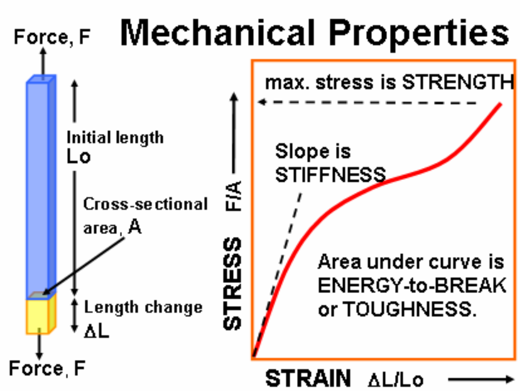
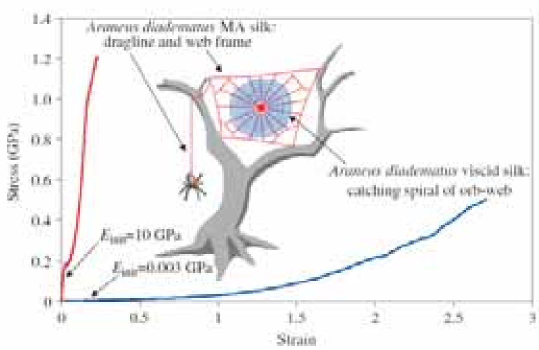
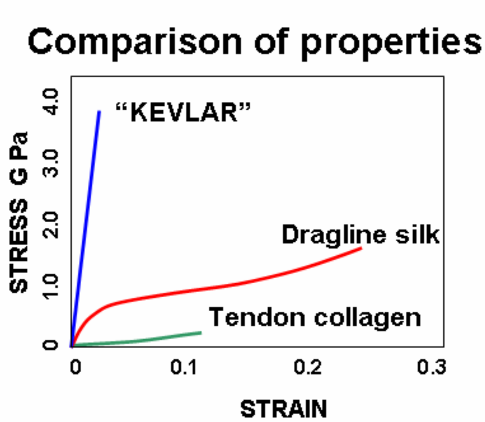
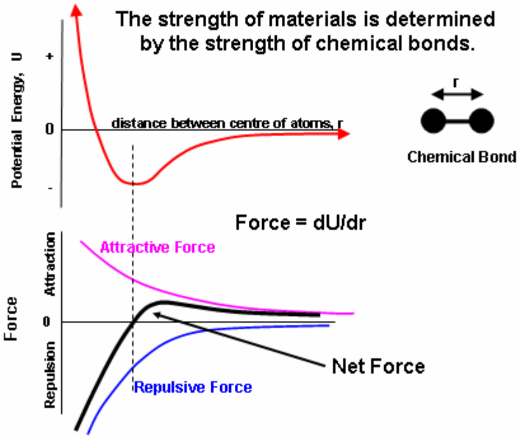
The remarkable properties of spider silks.

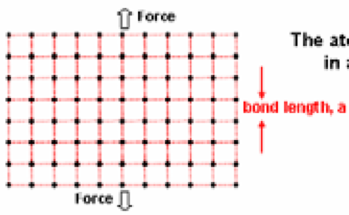






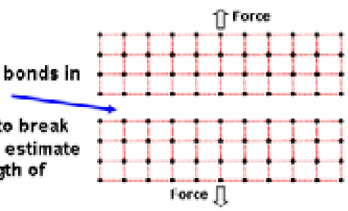
The strength of materials is determined by the strength of chemical bonds.





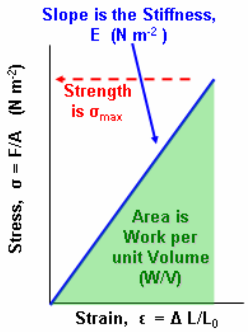
The atomic lattice of atoms in a strong material

Fracture occurs when all bonds in a plane break.



Calculating the energy to break these bonds provides an estimate the theoretical strength of materials

Calculating the energy to break the in a single layer of bonds



$W / V = (\sigma \times \varepsilon)/2$

$W / V = \sigma^2 / 2E$

$$\frac{W}{\text{Area Length}} = \frac{\sigma^2}{2E}$$

$$\frac{W}{A} = \frac{\sigma^2 L}{2E}$$

Assume the volume is one crystal layer, L = a, the bond length.

$$\frac{W}{A} = \text{Surface Energy} = 2\gamma = \frac{\sigma^2 a}{2E}$$

$$\sigma_{th} = (E\gamma/a)^{1/2}$$

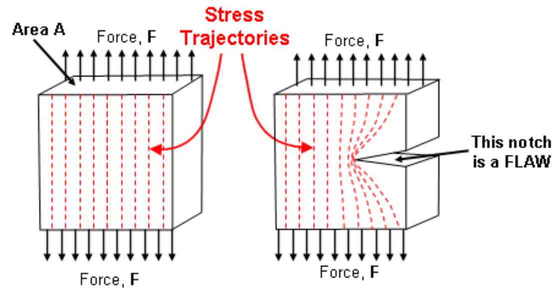
Theoretical Strength

Surface energy, γ, Theoretical Strength, σ_{th}, and the Strength of Materials

Material	γ (J/m^2)	Strength of Material (G Pa)	
		Theory	Observed
Iron	2.0	40	0.3 cast iron 1.5 HT steel
Glass	0.5	16	0.1 bulk 4 fibre
Al_2O_3	1.0	46	ca. 2 bulk 15 whisker

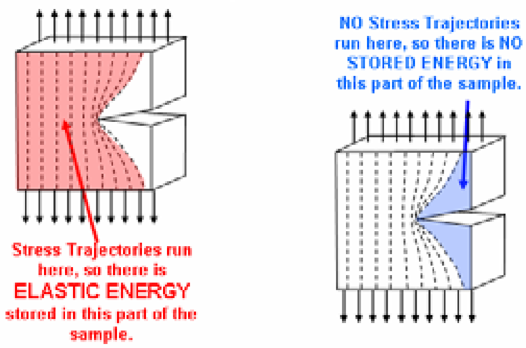
Why are materials so weak?

Failure of a Rigid Structure

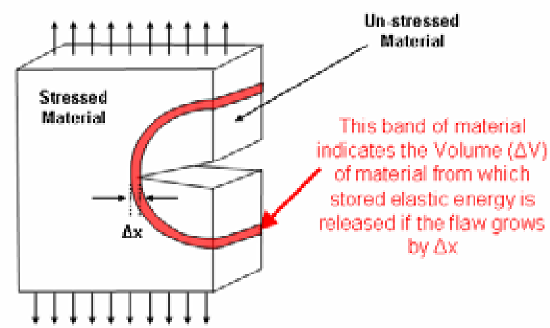


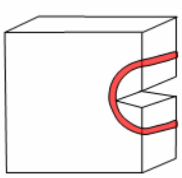
The average stress in this block of material, $\sigma_{av} = F/A$	**Stress trajectories** are tightly packed at the flaw tip. This creates a **STRESS CONCENTRATION**. Local stress at the flaw tip can exceed the average stress by orders of magnitude

The growth of a flaw or crack in a solid material is determined largely by the release of energy stored in the stressed portion of the material



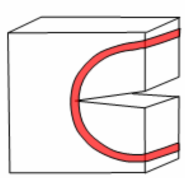
If the flaw grows in length, strain energy is released from parts of the stressed material in the test sample.





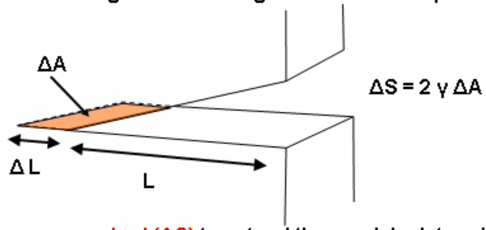
ΔV is small for a short flaw; ΔW is small

The energy released (ΔW) when a flaw grows is determined by the volume (ΔV) of material unloaded and the stress in this volume. Long flaws release more energy.



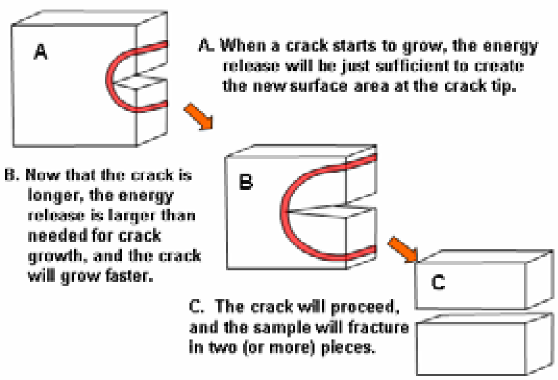
ΔV is large for a long flaw; ΔW is large

Crack growth will occur if the energy released (ΔW) is sufficient to break the chemical bonds that hold the atoms together in the region of the crack tip



The energy required (ΔS) to extend the crack is determined by the WORK OF FRACTURE (γ , units are J/m^2) of the material and the amount of new surface area created (ΔA).

Once crack growth starts, failure is catastrophic

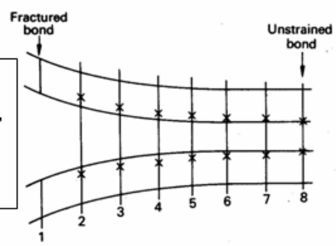


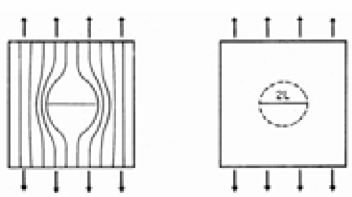
How does the strain energy released from distant sites create new crack surfaces?

Stress concentration provides the mechanism. Large forces at the crack tip break chemical bonds.

Bonds break sequentially, releasing more energy, and the crack propagates across the entire test sample.

Diagram of a crack tip in an elastic solid. As the crack extends from 1 to 2, each pair of atoms must move to the position shown by (x) in the diagram.





$$W = \left(\frac{\sigma^2}{E}\right) \pi L^2$$

$$dW = \left(\frac{\sigma^2}{E}\right) \pi L \, dL$$

$$dS = 4 \gamma \, dL$$

When dW = dS, crack growth will occur.

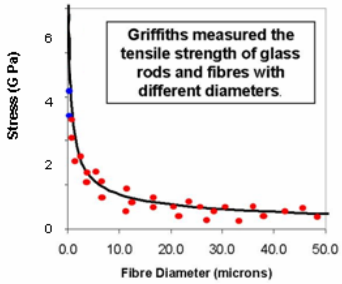
$$4 \gamma \, dL = \left(\frac{\sigma^2}{E}\right) \pi L \, dL$$

Failure stress, σ_{fail}, is determined by the flaw length, L. This is the Griffiths' Equation that forms the basis for Fracture Mechanics

$$\sigma_{fail} = \left(\frac{4 E \gamma}{\pi L}\right)^{1/2}$$

Griffiths' Equation
(the exact solution)

$$\sigma_{fail} = \left(\frac{2E\,\gamma}{\pi L}\right)^{½}$$

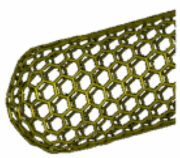


Failure stress should increase as flaw length (L) decreases

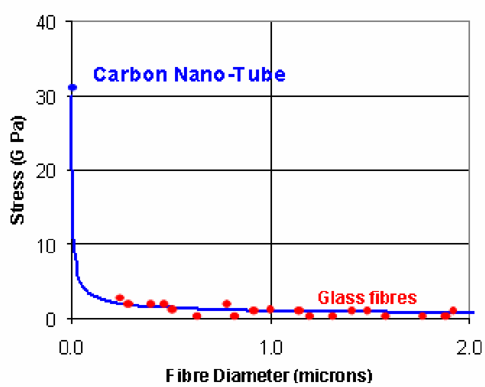
$$\sigma_{fail}\ \alpha\ (1/L)^{½}$$

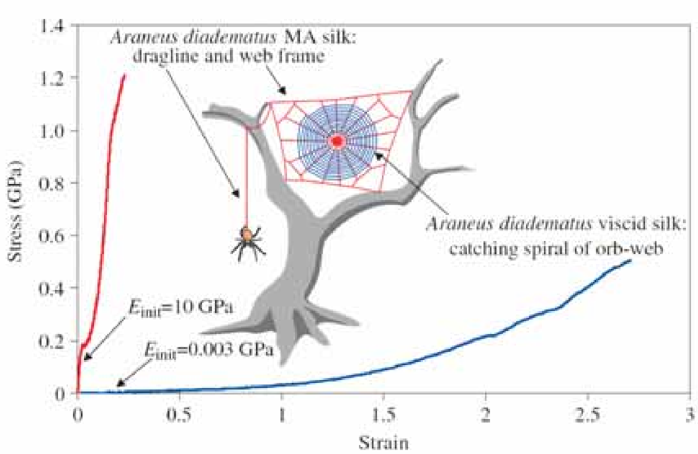
Carbon Nano-Tubes

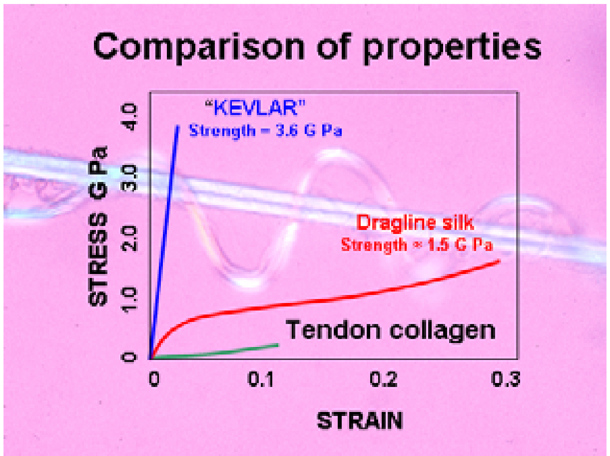
Single Wall Nano-Tube; diameter 1.2 nm

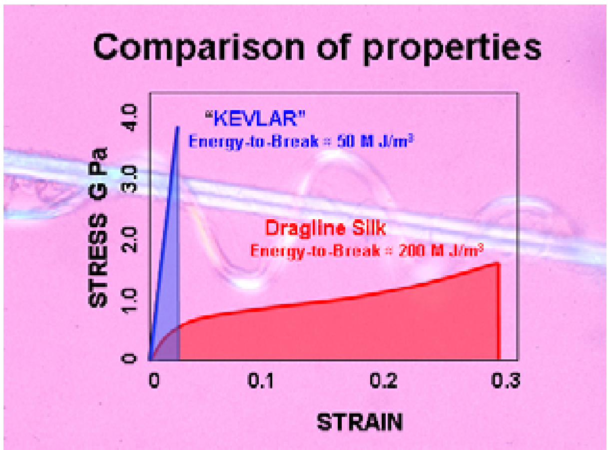


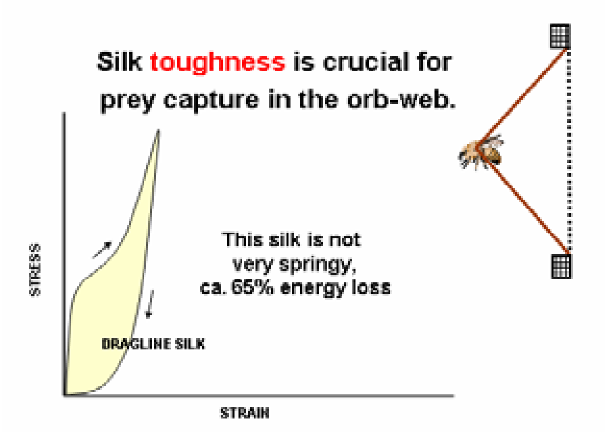
Stiffness, E = 1.0 TPa
Strength, ca. 30 GPa

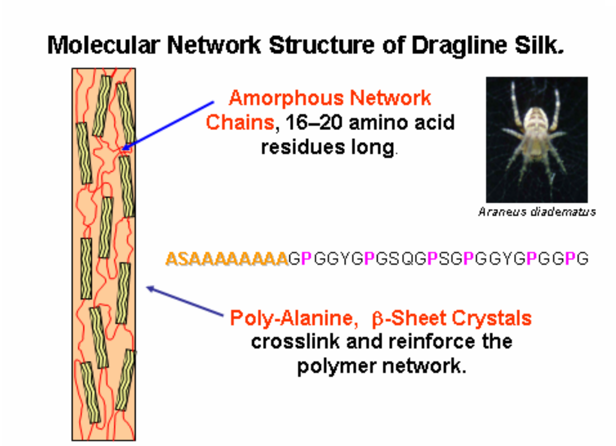





Comparison of properties
"KEVLAR"
Strength = 3.6 G Pa
Dragline silk
Strength = 1.5 G Pa
Tendon collagen
STRESS G Pa
0
1.0
2.0
3.0
4.0
0
0.1
0.2
0.3
STRAIN


Comparison of properties
"KEVLAR"
Energy-to-Break = 50 M J/m³
Dragline Silk
Energy-to-Break = 200 M J/m³
STRESS G Pa
0
1.0
2.0
3.0
4.0
0
0.1
0.2
0.3
STRAIN

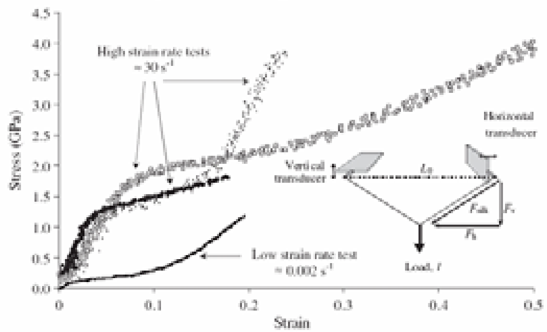

Silk toughness is crucial for prey capture in the orb-web.
This silk is not very springy, ca. 65% energy loss
DRAGLINE SILK
STRESS
STRAIN


Molecular Network Structure of Dragline Silk.
Amorphous Network Chains, 16–20 amino acid residues long.
Araneus diadematus
ASAAAAAAAAGPGGYGPGSQGPSGPGGYGPGGPG
Poly-Alanine, β-Sheet Crystals crosslink and reinforce the polymer network.

Toughness of Strong Fibres

Material	Energy-to-Break (M Jm^3)
Kevlar	**~50**
Dragline silk	**~200**
Carbon Nano-Tubes	**~450**

Mechanical properties of dragline silk improve at high strain rates.



Spider's dragline silk may be the toughest material known.