fatigue-resistant stretchable materials

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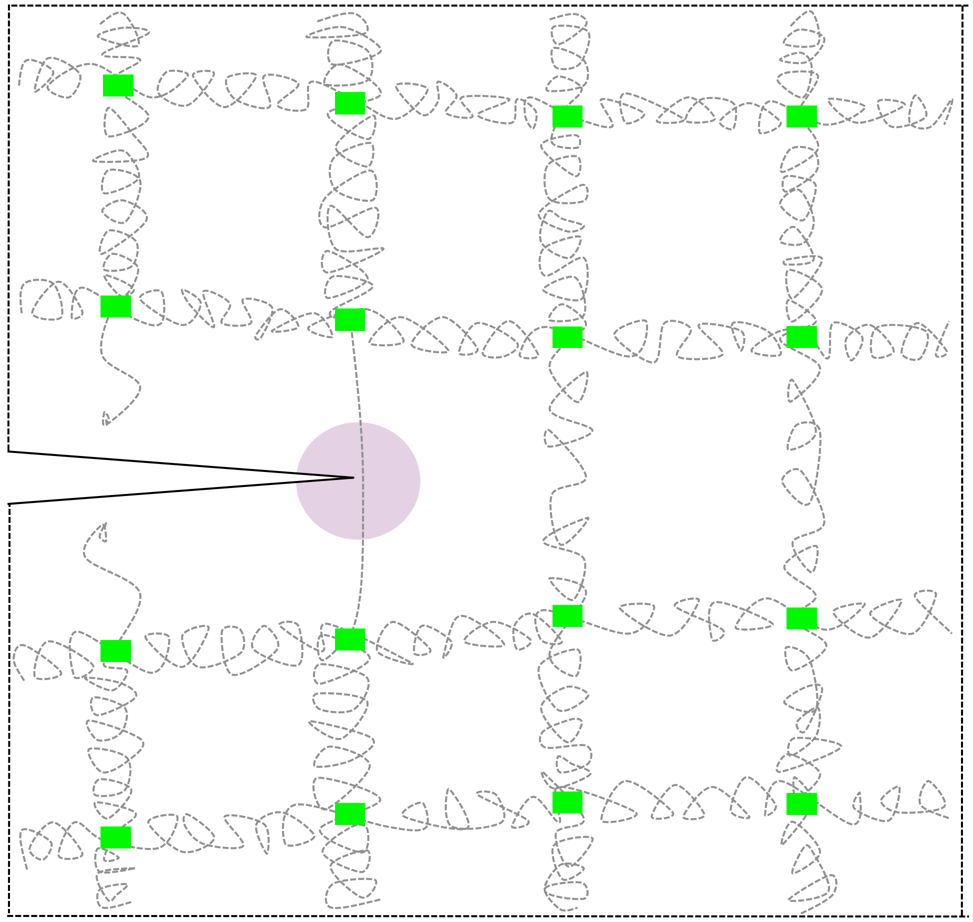
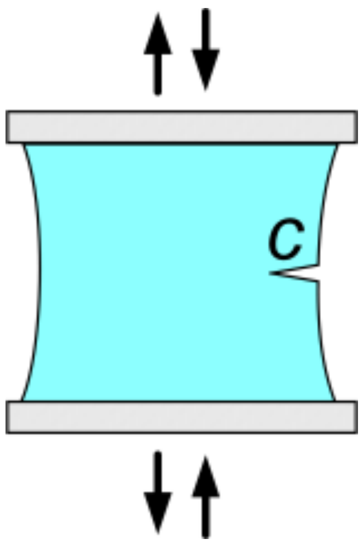
Hypothesis: an elastic network will *not* suffer fatigue

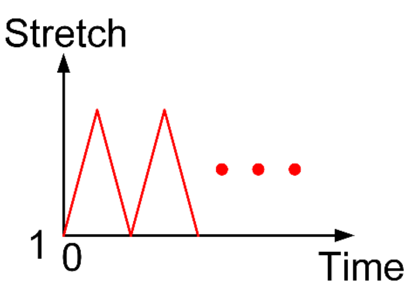


This hypothesis is wrong!

Tang, Li, Vlassak, Suo. Extreme Mechanics Letters (2017)

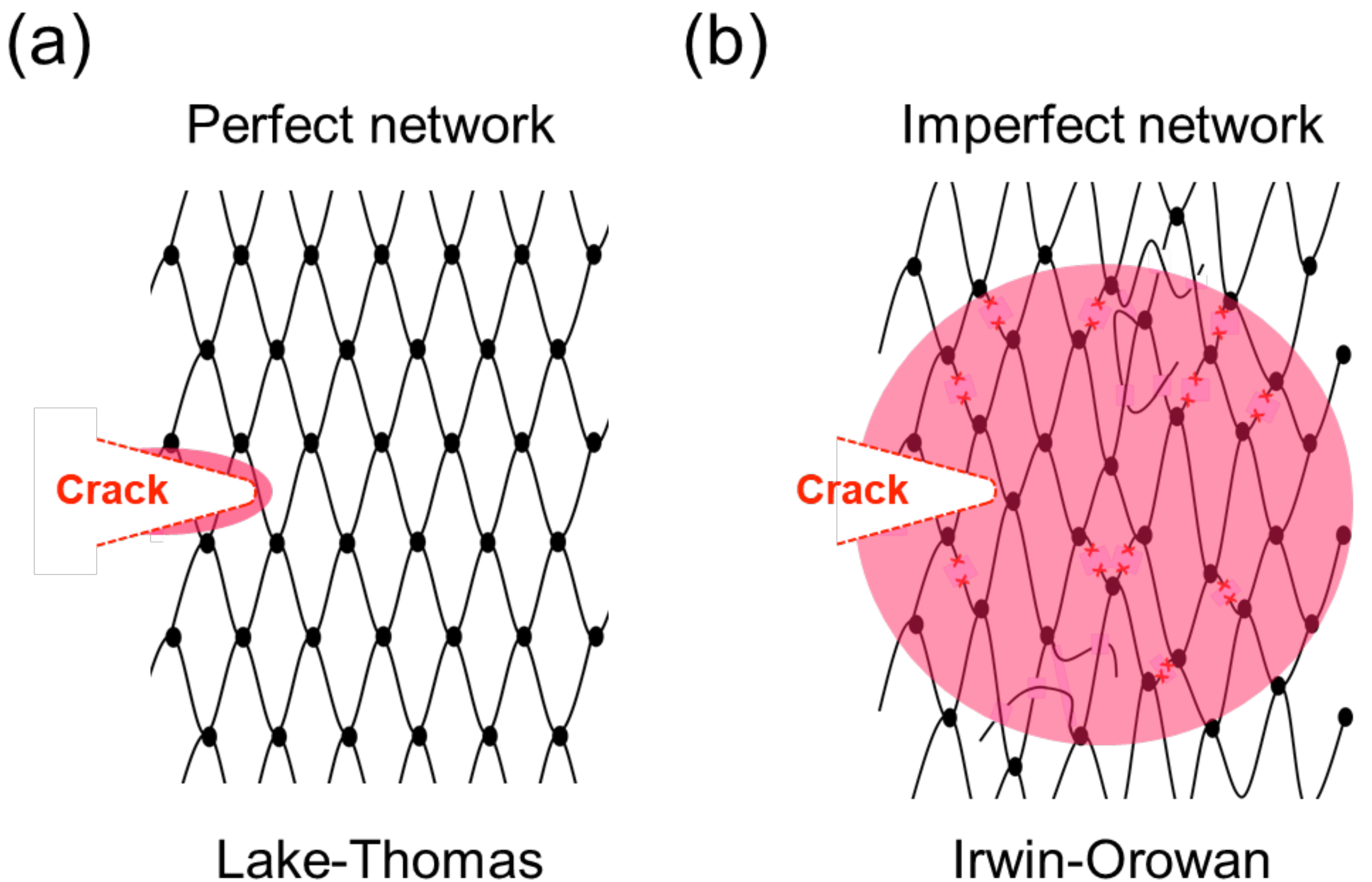
Fatigue fracture of hydrogel



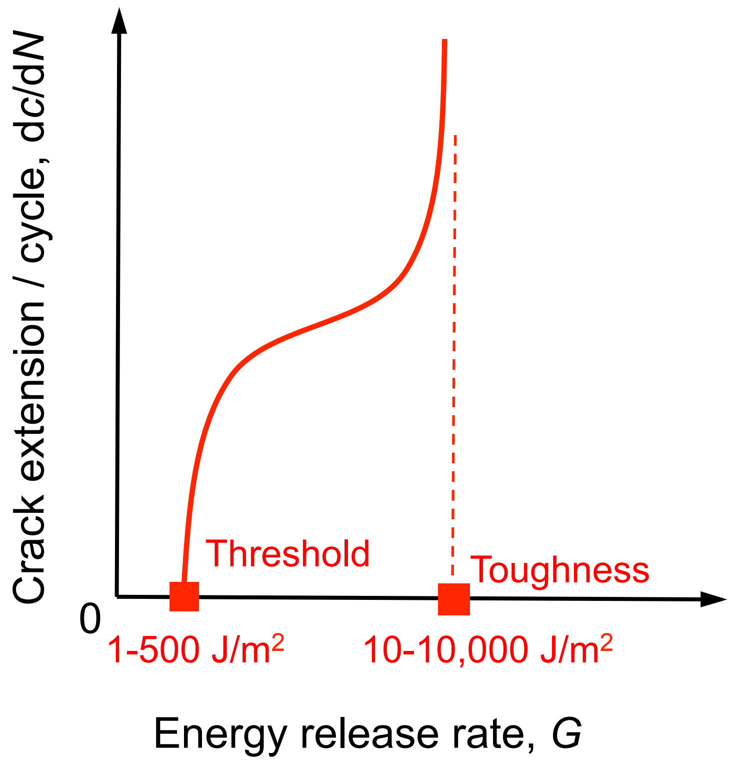


Tang, Li, Vlassak, Suo. Extreme Mechanics Letters (2017)

A mechanism of fatigue in an elastic network



Yang, Yin, Suo. Journal of the Mechanics and Physics of Solids 2019

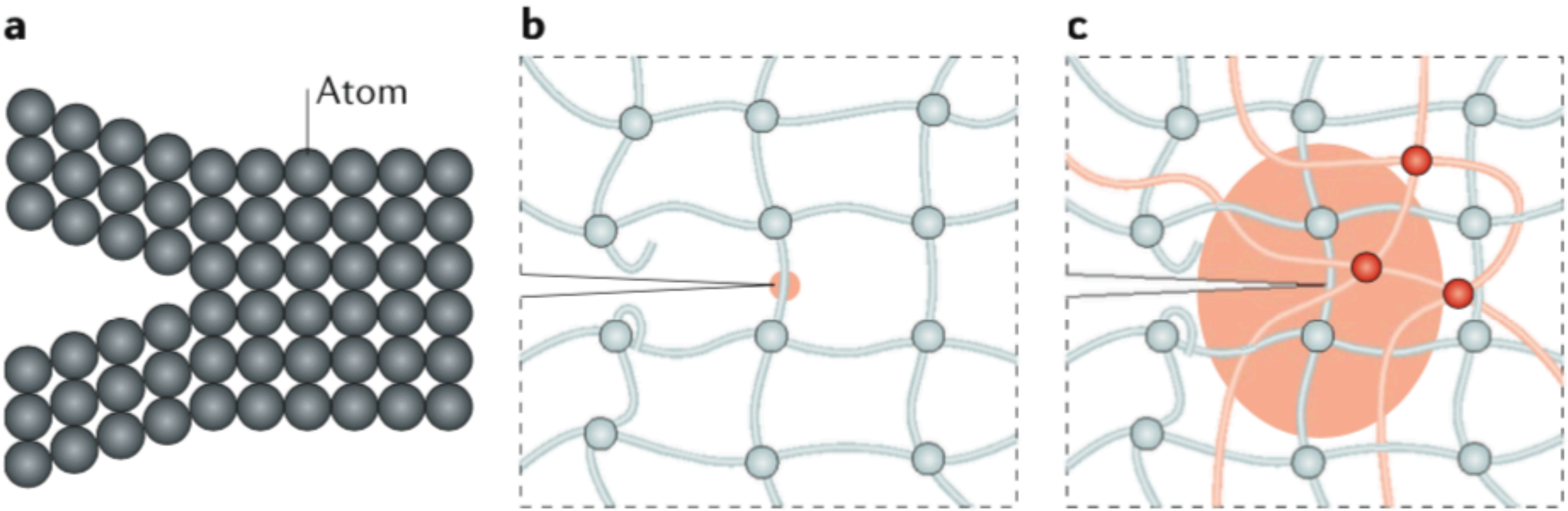


- Toughness of hydrogels has been extensively studied in last 16 years.
- Threshold of hydrogels is a new game in last 2 years.

Bai, Yang, Suo. Fatigue of hydrogel. European Journal of Mechanics A. Solids 2019

Toughness

Griffith 1921 | Lake-Thomas 1967 | Irwin-Orowan 1940s



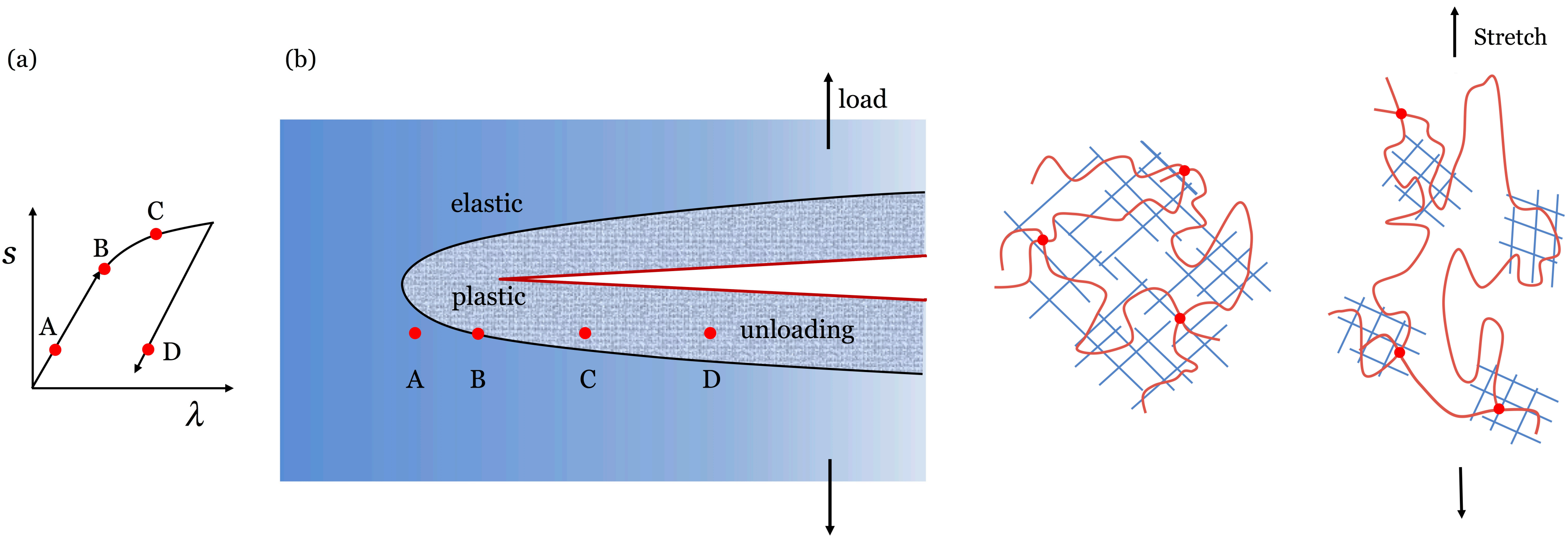
Break a layer of bonds
Toughness ~ 1 J/m^2

Snap a layer of chains
Toughness ~ 10-1000 J/m^2

Dissipate energy in the bulk
Toughness ~ 100-10000 J/m^2

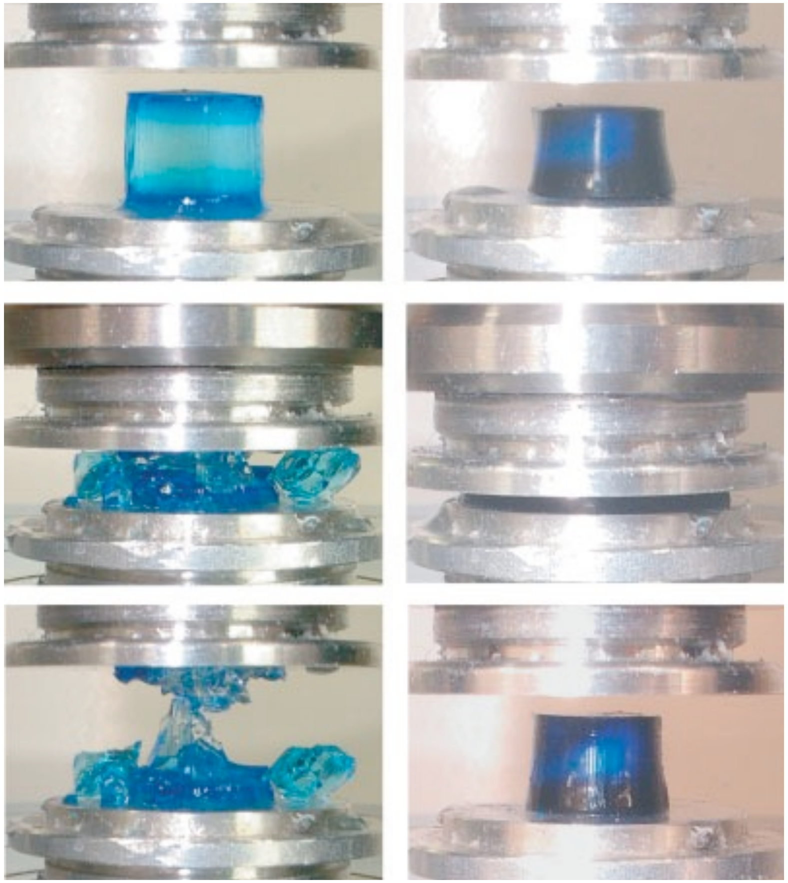
Yang, Suo. Nature Reviews Materials 2018

Double-network hydrogel



Gong, Katsuyama, Kurokawa, Osada, Advanced Materials 15, 1155 (2003)

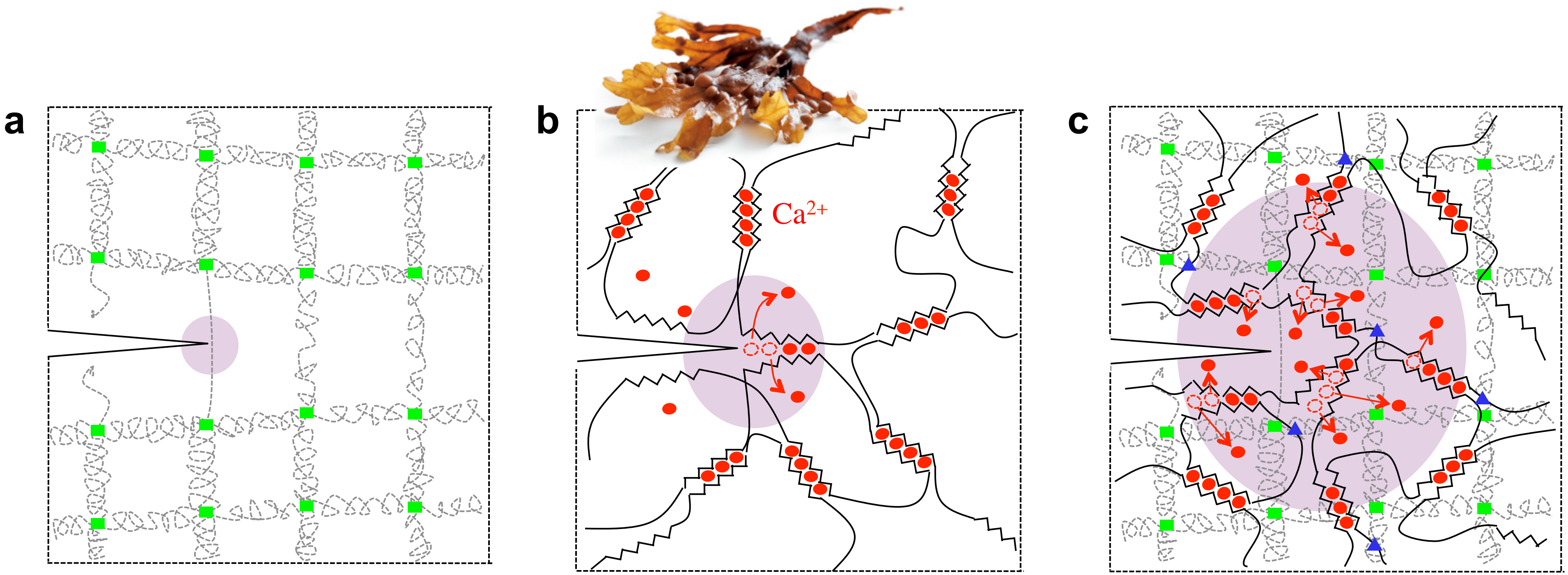
Double-network gels



Single-network gel Double-network gel

Gong, Katsuyama, Kurokawa, Osada, Advanced Materials 15, 1155 (2003)

brittle + brittle = tough



Polyacrylamide gel $100\ J/m^2$

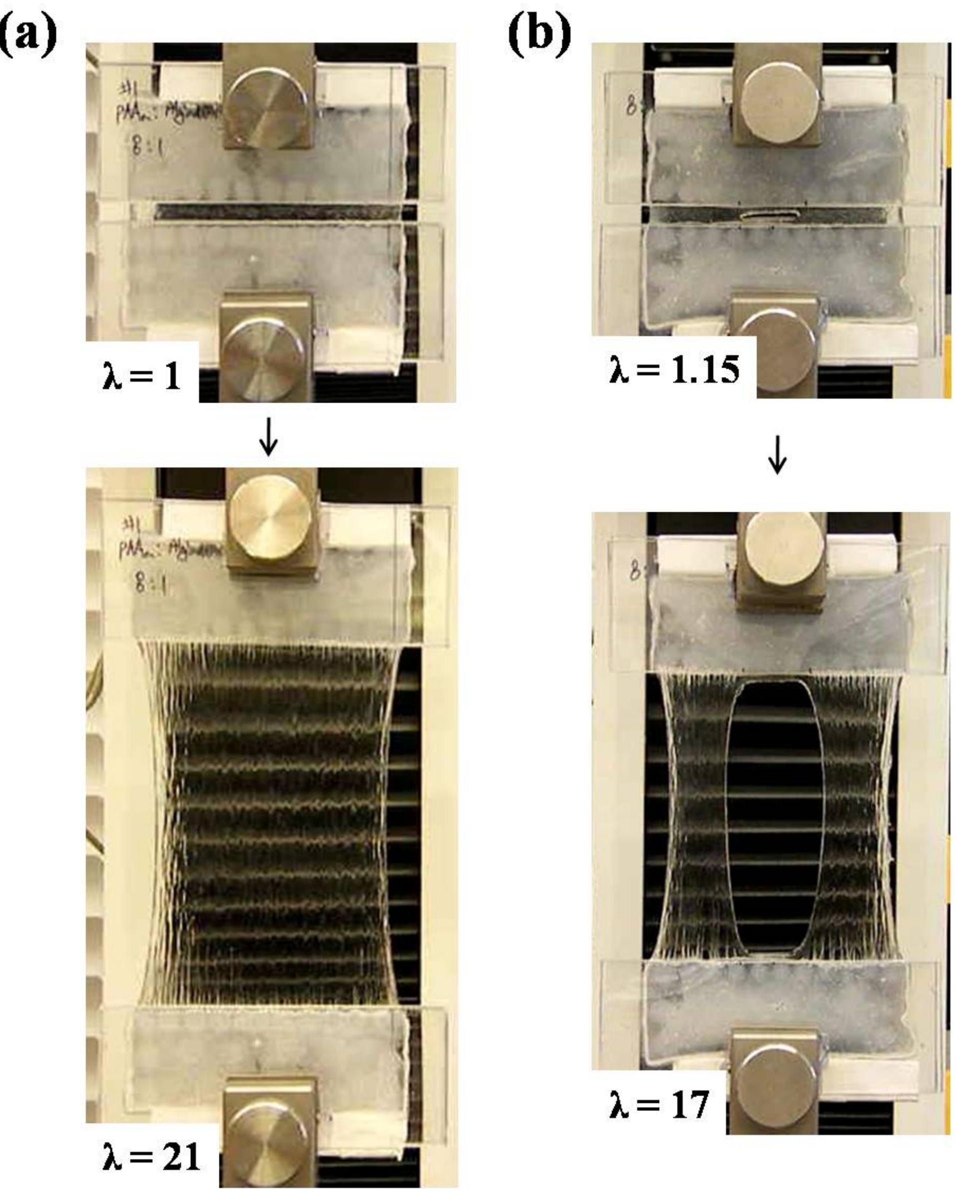
Alginate gel $10\ J/m^2$

Hybrid gel $9000\ J/m^2$

Plastic zone near the crack tip

Sun, Zhao, Illeperuma, Chaudhuri, Oh, Mooney, Vlassak, Suo. Nature 489, 133 (2012)

Highly stretchable and tough hydrogels

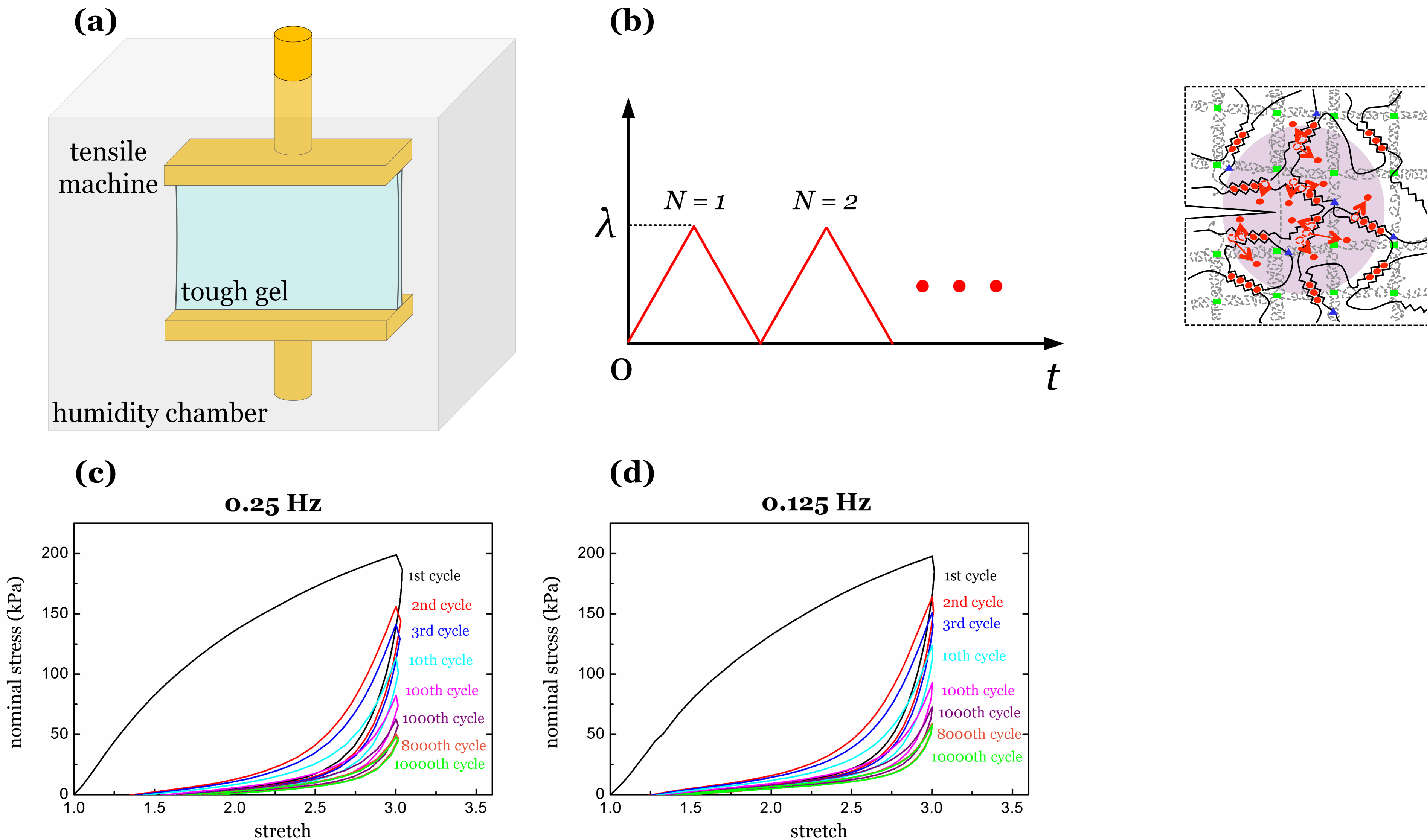


•Water: 90%
•Stretch: 21
•Fracture energy: 9000 J/m^2

~10 J/m^2, tofu, jello
~10 J/m^2, most gels
~100 J/m^2, contact lenses
~1000 J/m^2, cartilage
~1000 J/m^2, double network gels (Gong 2003)
~1000 J/m^2, VHB
~10,000 J/m^2, natural rubber

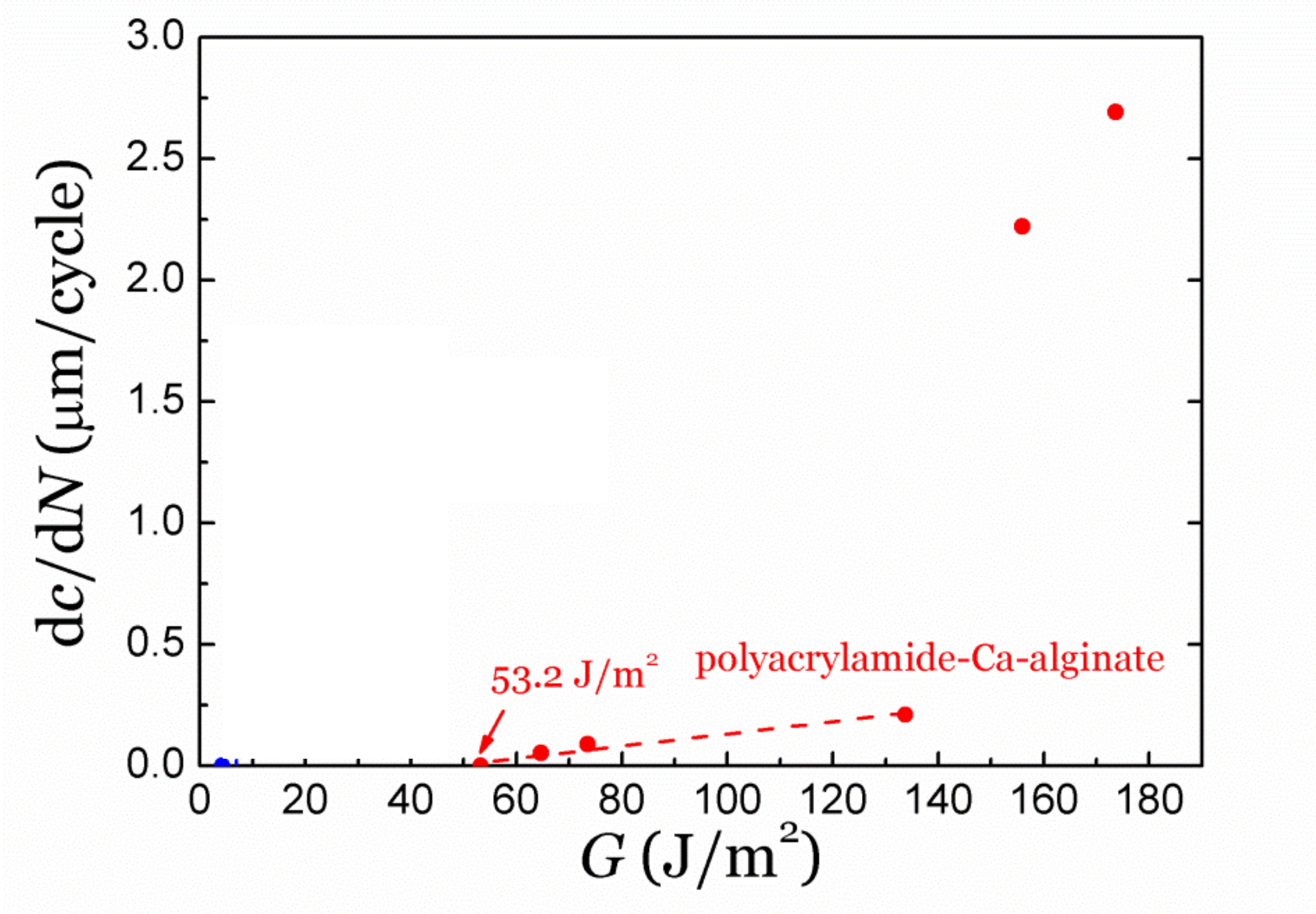
Sun, Zhao, Illeperuma, Chaudhuri, Oh, Mooney, Vlassak, Suo. Nature 489, 133 (2012)

Shakedown of tough gel



Bai, Yang, Tang, Morelle, Vlassak, Suo. Extreme Mechanics Letters (2017)

Alginate-polyacrylamide hydrogel

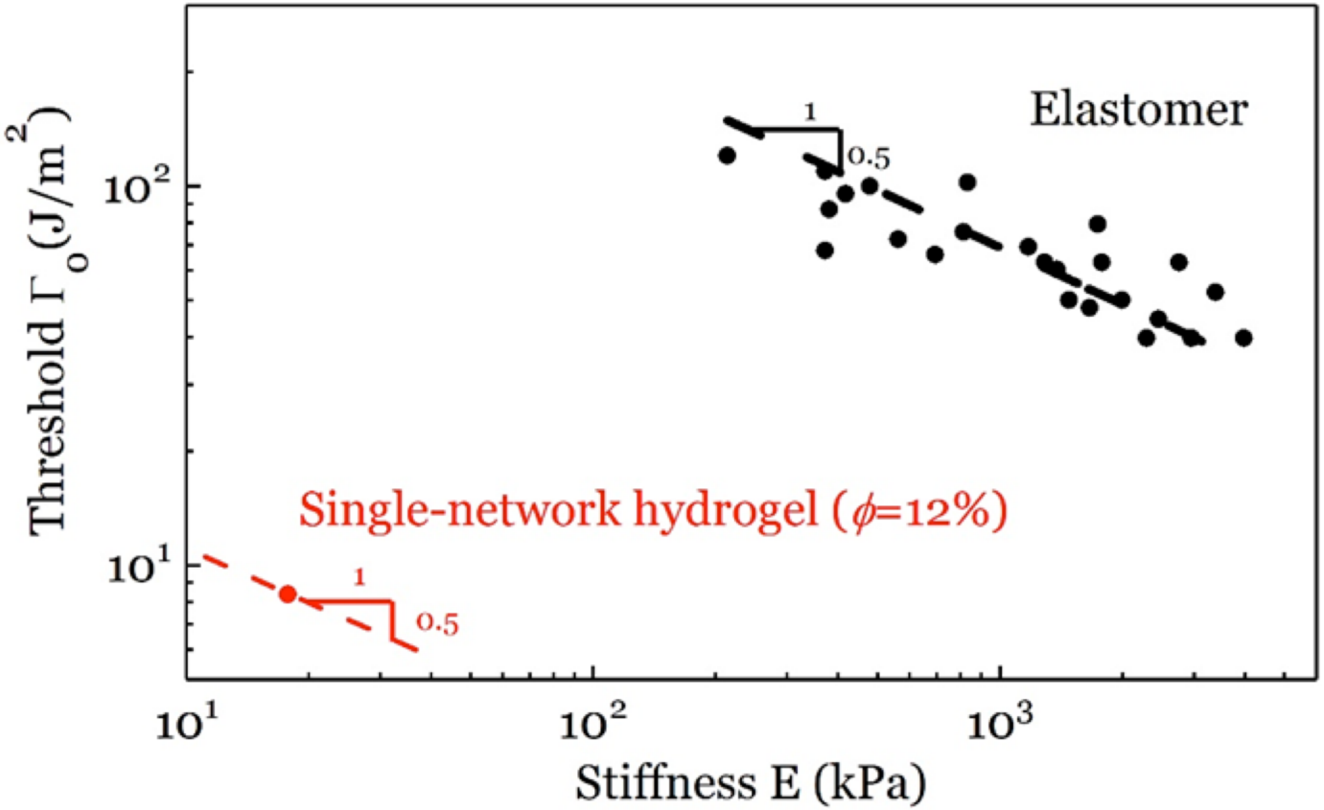


Tough for the first loading.
But suffers fatigue fracture.

Bai, Yang, Tang, Morelle, Vlassak, Suo, Extreme Mechanics Letters (2017)

Stiffness-threshold conflict

$$\mu \sim \frac{1}{n}, \qquad \Gamma_{th} \sim \sqrt{n}$$

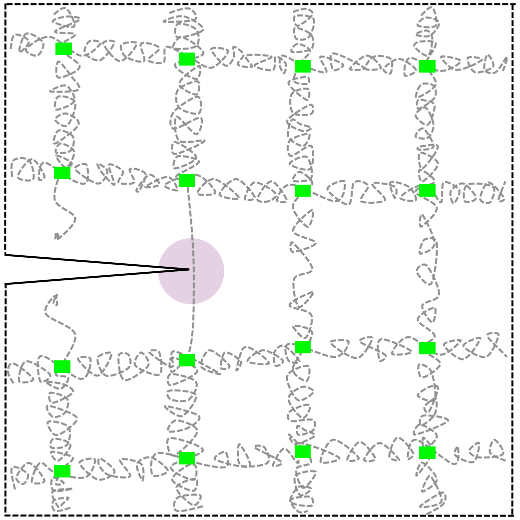


Zhou, Zhang, Hu, Tang, Suo, Lu. JAM 2019

Remove the stiffness-threshold conflict

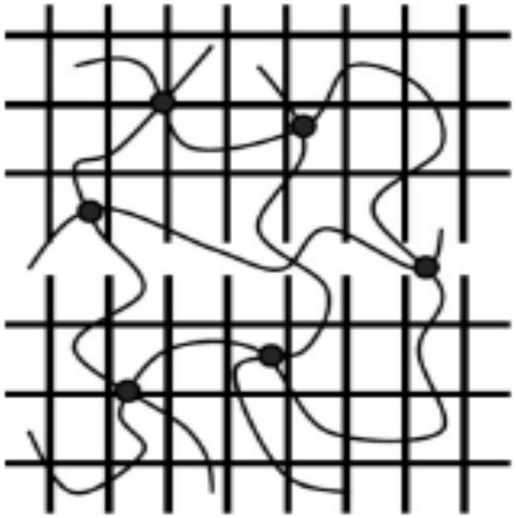
Single network

$$\mu \sim \frac{1}{n}, \qquad \Gamma_{th} \sim \sqrt{n}$$

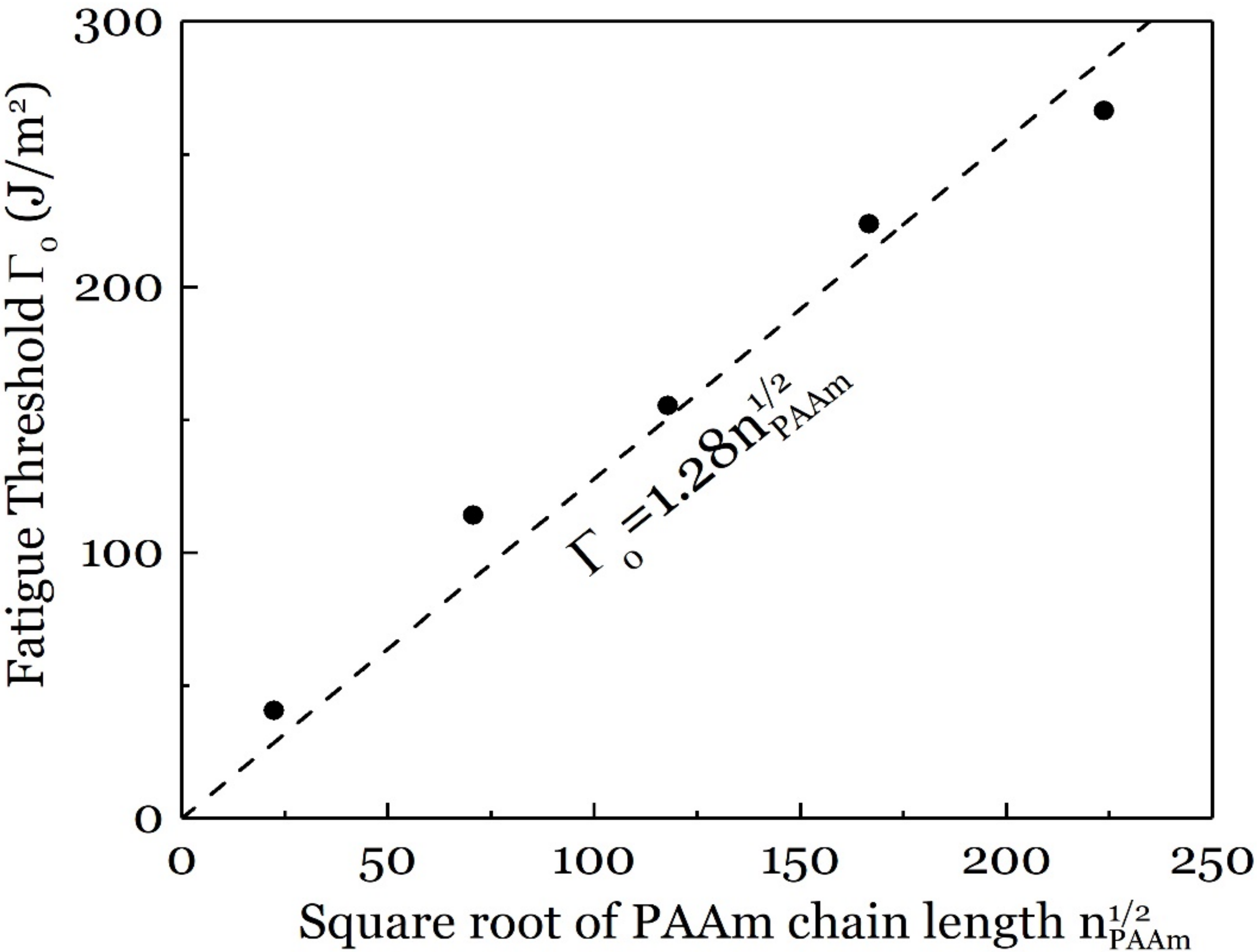


Double network

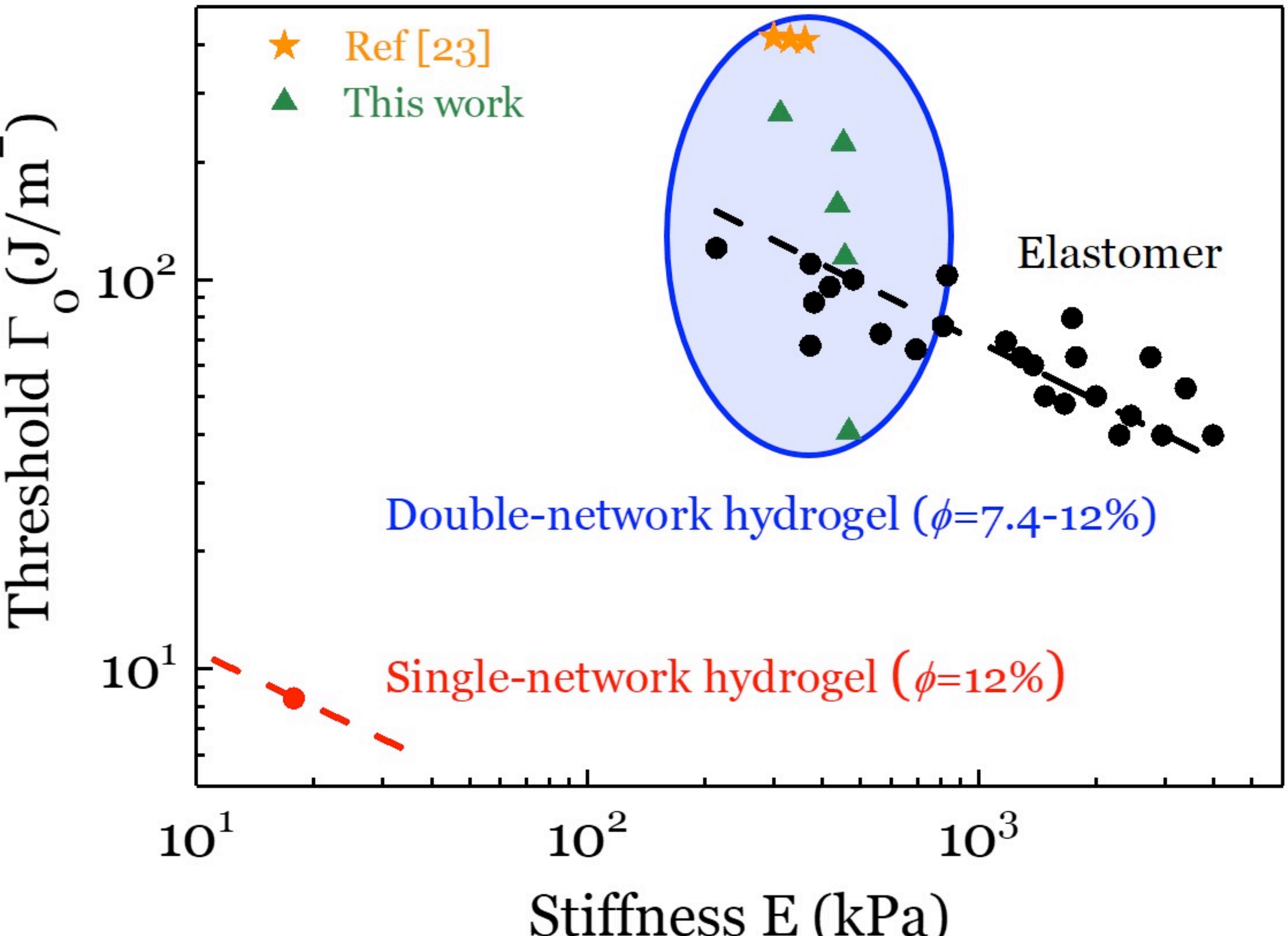
$$\mu \sim \frac{1}{n_A}, \qquad \Gamma_{th} \sim \sqrt{n_B}$$



Zhou, Zhang, Hu, Tang, Suo, Lu. JAM 2019



Zhou, Zhang, Hu, Tang, Suo, Lu. JAM 2019

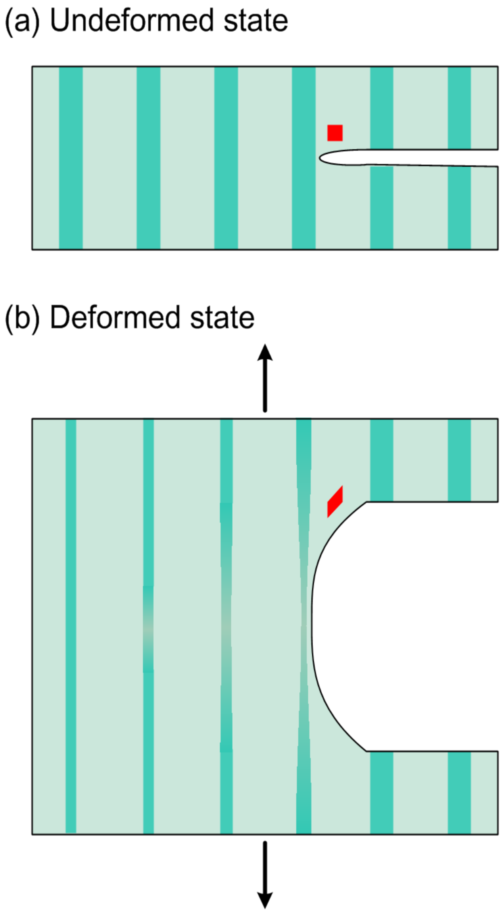


Zhou, Zhang, Hu, Tang, Suo, Lu. JAM 2019

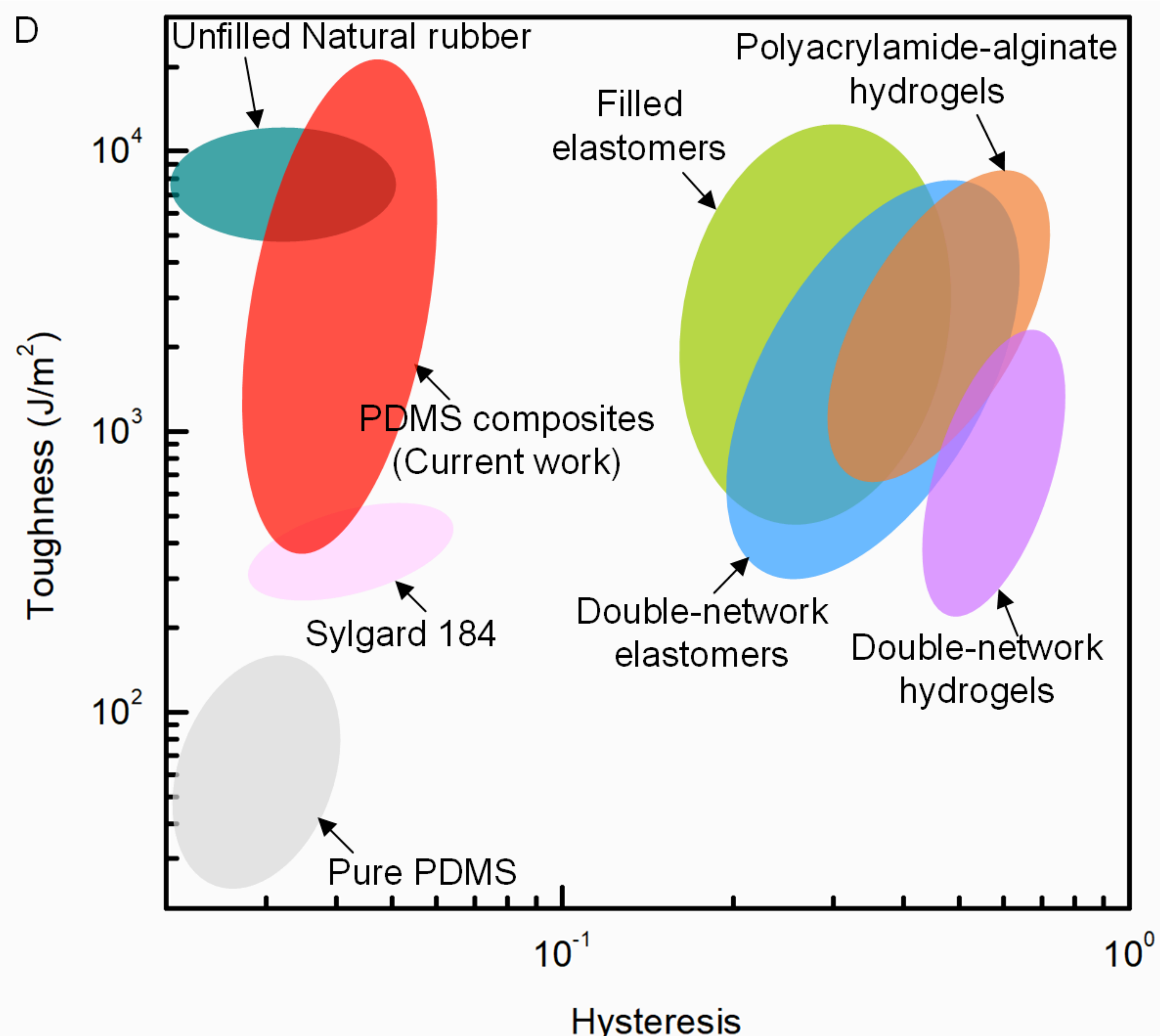
Elastic dissipater

Liu, Yang, Yin, Wang, Qu, Suo, JMPS 2019

Elastic dissipater



Wang, Xiang, Yao, Le Floch, Mendez, Suo, PNAS 2019
Xiang, Wang, Yang, Yao, Wang, Suo, Materials Today 2019



Wang, Xiang, Yao, Le Floch, Mendez, Suo. PNAS 2019

(a) λ_m =2.303, G =4,441 J/m^2, N=1

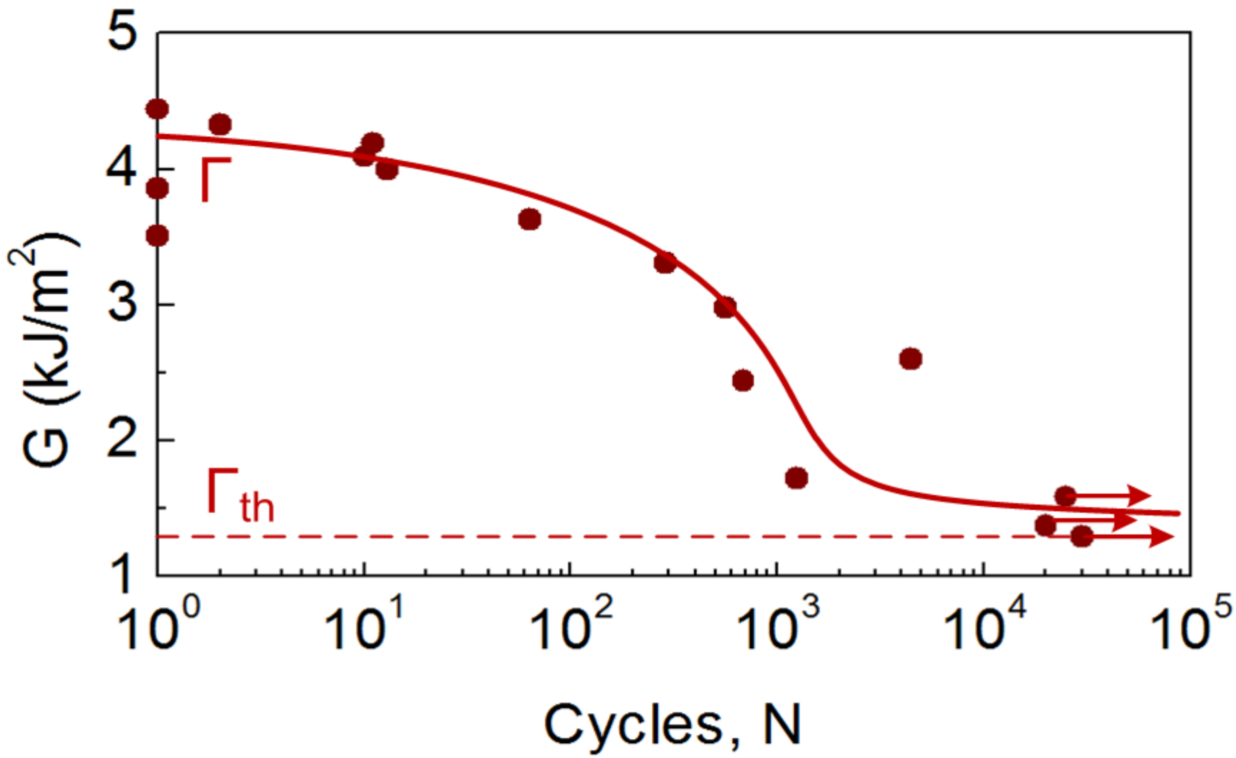
(b) λ_m =2.261, G =4,092 J/m^2, N=10

(c) λ_m =2.107, G =2,978 J/m^2, N=565

(d) λ_m =1.780, G =1,372 J/m^2, N=20,000

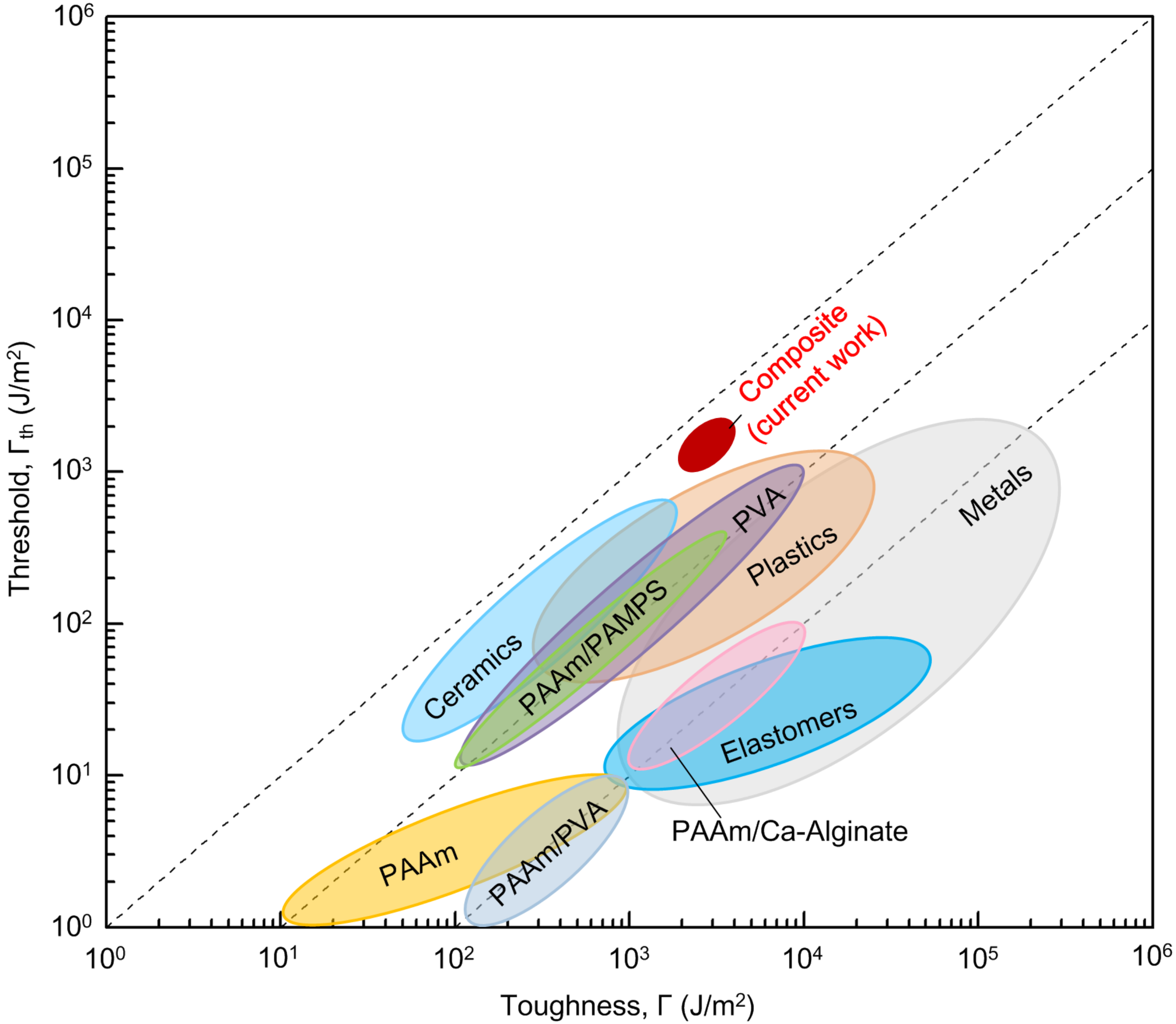
(e) λ_m =1.725, G =1,290 J/m^2, N=30,000

- Matrix: PAAm hydrogel
- Fibers: PDMS elastomer



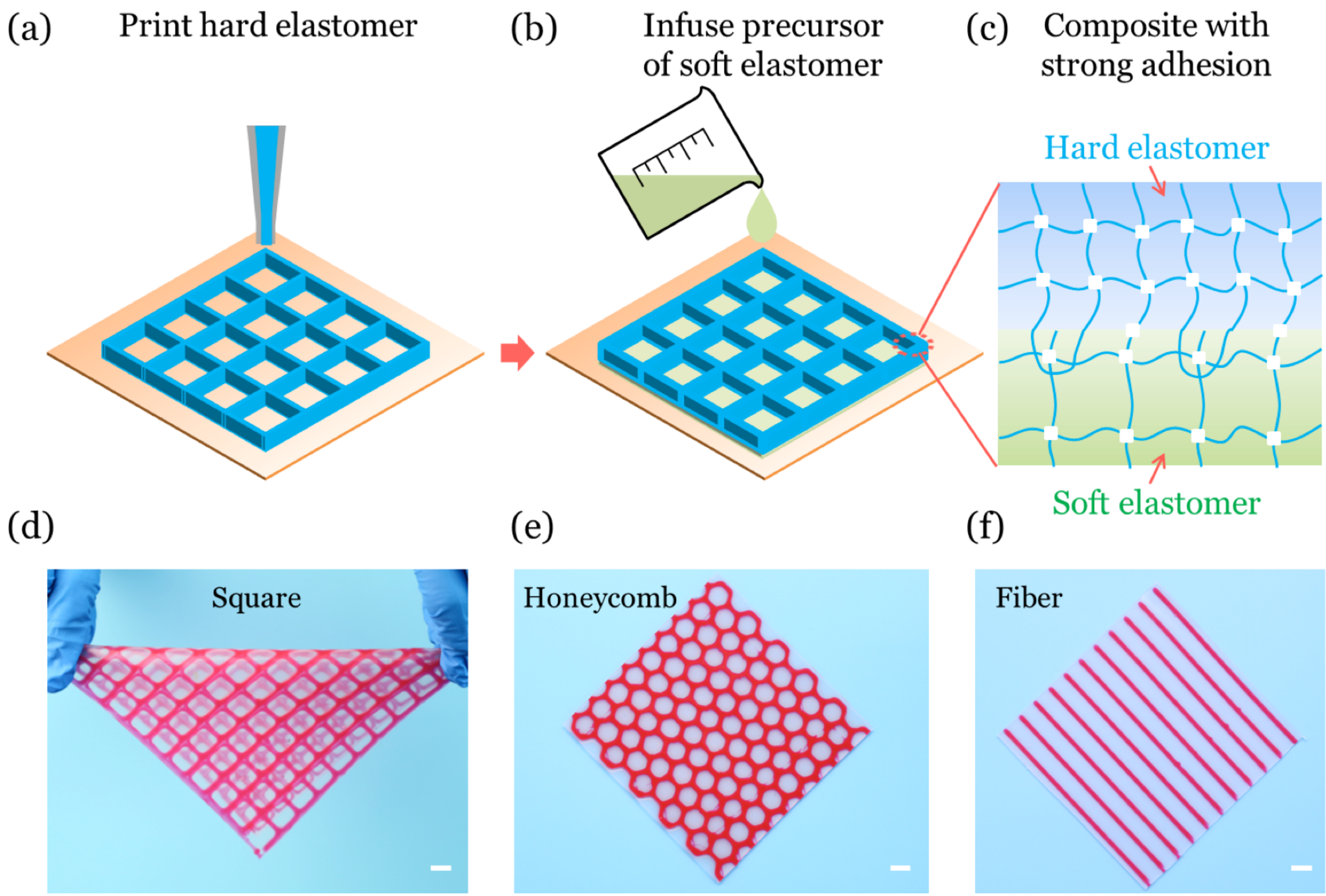
Xiang, Wang, Yang, Yao, Wang, Suo. Materials Today 2019

Fatigue-resistant hydrogel-elastomer hybrid



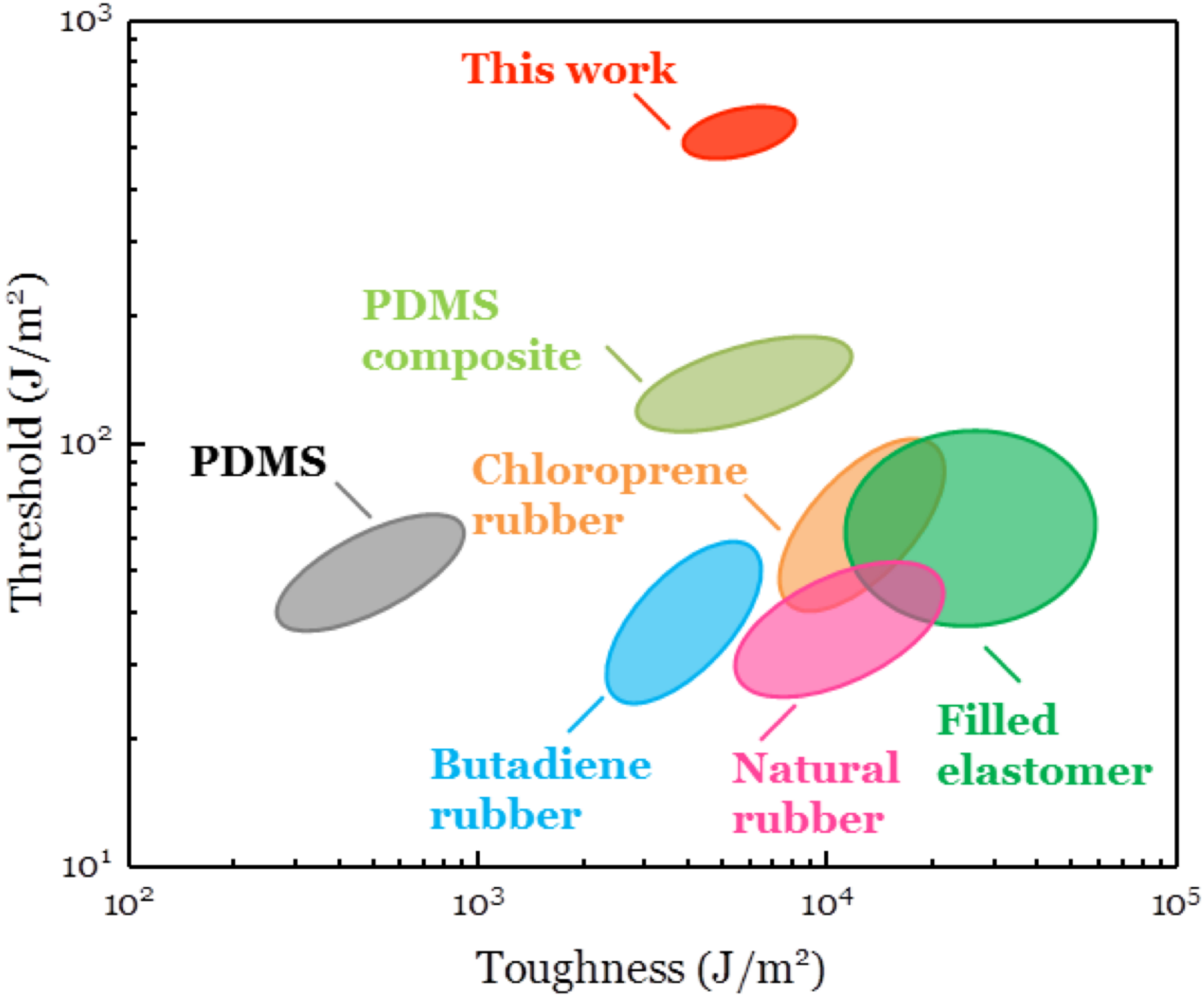
Xiang, Wang, Yang, Yao, Wang, Suo. Materials Today 2019

Elastic dissipater of any architecture



Li, Yang, Suo, Tang, JMPS 2019

Fatigue-resistant elastomer



Li, Yang, Suo, Tang, JMPS 2019

Summary

- Inelastic dissipater enhances toughness, but not threshold.
- Double networks remove the stiffness-threshold conflict.
- Elastic dissipater: low hysteresis, high toughness, high threshold.

- Winning the war on fatigue.