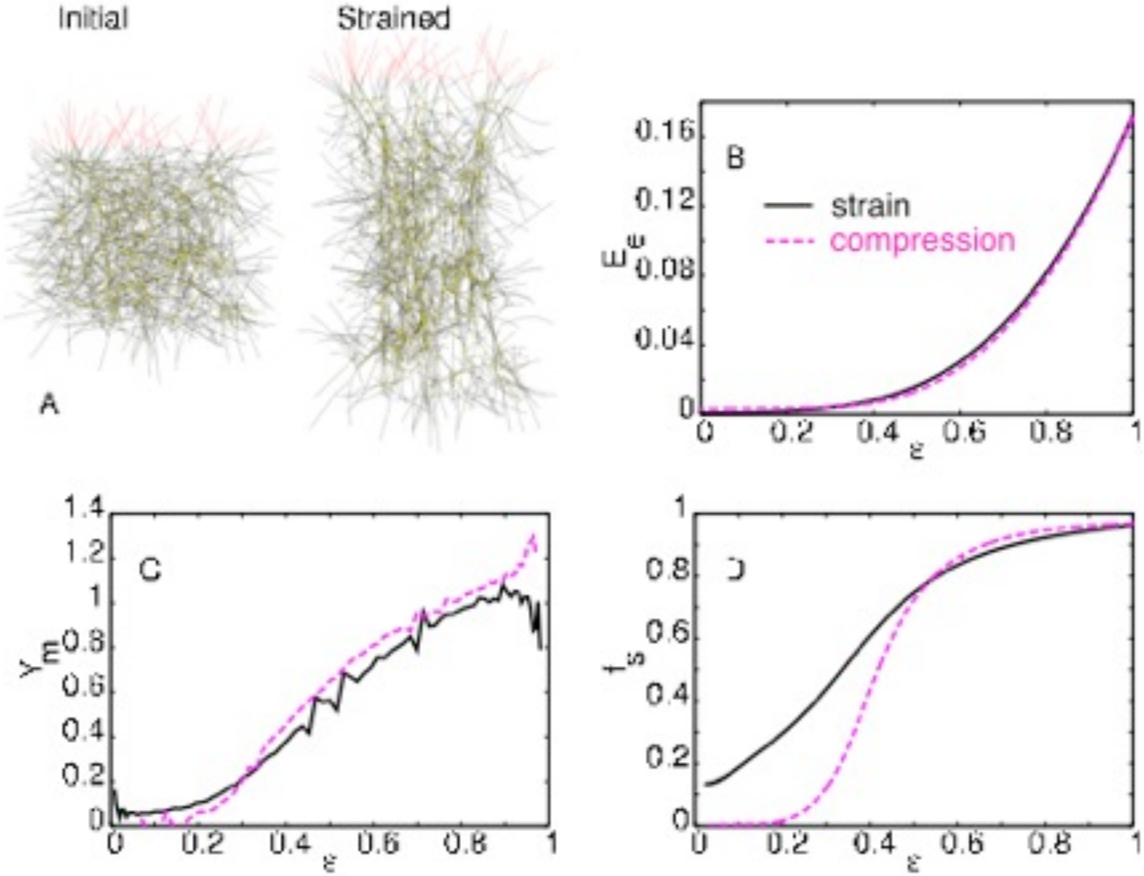



Initial
Strained
A
B
strain
compression
E_e
0.16
0.12
0.08
0.04
0
0.2
0.4
0.6
0.8
1
ε
C
Y_m
1.4
1.2
1
0.8
0.6
0.4
0.2
D
f_s

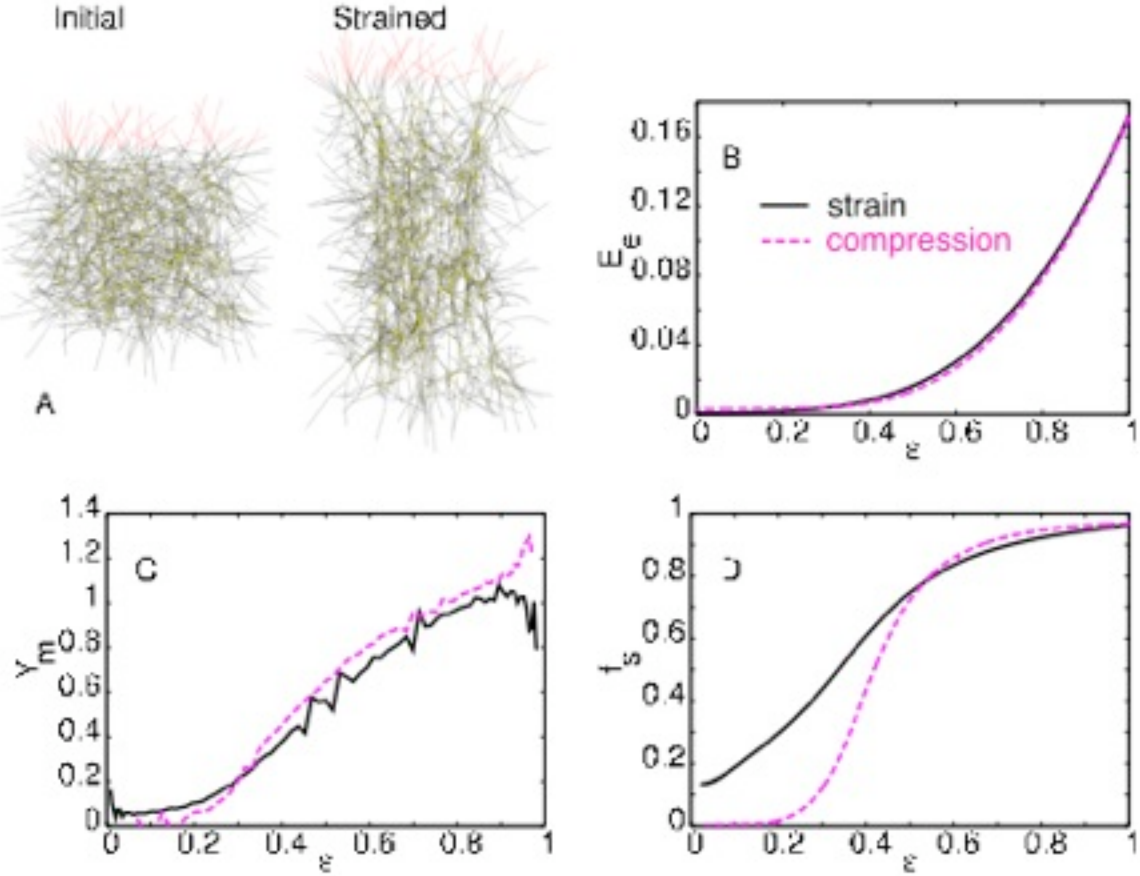


A.) Snapshots of a mesh with passive crosslinks at zero (left) and 100% strain (right).



A.) Snapshots of a mesh with passive crosslinks at zero (left) and 100% strain (right).

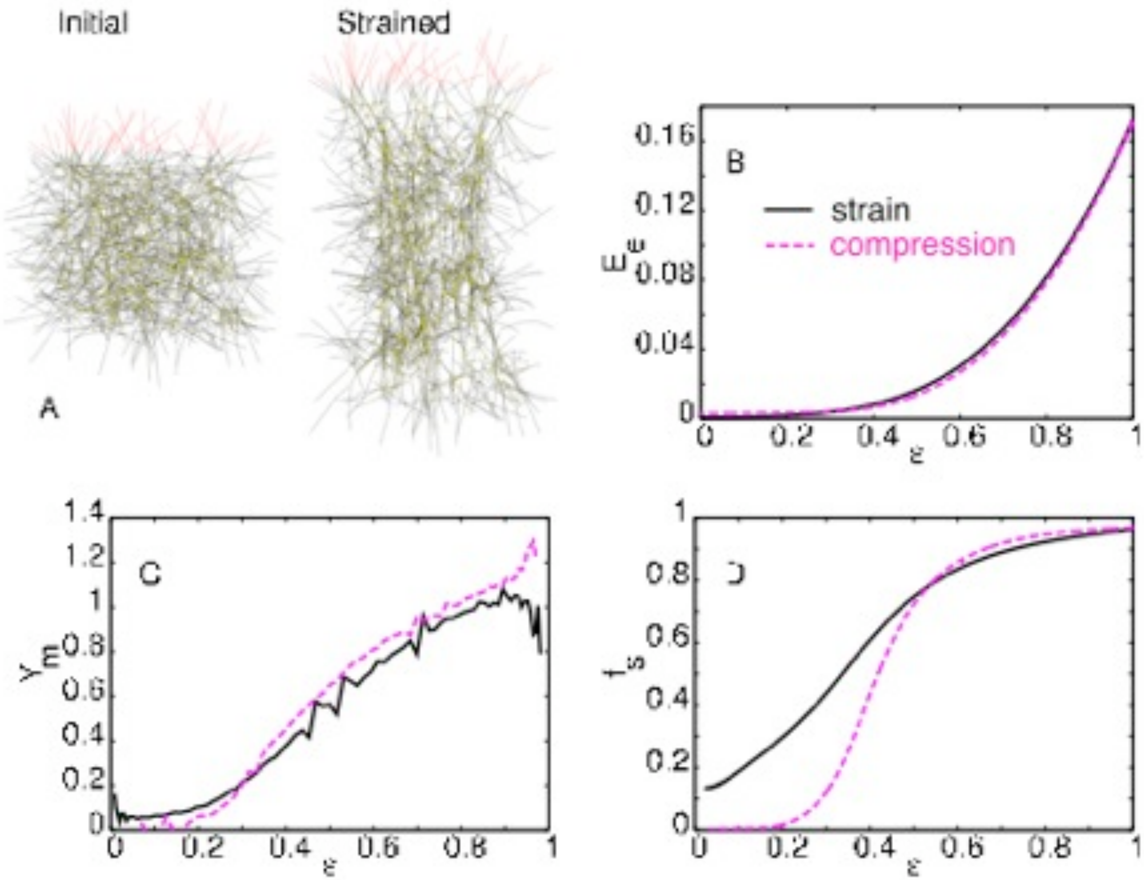
B.) The elastic energy of the fibers for the mesh as a function of strain



A.) Snapshots of a mesh with passive crosslinks at zero (left) and 100% strain (right).

B.) The elastic energy of the fibers for the mesh as a function of strain

C.) The second numerical derivative of the curve in Fig. B with respect to strain (Young's modulus of the mesh) as function of strain.



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D.) Affine measure: The fraction of elastic energy of the fibers related to fiber stretching (as opposed to bending, stretching or torsion) as function of strain.

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Links are allowed to break when they are stretched beyond a threshold

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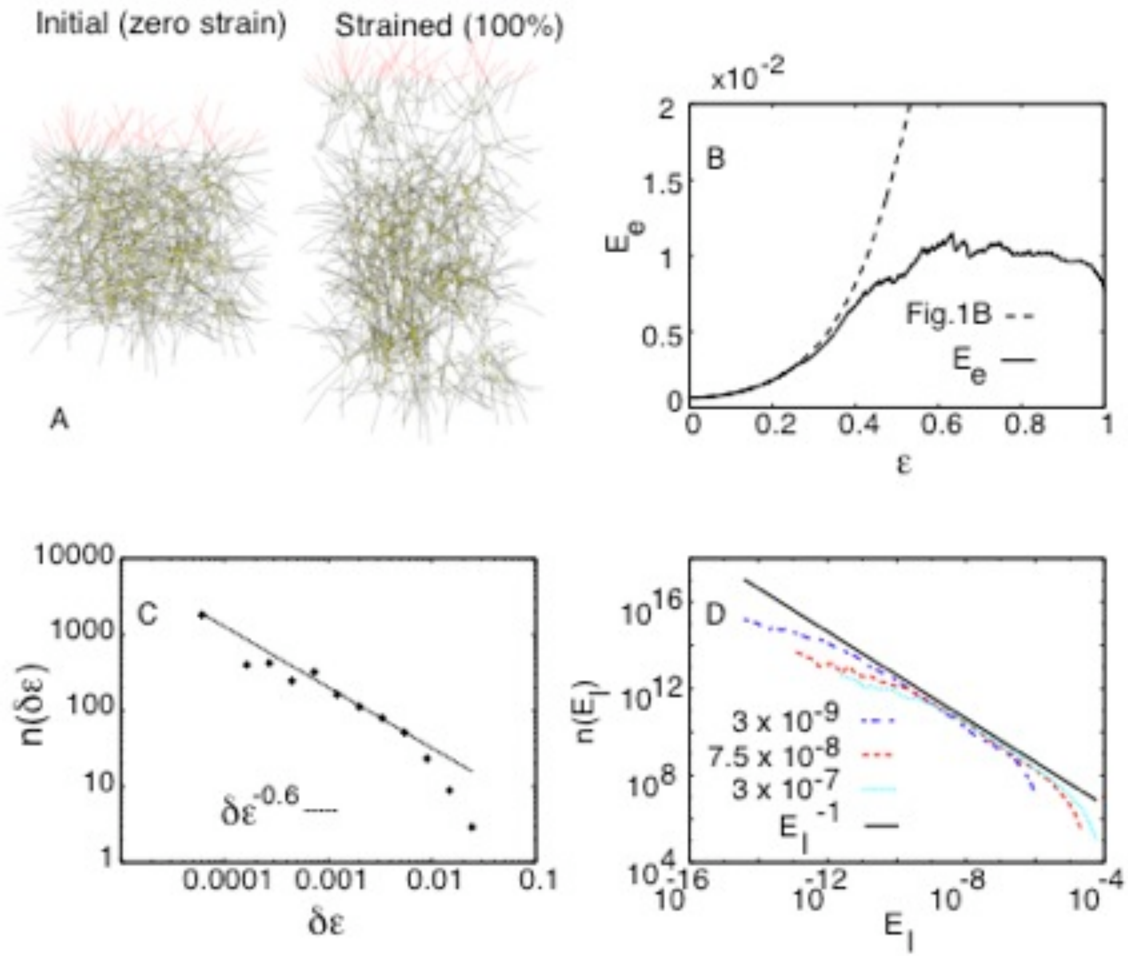

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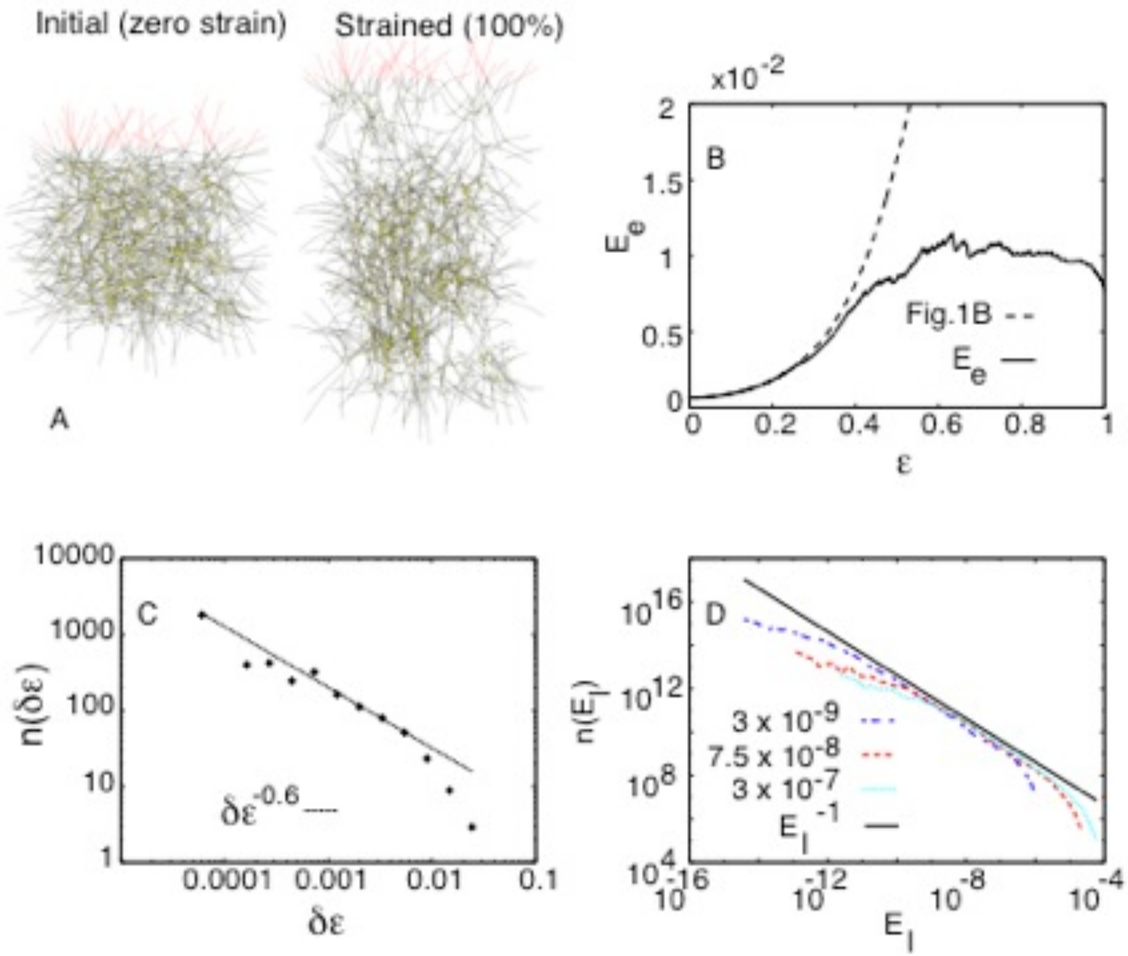

A.) Snapshots of a mesh with semi-passive cross links at zero strain (left) and 100 % strain.

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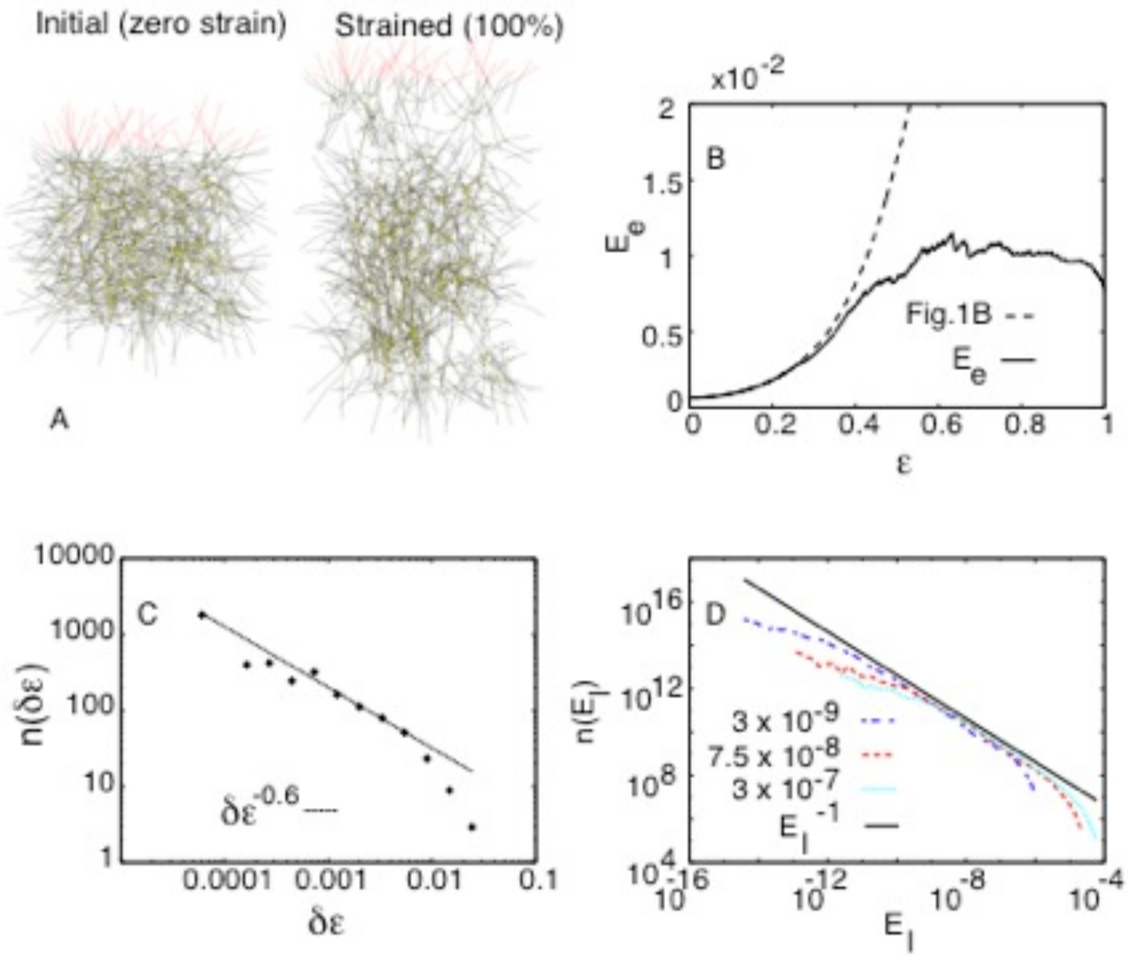

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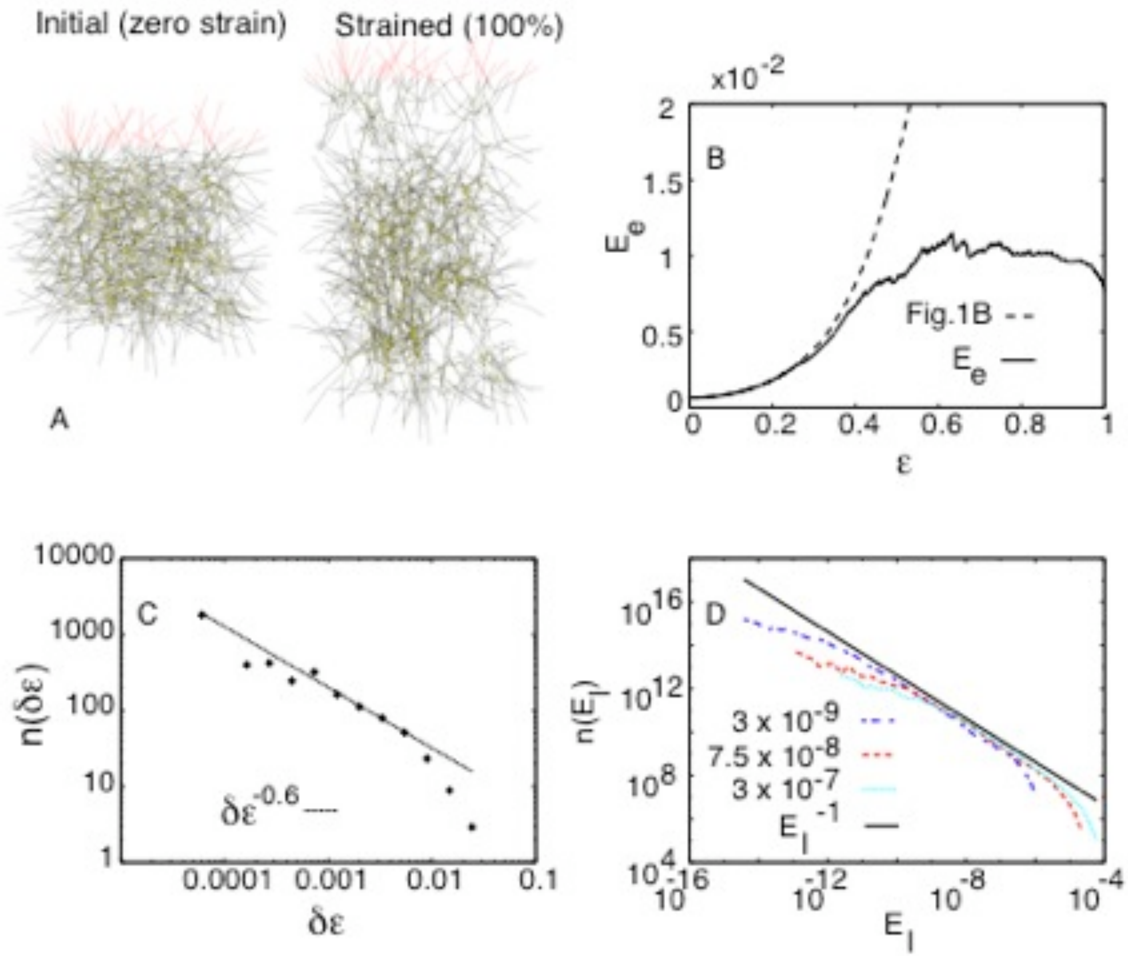

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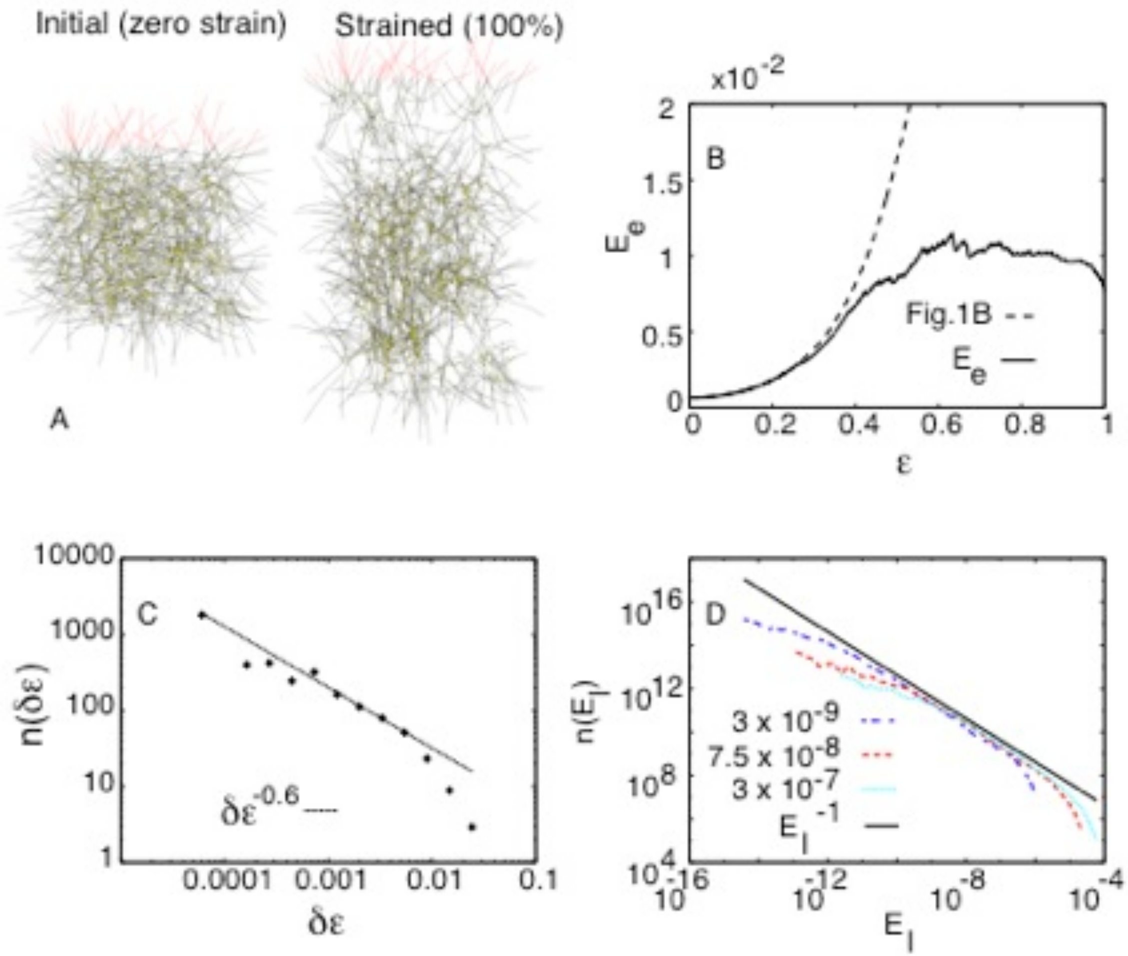
B.) The elastic energy of the fibers in mesh as a function of strain. Dotted line: curve from passive case for comparison.

C.) The distribution of the strain at the links, between adjacent link fractures, for semi-passive links.

Semi passive links:

Links are allowed to break when they are stretched beyond a threshold



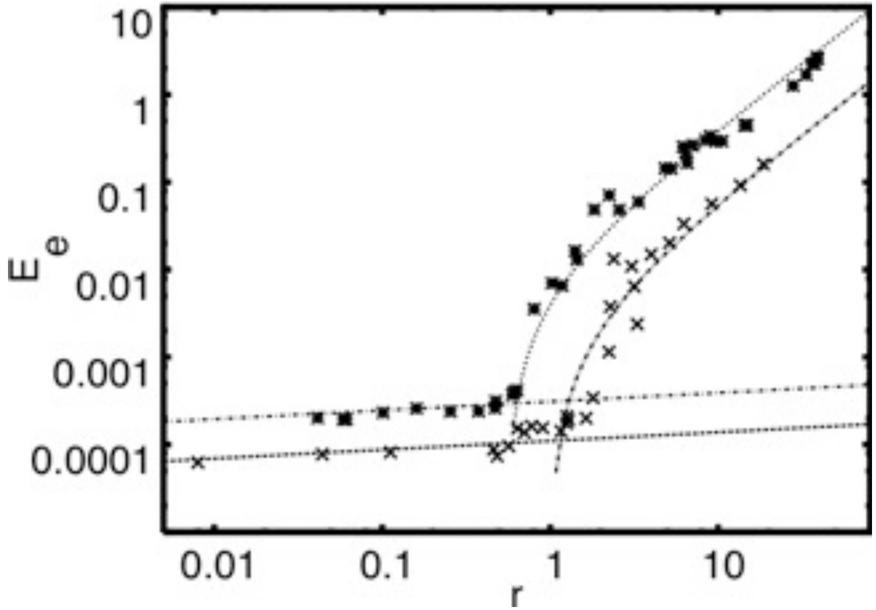
A.) Snapshots of a mesh with semi-passive cross links at zero strain (left) and 100 % strain.

B.) The elastic energy of the fibers in mesh as a function of strain. Dotted line: curve from passive case for comparison.

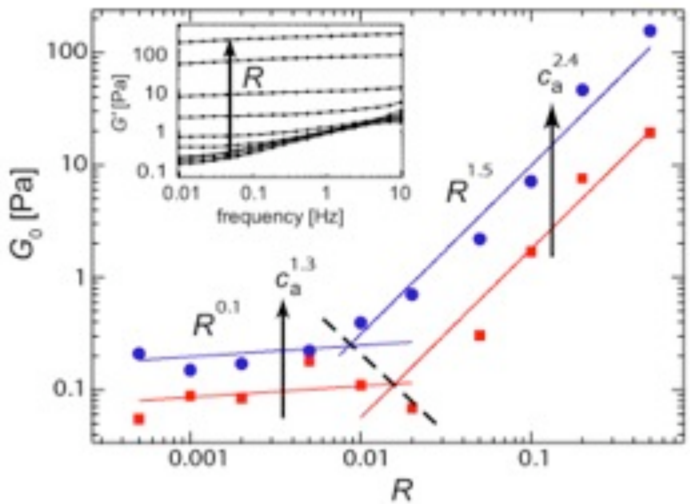
C.) The distribution of the strain at the links, between adjacent link fractures, for semi-passive links.

D.) Elastic energy distribution of the links for small strain (i.e. before any link fractures). The distribution functions are approximately power-laws with 'cut-offs' at small and large strains.

Comparison with experiments



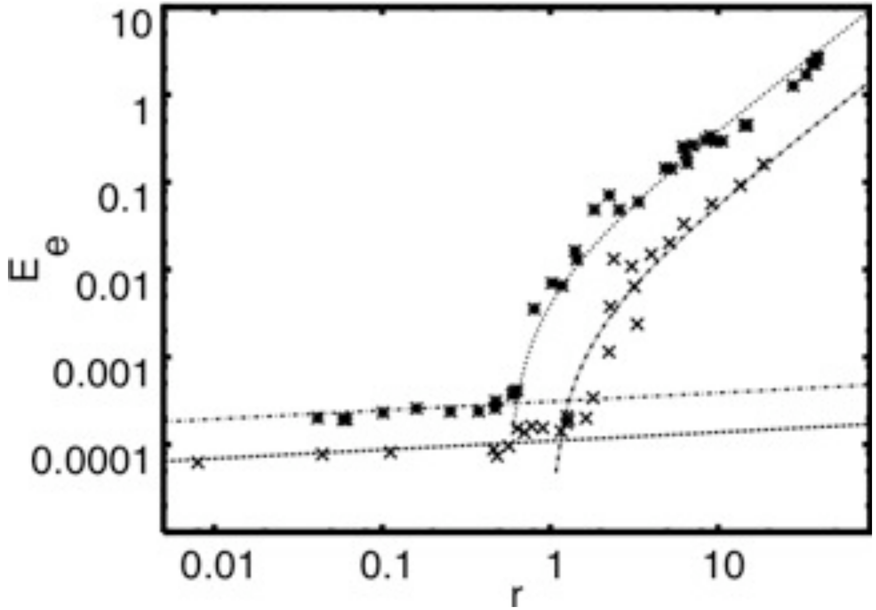
Below the transition, the elastic energy (Ee) has a weak dependence on r and above the critical value it varies as $(r - r_c)^{1.5}$



Plateau modulus G_0 as a function of the molar ratio R of fascin with respect to actin for two different concentrations of actin: 0.4 mg/ml (circles) and 0.2 mg/ml (squares).

O. Lieleg *et. al.* Phys. Rev. Lett., **99**, 088102 (2007).

Comparison with experiments



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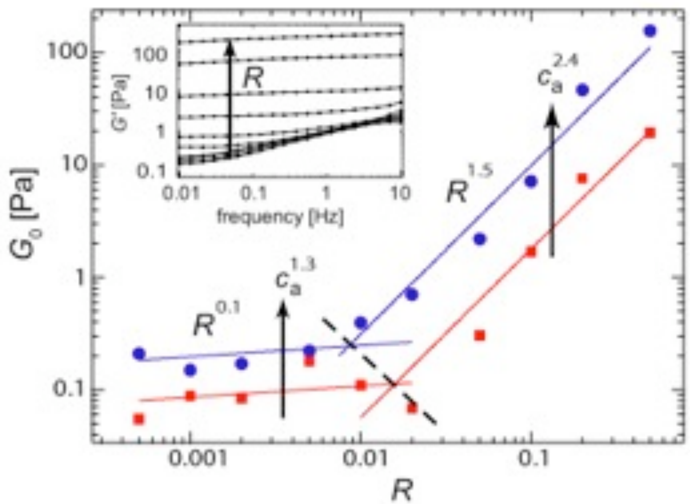
J. Astrom, P.B. S. K., M. Karttunen and I. Vattulainen Phys. Rev. E **77**, 051913 (2008)



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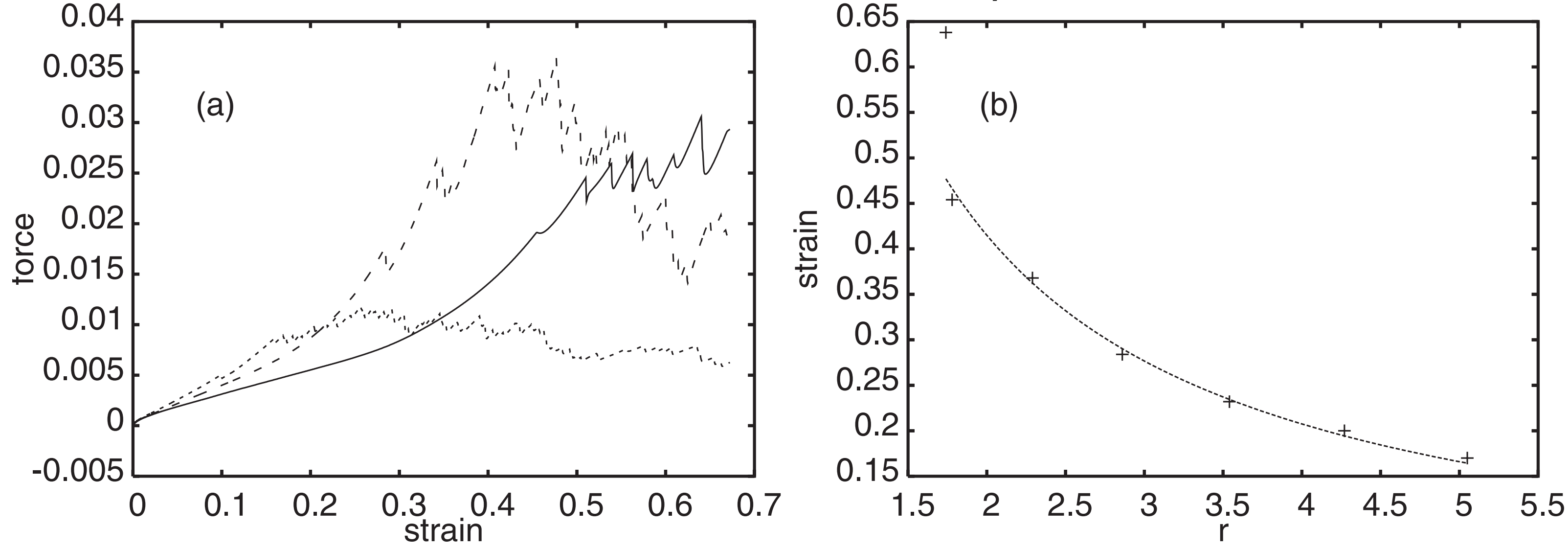

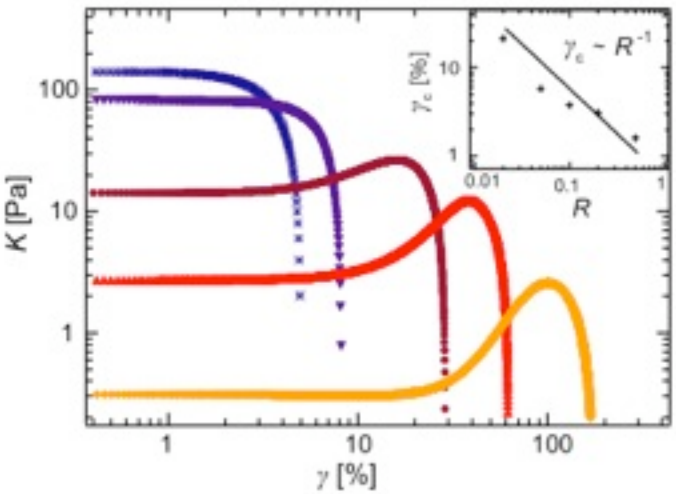

Differential modulus K versus deformation for fascin networks in the bundle phase and increasing R. The inset shows the critical strain in dependence on R.

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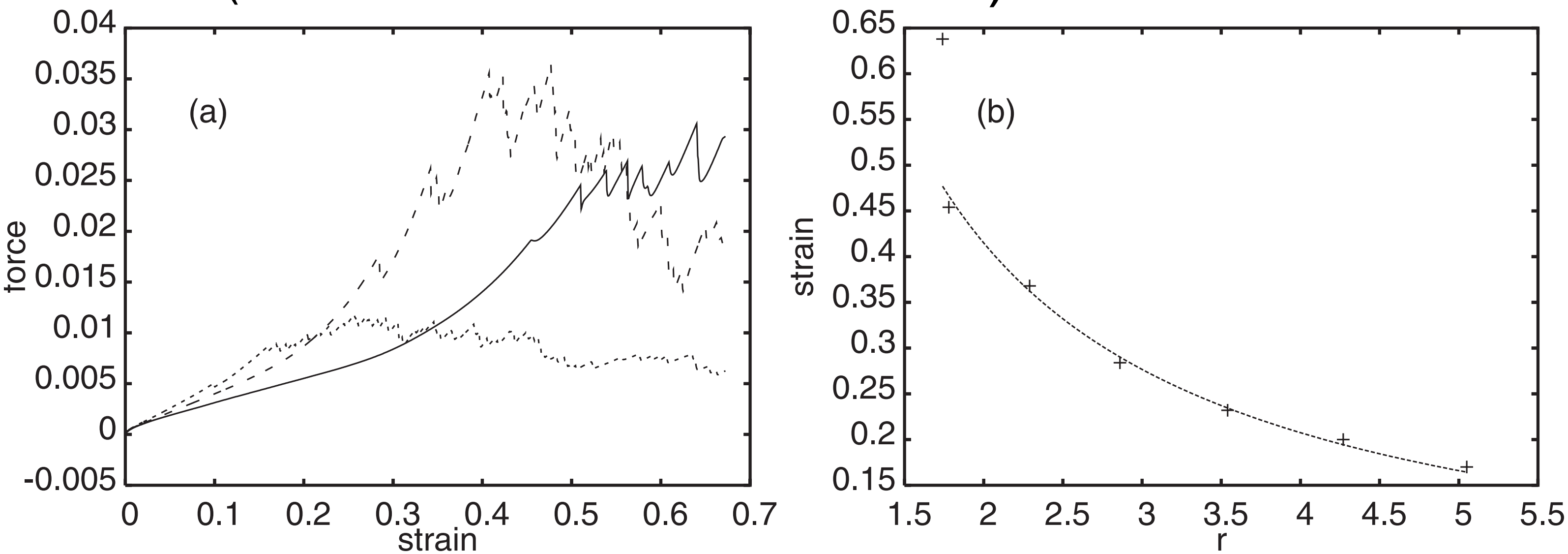

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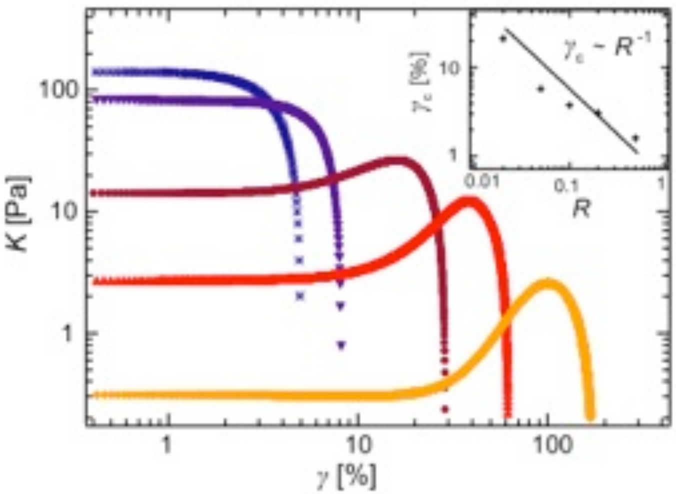

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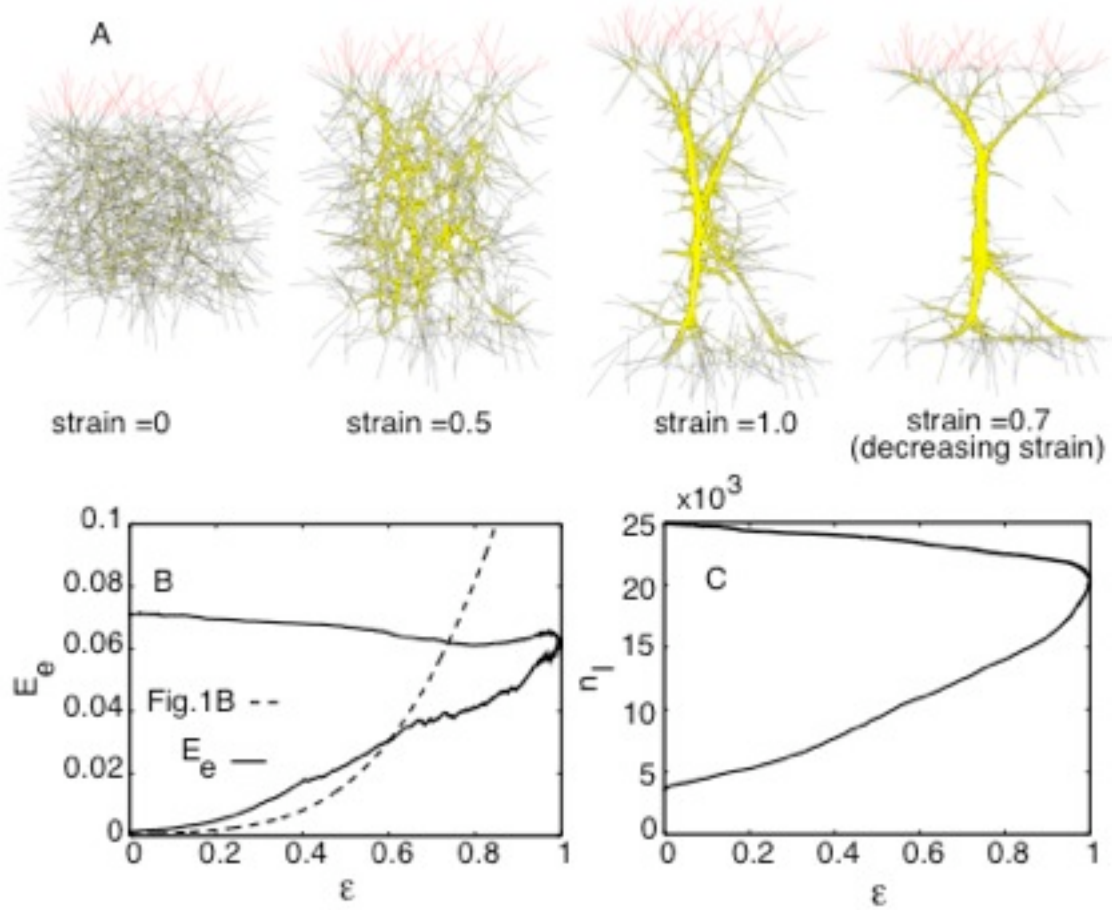

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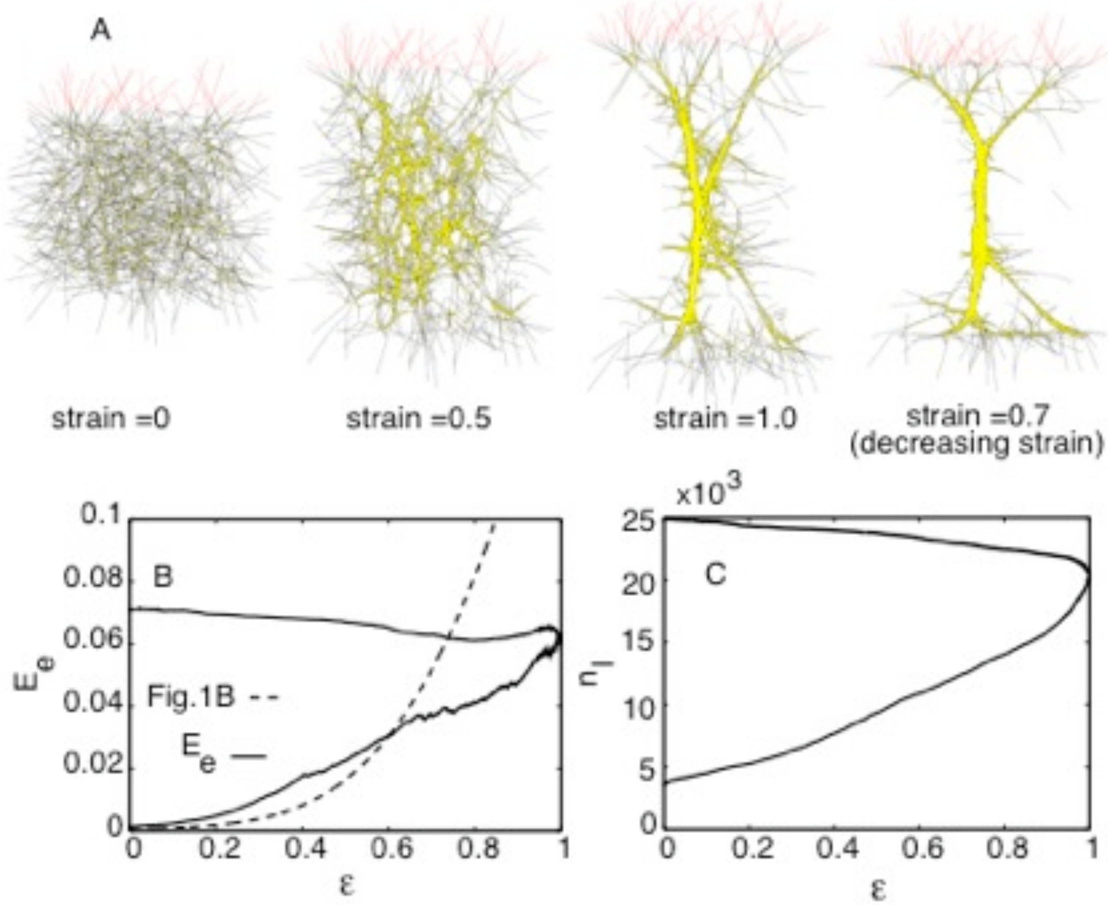

A.) Snapshots of a mesh with active cross links at different strains. The first three snapshots are prior to the stress maximum while the last is after maximum strain is reached.

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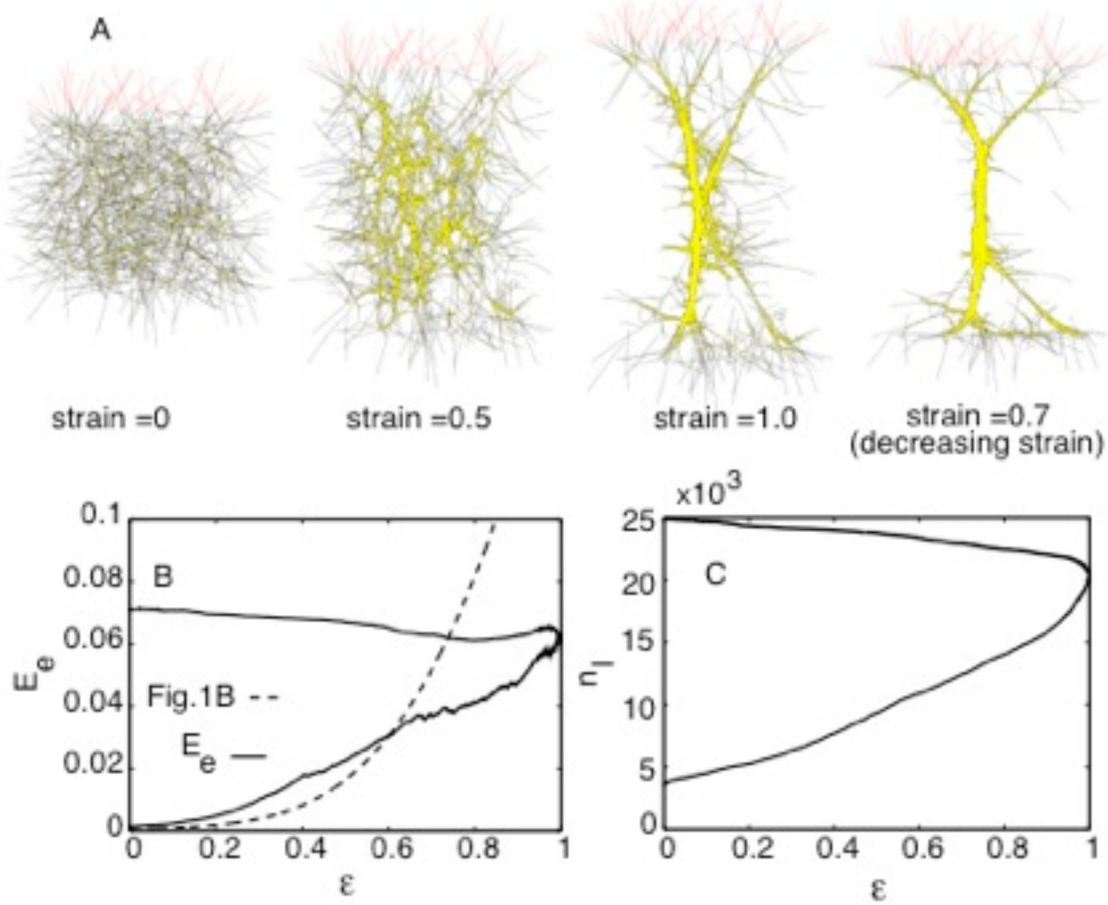

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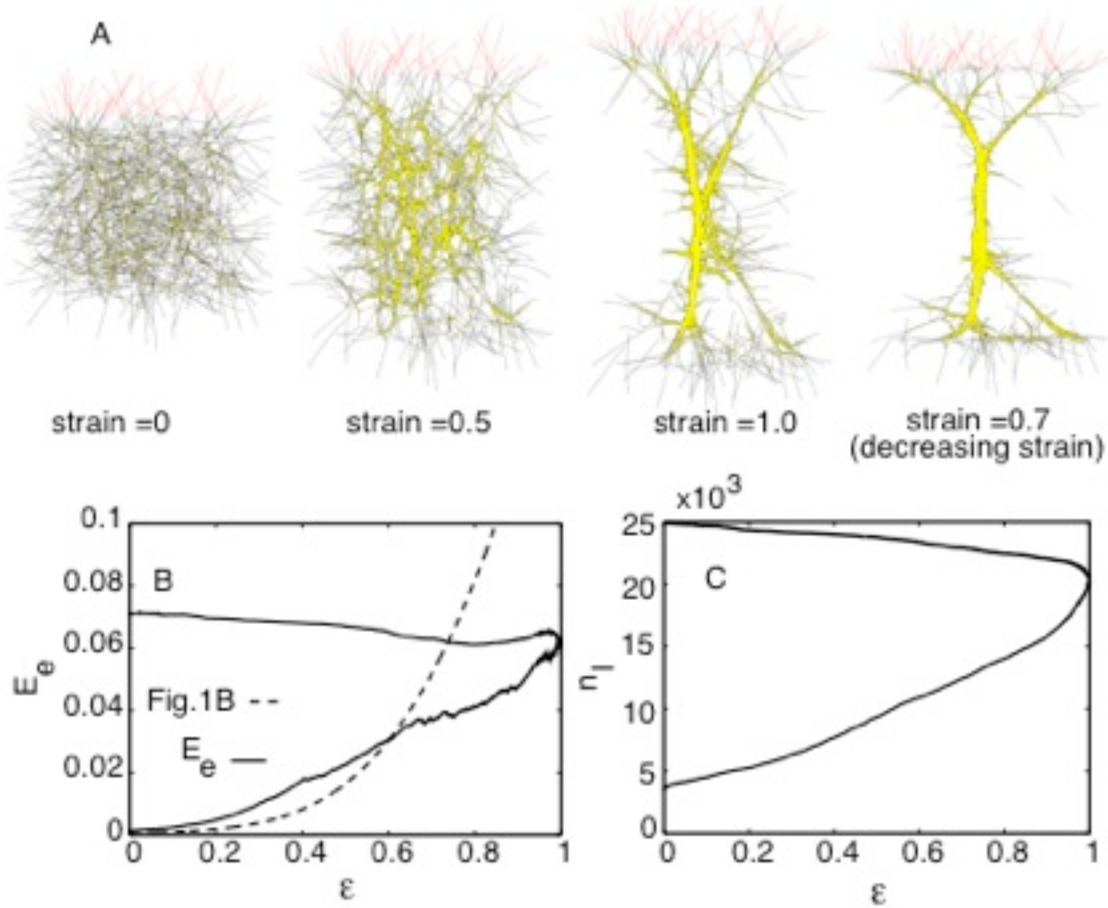

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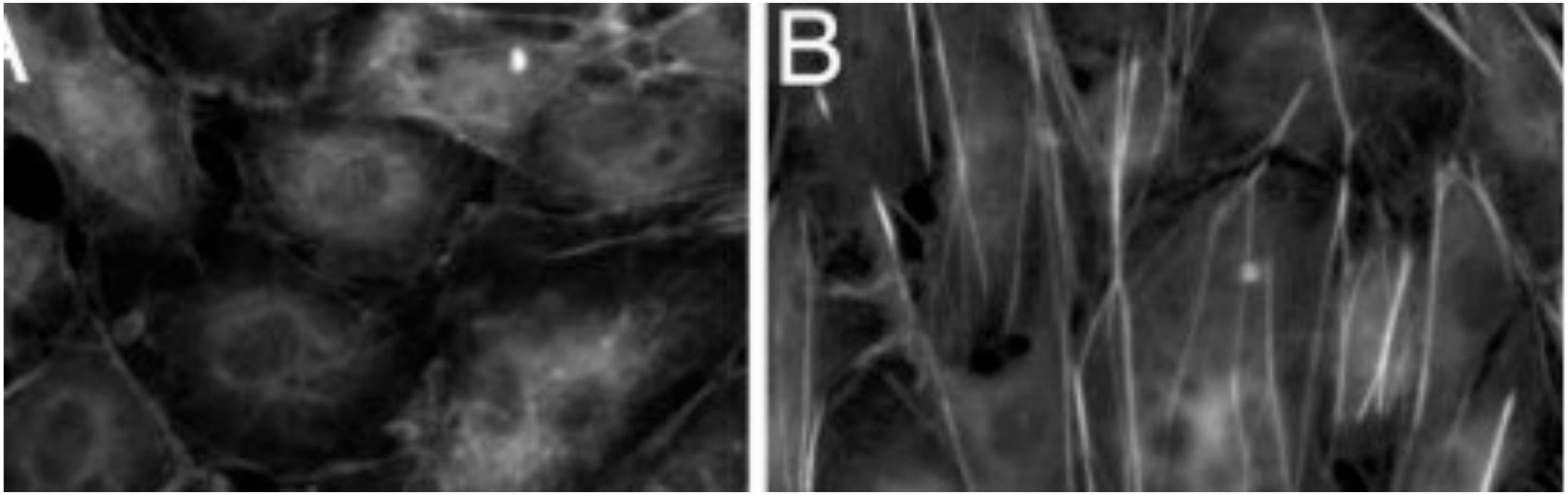

Stretch induced stress fiber formation in cells in Bovine aortic endothelial cells. Cells were stained with rhodamine-phalloidin to identify f-actin bundles

R. Kaunas, P. Nguyen , S. Usami , and S.Chien , PNAS 102, 15895 ((2005)

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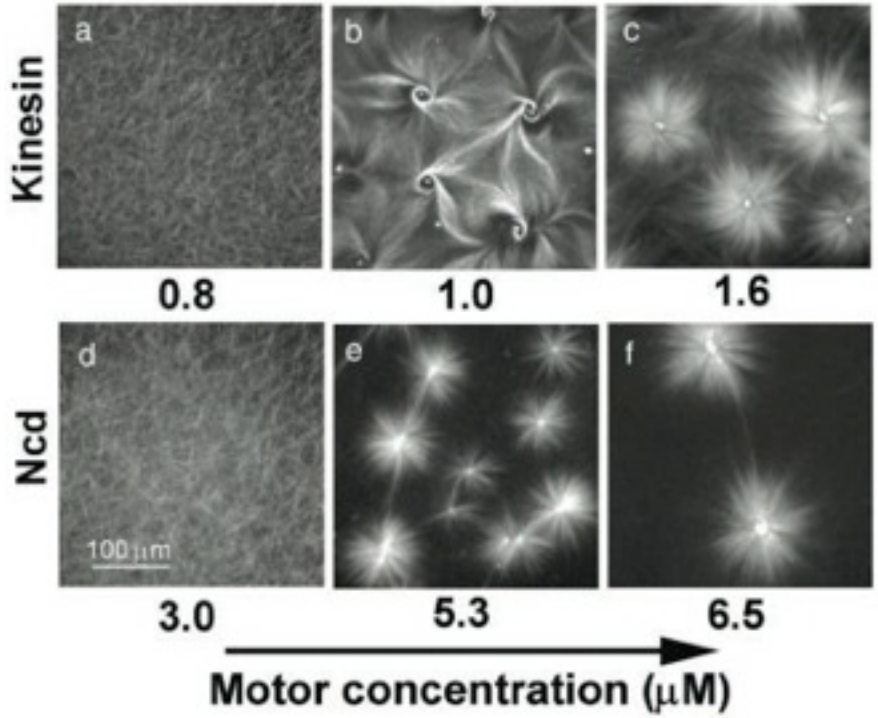

Thomas Surrey, *et al. Science* , 1167 (2001); 292

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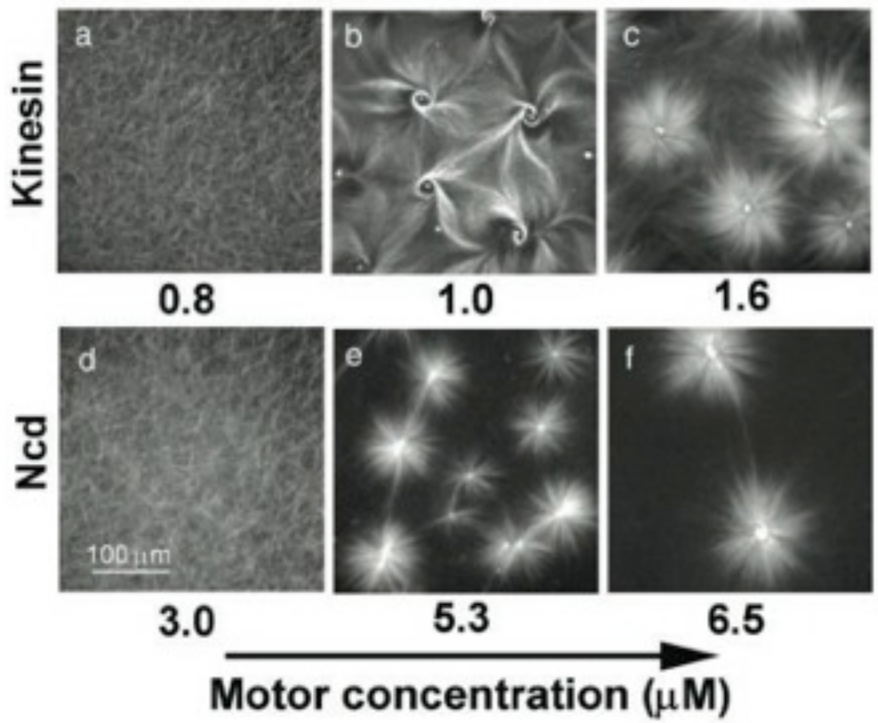

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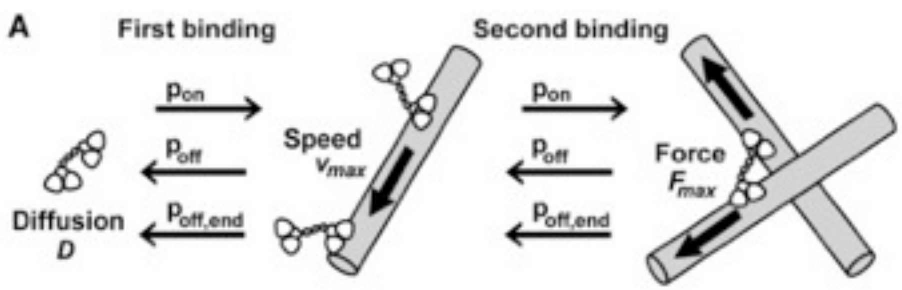

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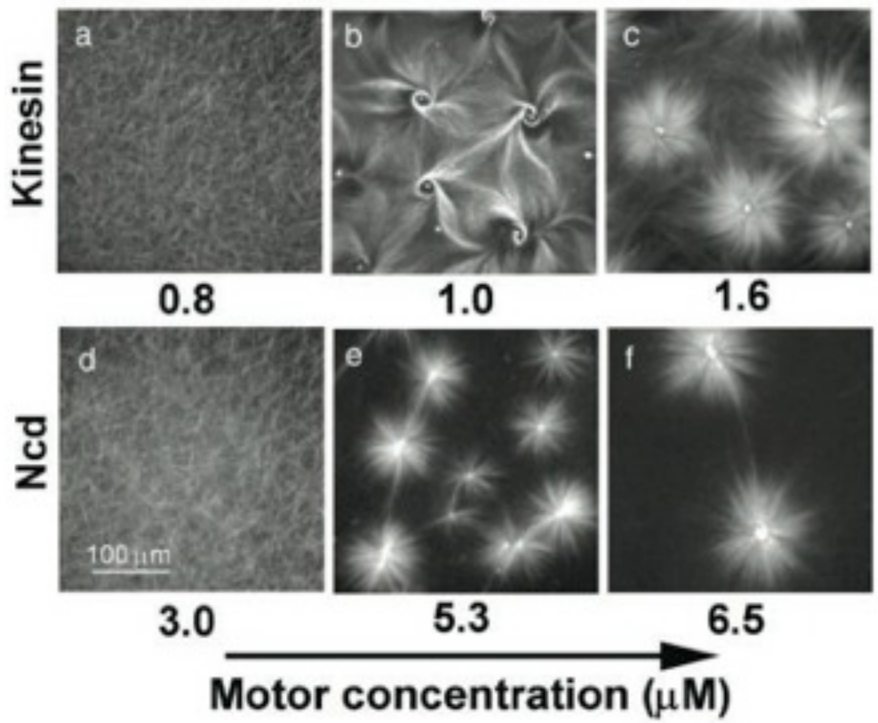

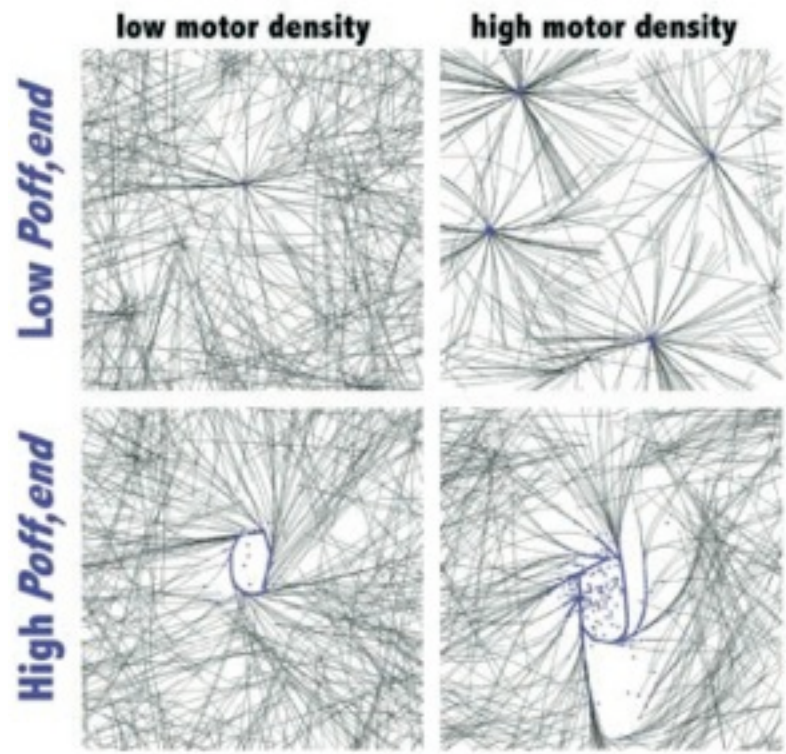

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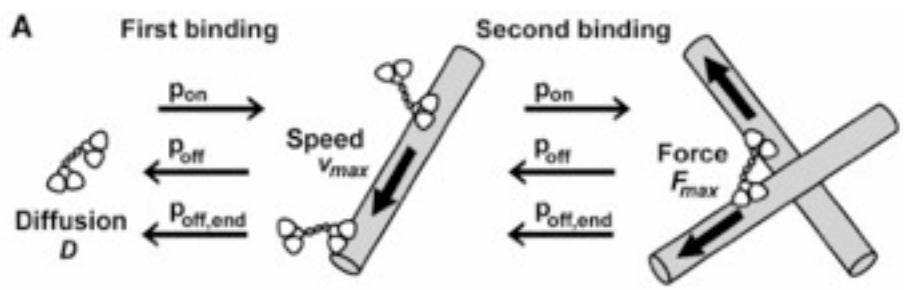

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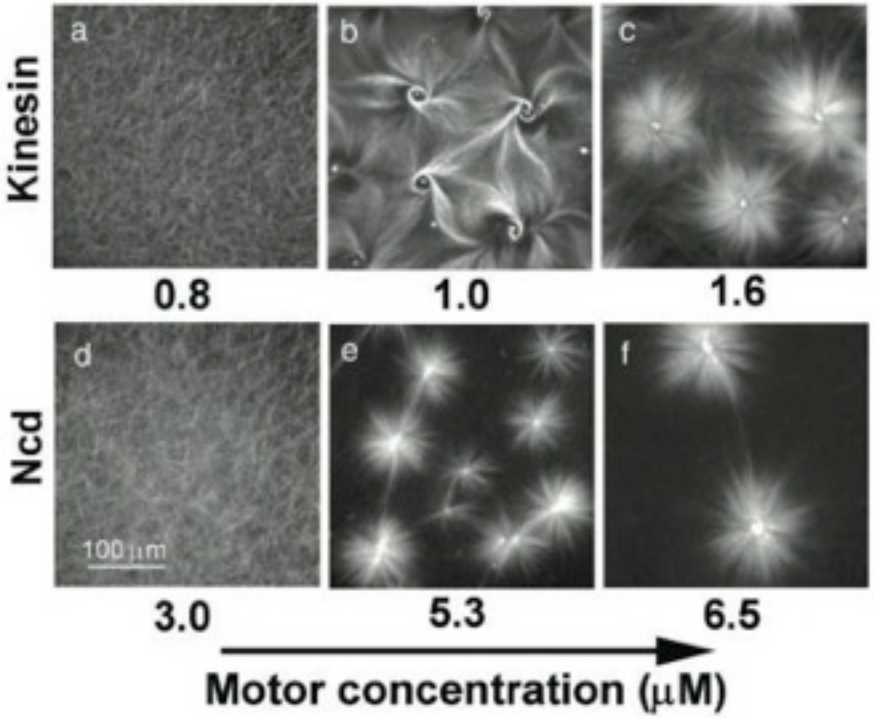

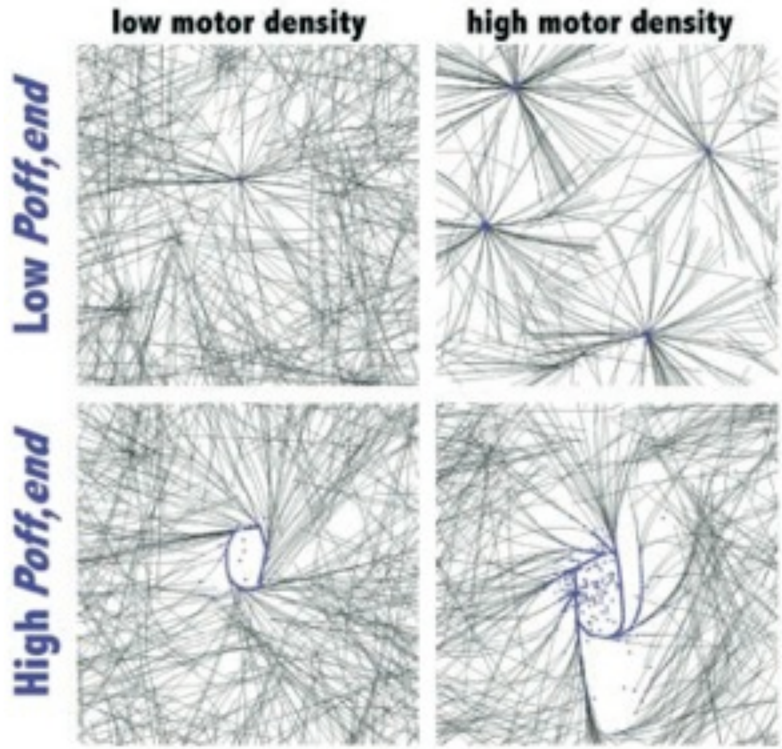

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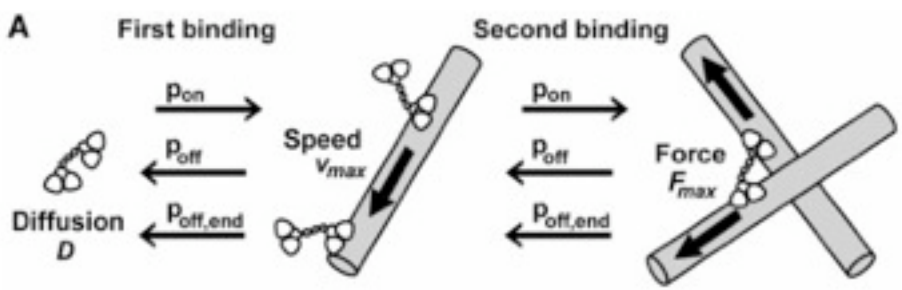

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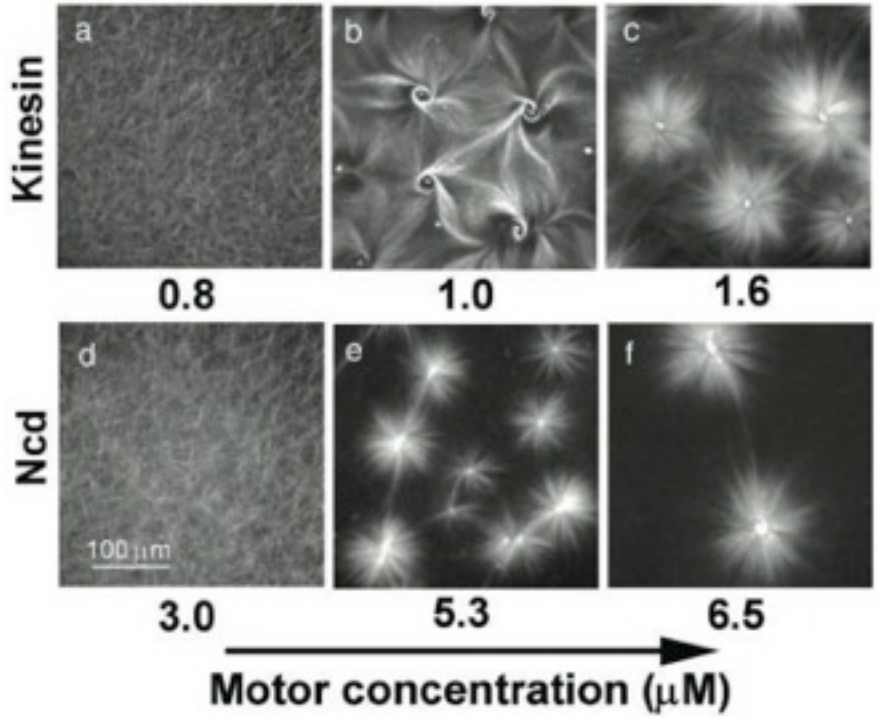

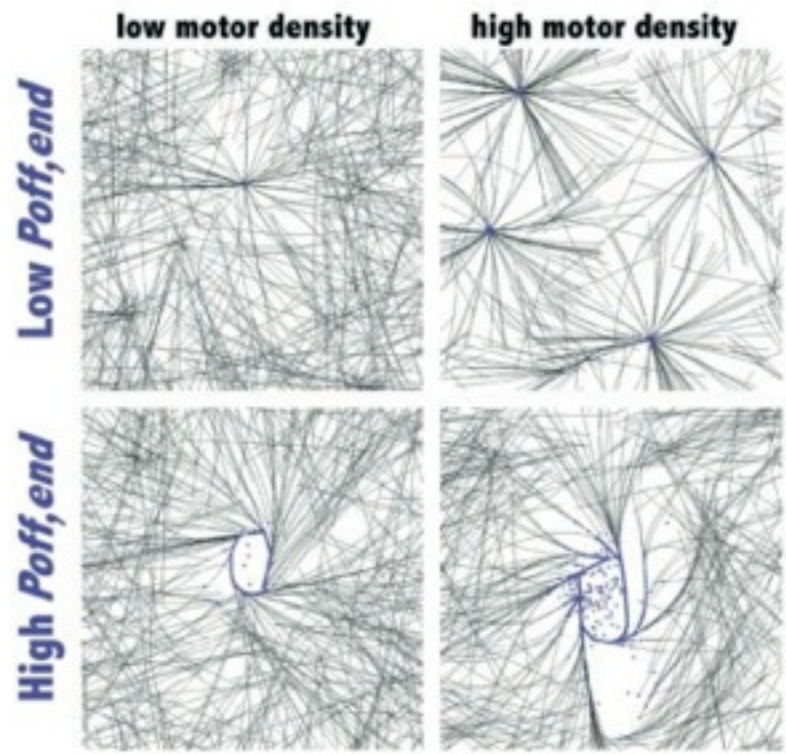

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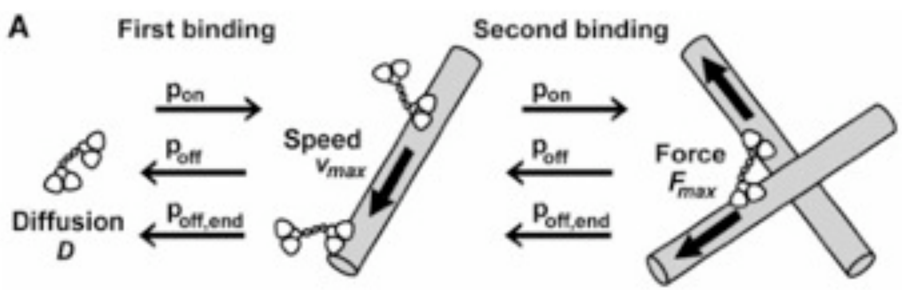

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S.Sankararaman, G. Menon, P.B.S.K. Phys. Rev. E. **70**, 031905 (2004) - a hydrodynamic model

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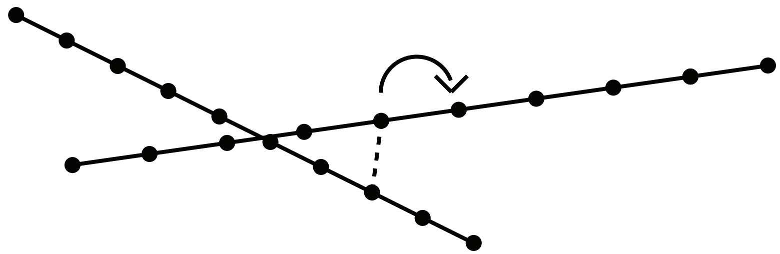

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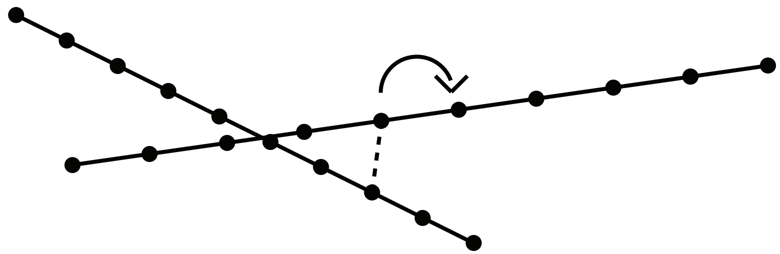

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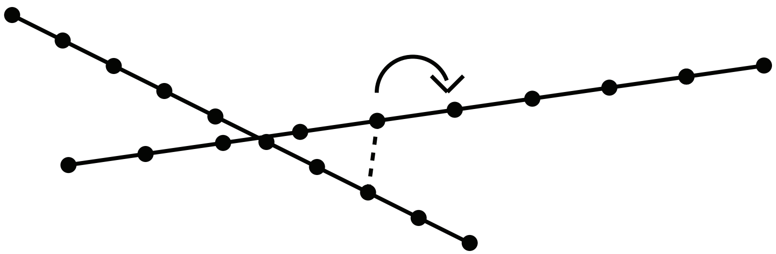

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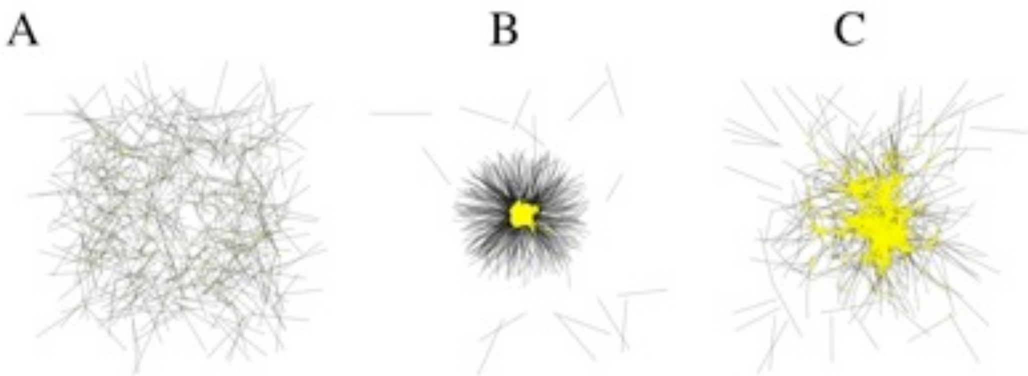
(B) When motors are unidirectional asters form

(C) Stead state configuration with bi-directional motors.



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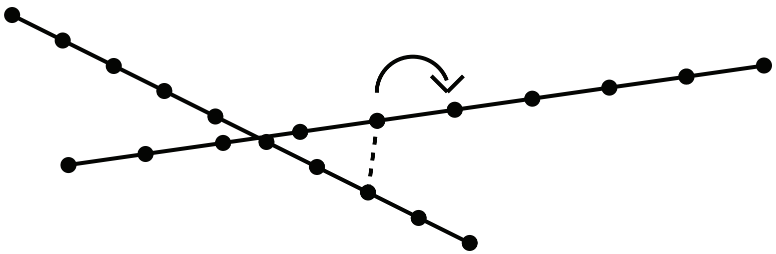

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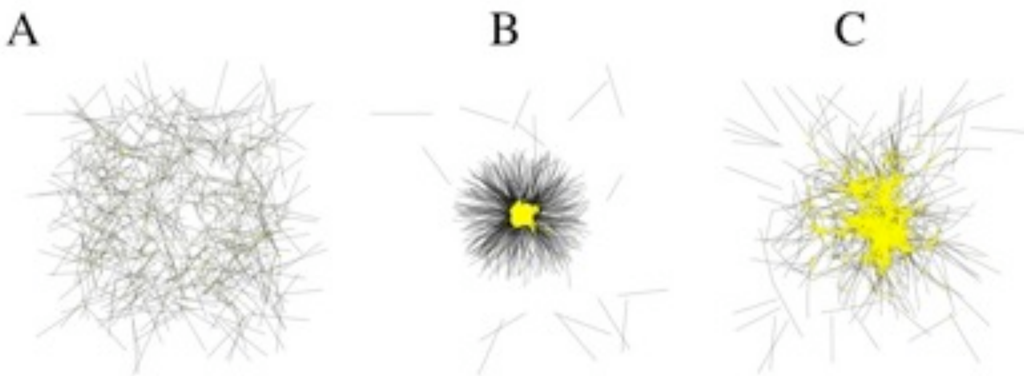
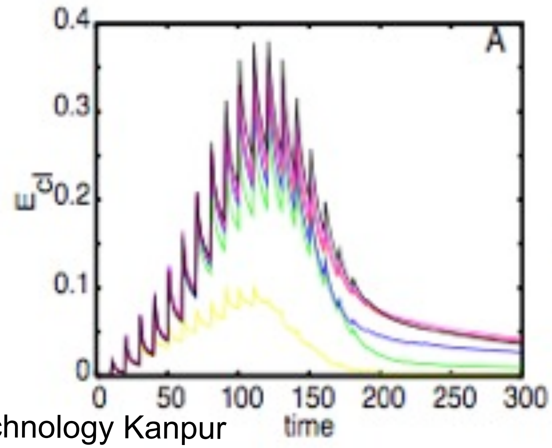
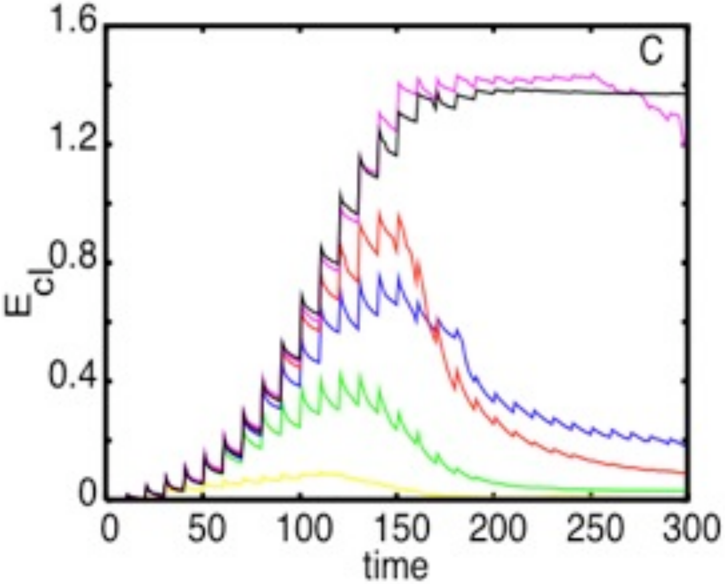


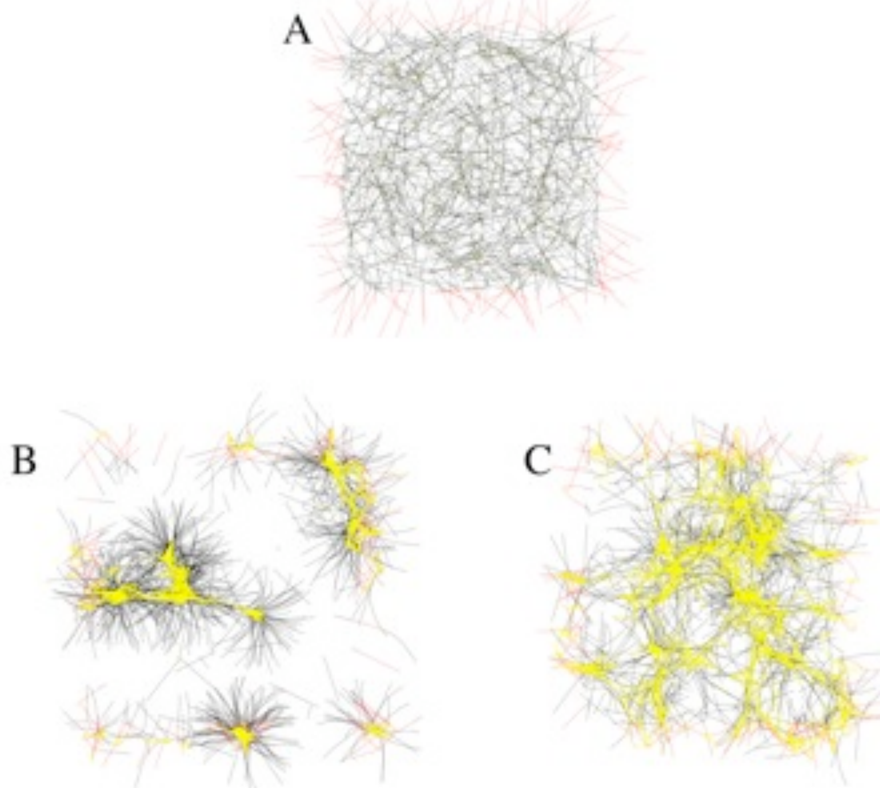
J. Astrom, P. B. S. K. and M. Karttunen: Soft Matter , **5**, 2869 (2009)

Elastic energy as a function of time





The elastic energy stored in the motors E_{cl} as function of time for τ_b = 0.2,0.3,....,0.7(yellow, green, blue, red, magenta, black) with τ_c =0.3



(A) Initial configuration with clamped boundary. The mesh contains 1000 fibers.
Its size 4.2 X 4.2 X 1. τ_c =0.2
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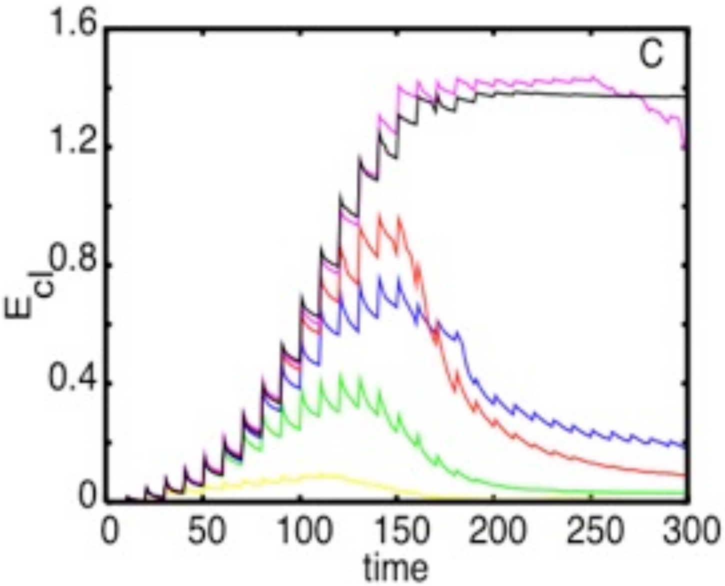
(C)Final steady state configuration for τ_b=0.6



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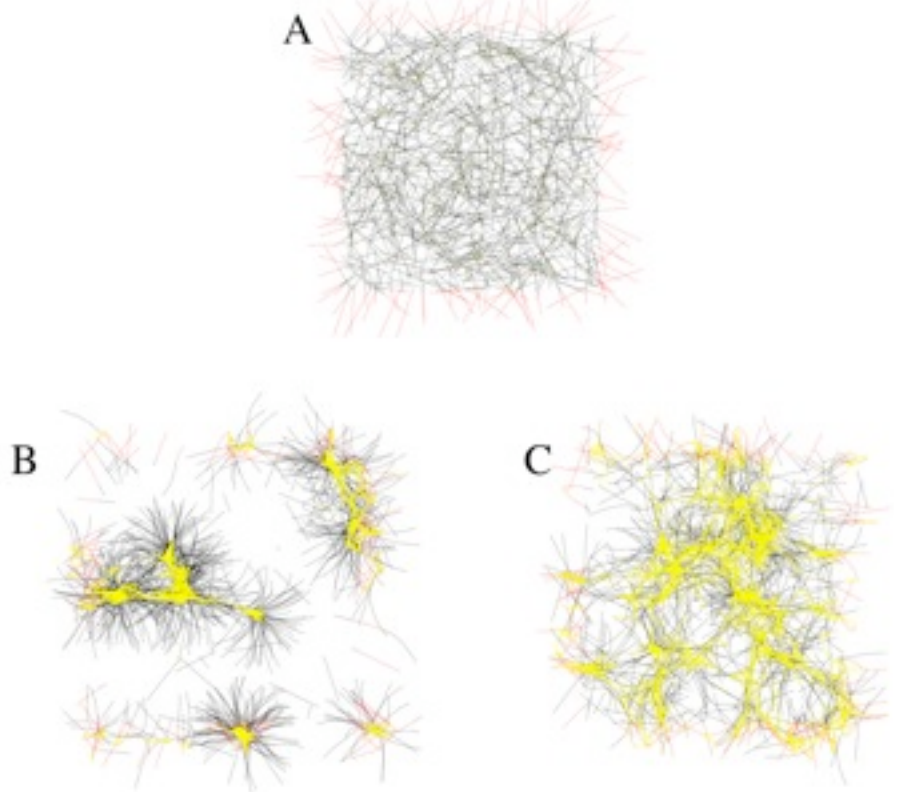

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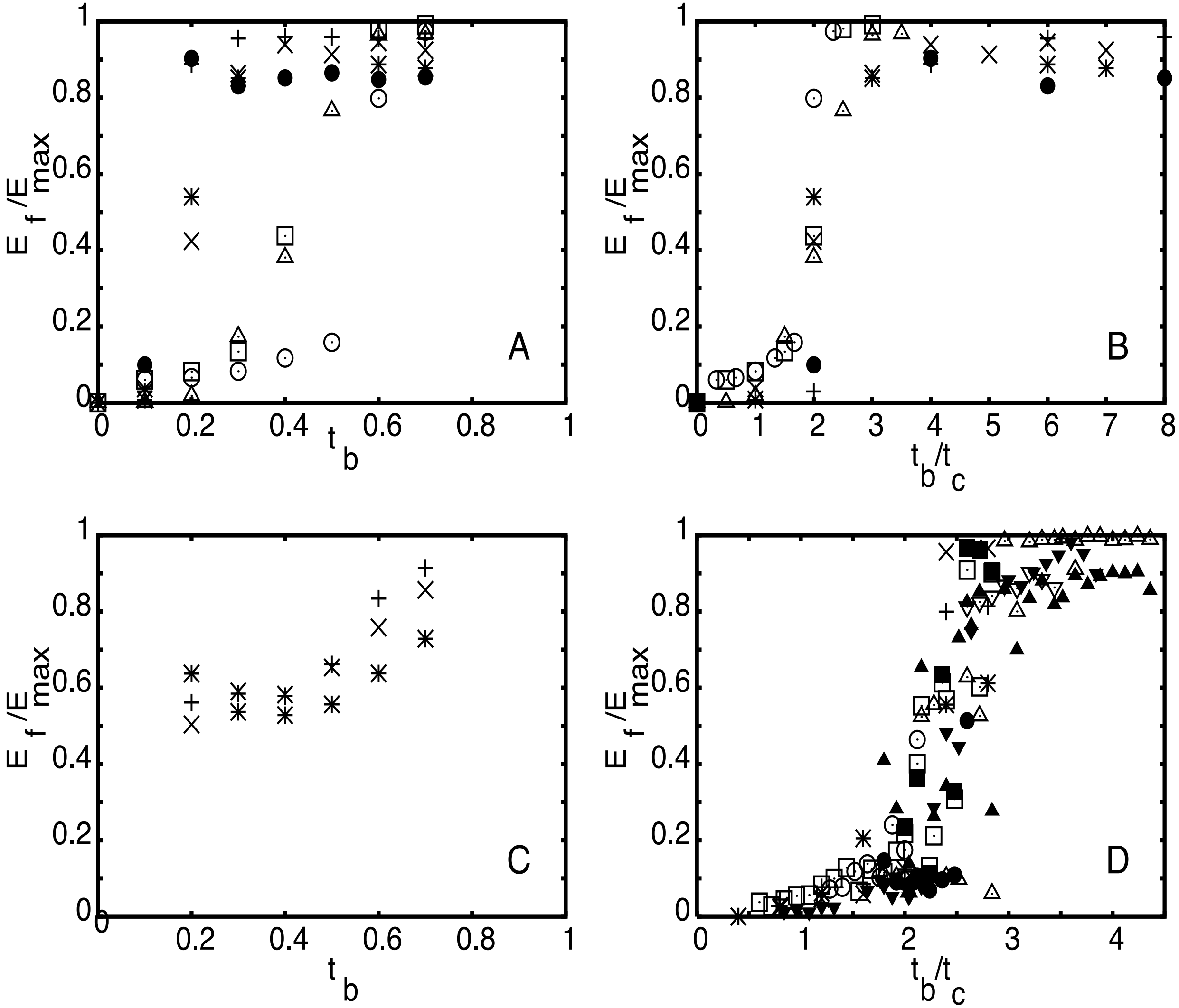

The ratio of the steady to the maximum value of elastic energy as a function of τ_b and τ_b/τ_c for different values of τ_b and τ_c for clamped (A,B,D) and free boundaries (C). Symbols are for different parameter values. The critical τ_b/τ_c seems to agree with experiments (see Nature **377**,251 (1995) , Nature 368, **113**, 1994)

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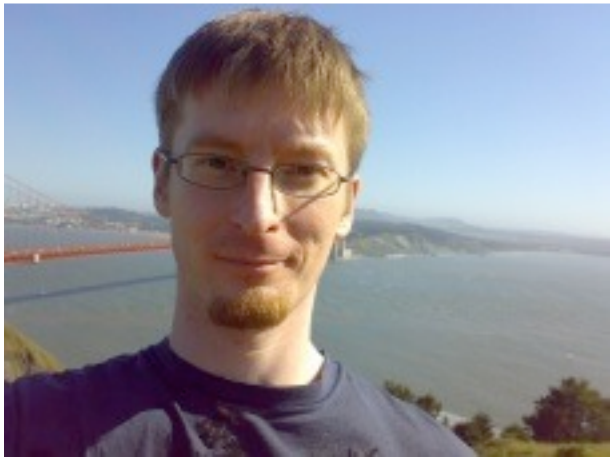
Jan

Mikko



Ilpo

Collaborators:
Jan Astrom - *CSC, Finnish IT Center for Science Helsinki , Finland*
Ilpo Vattulainen -*Tampere University of Technology, Finland*
Mikko Karttunen- *The University of Western Ontario, London, Ontario, Canada*
Computational resources - *University of Southern Denmark, CSC - Finland, HPCE- IIT Madras .*