Aalto University
School of Chemical Technology

CHEM-E2200: Polymer blends and composites

Fracture and toughness in composites

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Toughness

> *"The worst sin in an engineering material is not lack of strength or lack of stiffness, desirable as these properties are, but lack of toughness, that is to say, lack of resistance to the propagation of cracks"*

J.E. Gordon, The New Science of Strong Materials

Tension vs compression

- In most structures there is the need to carry **tensile** as well as compressive loads
- Brittle materials are okay in compression (mainly) as cracks are not “opened”
- Think of how, for example, masonry (brick, stone) is used in construction

Tension:
The Menai suspension bridge, Wales

Compression:
A Roman arch

Is toughness important?

Catastrophic failure!

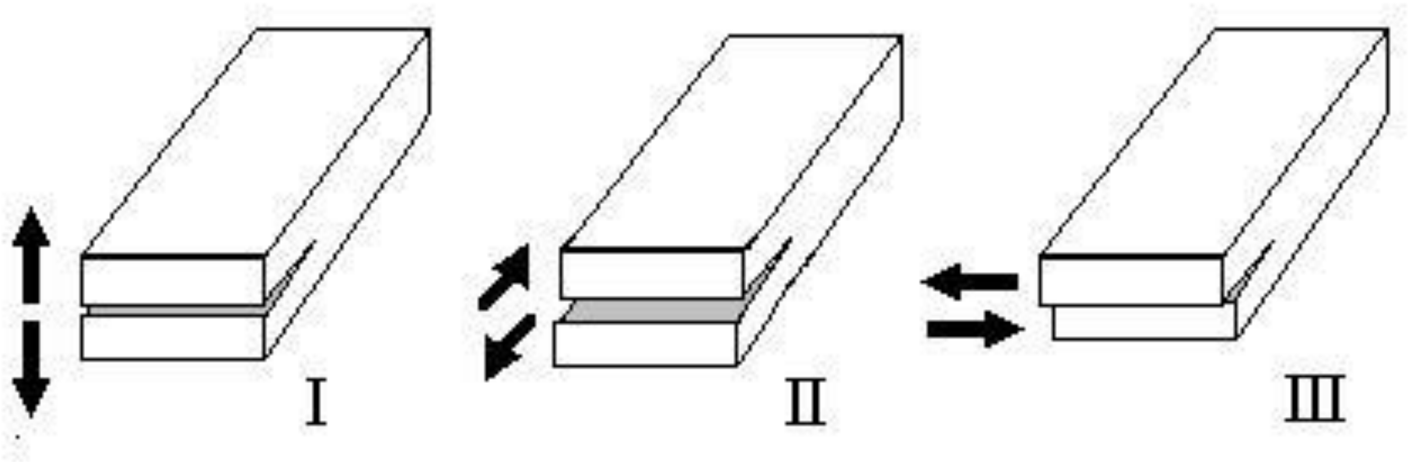
WW II Liberty ship

Are tough materials always tough and vice versa?

- Lower the temperature and certain steels can become brittle and in some cases can lead to catastrophic failure (as in the case of the Liberty ships – the failure changed from ductile to brittle when the temperature dropped in winter)
- Brittle materials such as glass, ceramics and certain polymers are intrinsically brittle but can be tough if combined

Properties of cracks

Crack opening modes



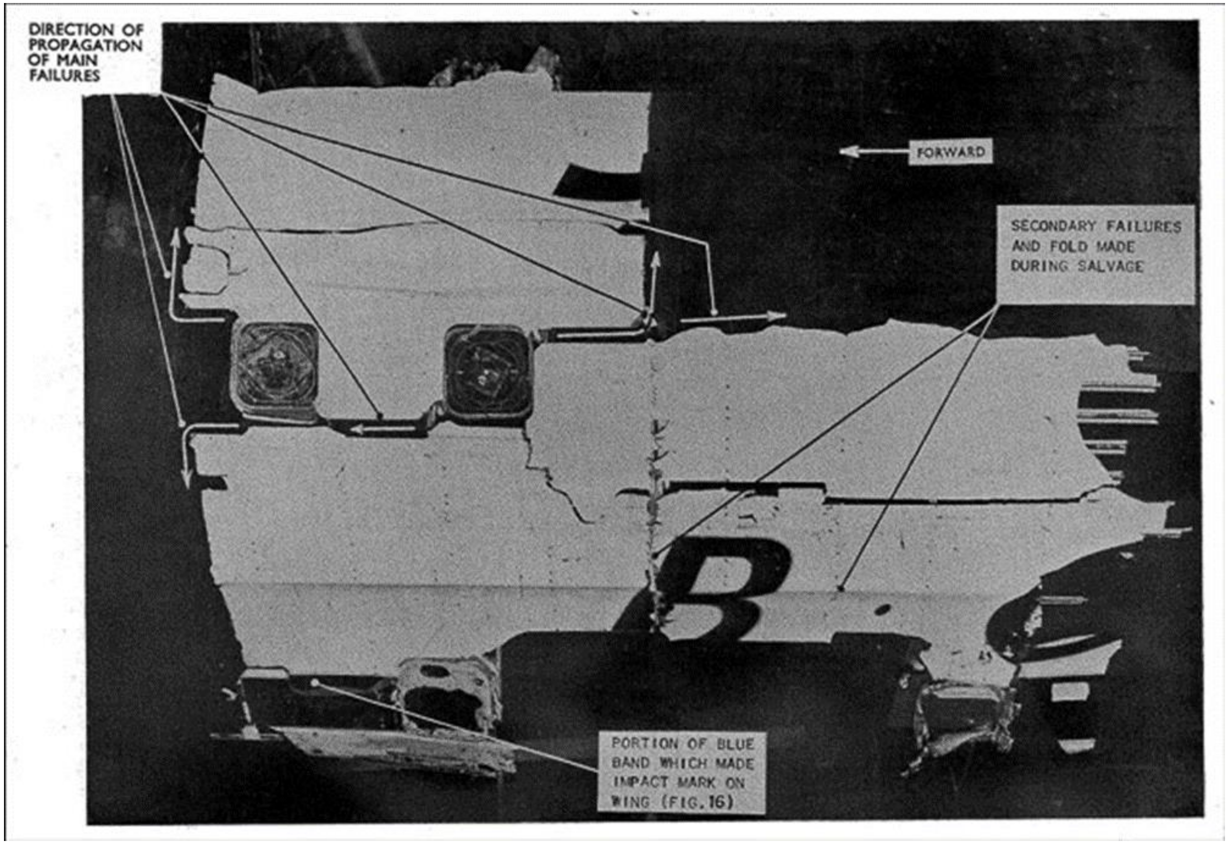
Cracks and “crack-like” defects

- All real materials contain cracks or crack-like defects at **some scale**
- These could be macroscopic cracks or “stress concentrators” or “stress risers” such a holes or sharp changes in section
  - The failure of the Liberty ships initiated at the corners of hatches (openings in the decks)
- Or they could be microscopic cracks
- There will be some kind of cracks or discontinuities (changes in section or in material properties) in all forms of material. Here cracks can initiate and propagate

What’s wrong with this picture?

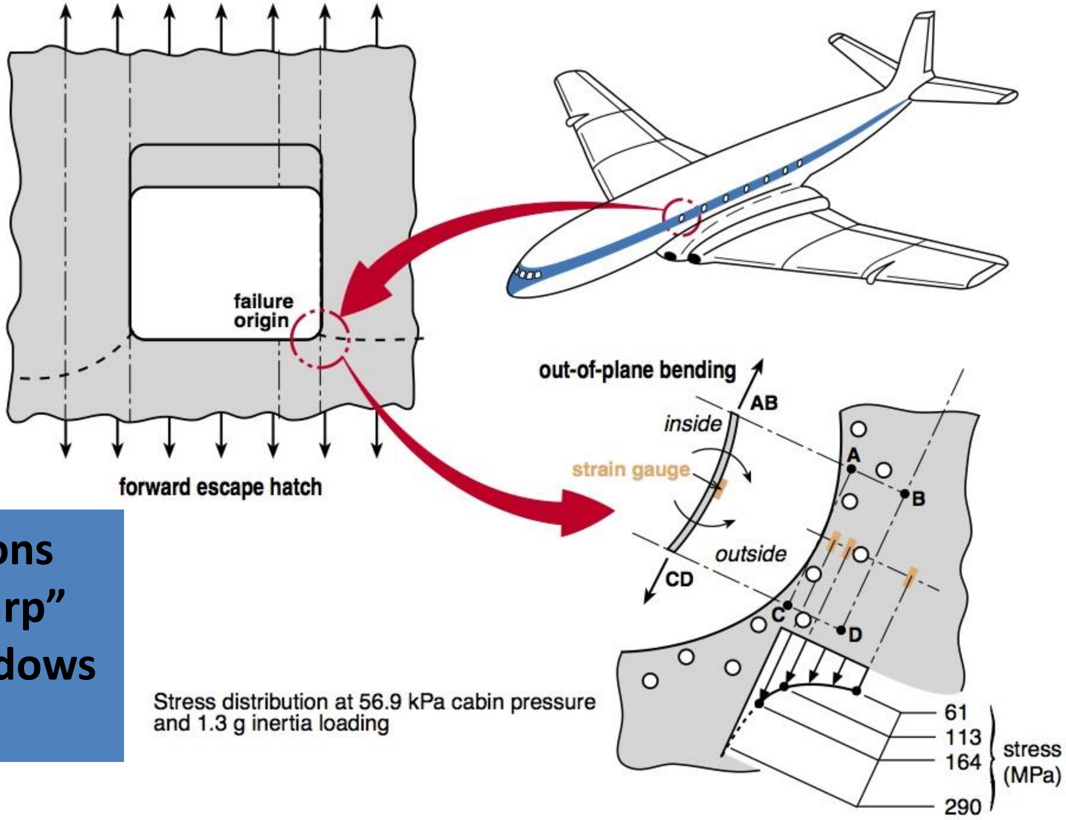
De Havilland Comet circa 1953

1950s de Havilland comet crashes



- Failure initiated at the ‘sharp’ corner of the window openings: large stress concentrations (http://lessonslearned.faa.gov/ll_main.cfm?TabID=1&LLID=28&LLTypeID=2#null)

1950s de Havilland comet crashes



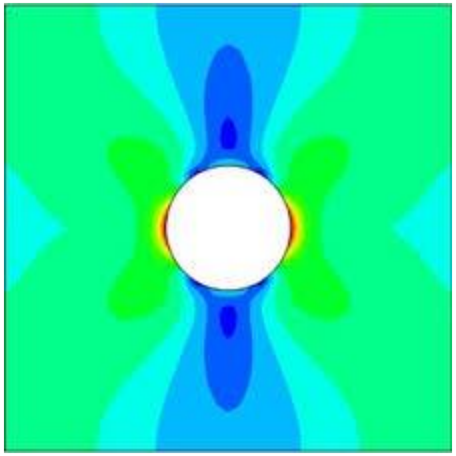
Stress distribution at 56.9 kPa cabin pressure and 1.3 g inertia loading

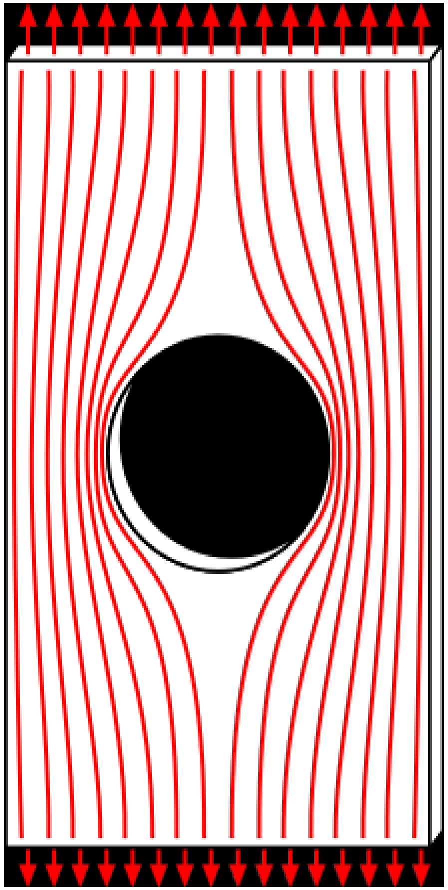
Stress concentrations caused by the “sharp” corners of the windows initiated failure

http://aerospaceengineeringblog.com/dehavilland-comet-crash/

What is the effect of a crack?

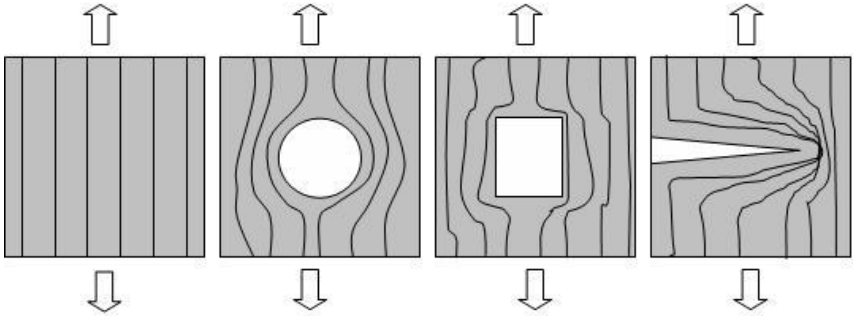
- These cracks result in localised stress concentrations, the magnitude of which depend upon the size and shape of the crack





What is the effect of a crack?

- If the stress concentrations are high enough, the material near the crack-tip may fail. Under certain conditions a crack may propagate catastrophically, leading to sudden failure of the material
- The crack-tip may, therefore, be viewed as a mechanism whereby local stresses in the material are raised sufficiently for fracture to occur



Cracks

- Stress concentration is dependent upon the shape of the crack
- Can be modelled as an ellipse
- As the crack tip radius approaches zero (i.e. very sharp – ratio of major to minor axis is high) then the theoretical stress concentration approaches infinity

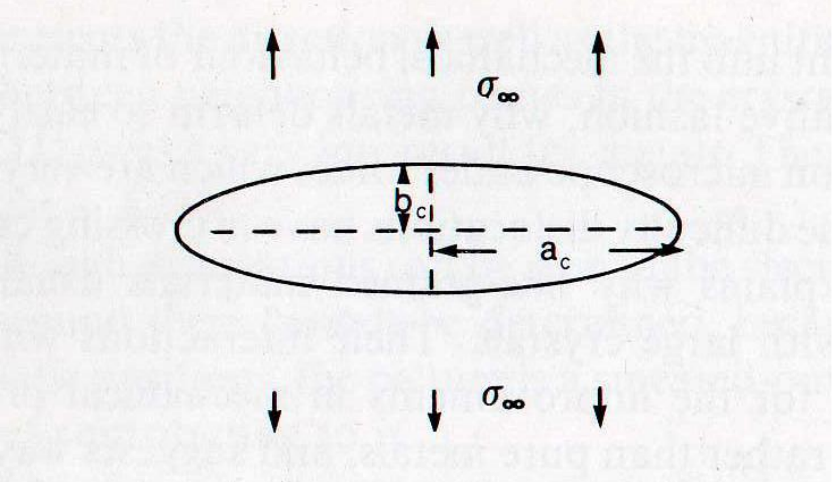


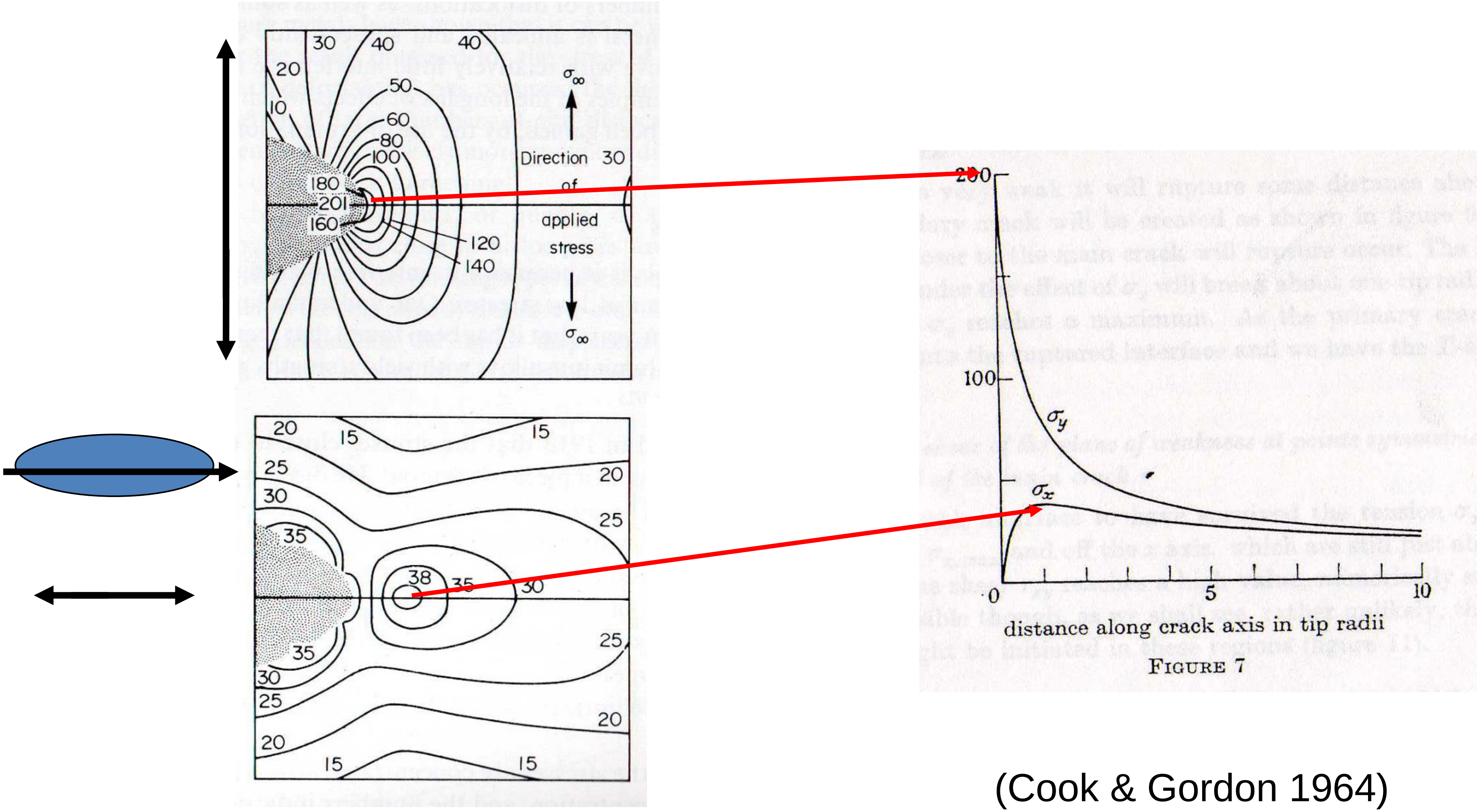
FIG. 2.9. Elliptic crack.

(Source: Piggott, 1980)

$$\sigma_{\max} = \sigma\left(1 + 2\frac{a}{b}\right)$$

Properties of heterogeneous materials: crack-blunting and crack-deflection

More about cracks…

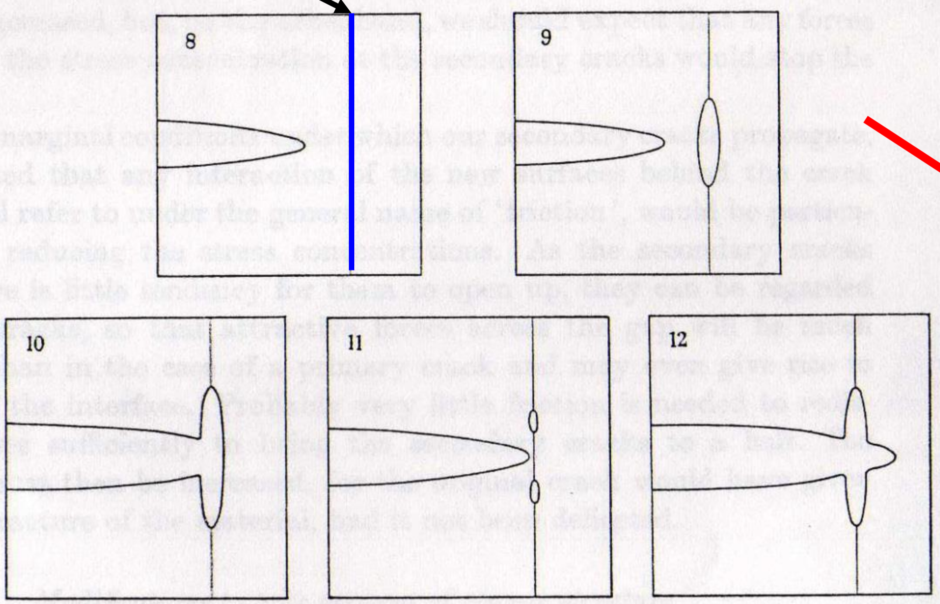


(Cook & Gordon 1964)

(Source: Piggott, 1980)

Crack-stopping mechanisms

Interface



FIGURES 8 to 12. Interaction between an advancing crack and a plane of weakness under various conditions.

Figure 7.18 Crack-stopping in a fractured rotor blade. The orientation of the secondary cracks corresponds to the microfibrillar orientation of the middle layer of the secondary cell wall (× 990, polarised light.) (© BRE.)

- Composites contain interfaces
- Wood contains multiple interfaces at several hierarchical levels!

Fracture and energy

Toughness of materials

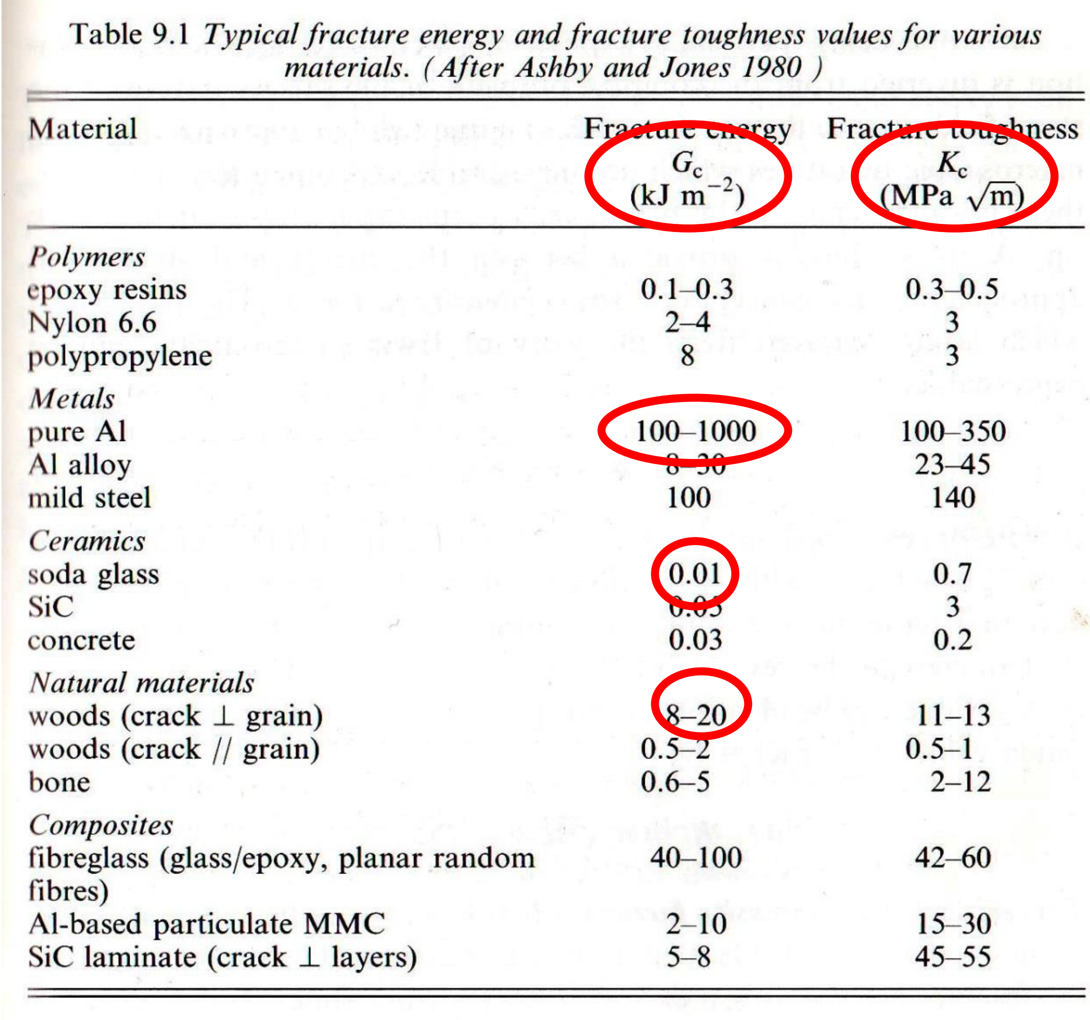


Table 9.1 *Typical fracture energy and fracture toughness values for various materials. (After Ashby and Jones 1980)*

Material	Fracture energy G_c (kJ m^{-2})	Fracture toughness K_c (MPa $\sqrt{m}$)
Polymers		
epoxy resins	0.1–0.3	0.3–0.5
Nylon 6.6	2–4	3
polypropylene	8	3
Metals		
pure Al	100–1000	100–350
Al alloy	8–30	23–45
mild steel	100	140
Ceramics		
soda glass	0.01	0.7
SiC	0.05	3
concrete	0.03	0.2
Natural materials		
woods (crack ⊥ grain)	8–20	11–13
woods (crack // grain)	0.5–2	0.5–1
bone	0.6–5	2–12
Composites		
fibreglass (glass/epoxy, planar random fibres)	40–100	42–60
Al-based particulate MMC	2–10	15–30
SiC laminate (crack ⊥ layers)	5–8	45–55

(Source Hull and Clyne 1996)

Energy & fracture

- To break a material you need to do work on it! In other words you need to supply energy
- When load a material it causes a deformation (work = force x distance)
- The stored ‘strain energy’ is available to propagate a crack
  - Think of a ‘longbow’ – the string is pulled back with the arrow and bends the bow. As the string is released the stored strain energy in the bow is converted to kinetic energy in the arrow
  - Or springs…
- If you need to do a lot of work to propagate a crack then the material is ‘tough’

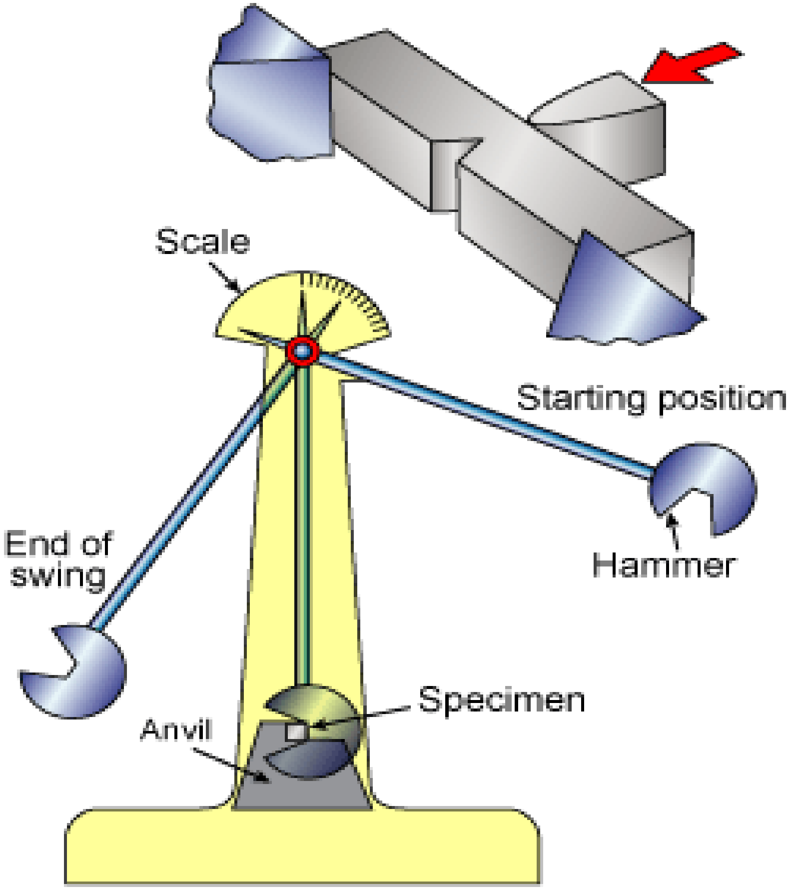
Energy & fracture

- Another way of looking at it is that if the material can “absorb” large amounts of energy when fracturing then it is likely to be tough
- If the material can absorb more energy when a crack advances than can be supplied by the stored strain energy (change in potential), then the crack will stop advancing

Measuring energy absorption during fracture is a convenient method of measuring the toughness of a material. This is why ‘impact tests’ such as the ‘Charpy test’ are so popular

Measurement of toughness

- "Charpy" or "Izod" tests provide a measure to toughness under impact conditions
- Work of fracture measured by loss of energy of a swinging pendulum
- Impact "strength" expressed as energy absorbed by specimen over fracture surface area



The Charpy impact test

Stress concentrations and energy

- So, cracks create stress concentrations in a material that can raise the local stress sufficiently to cause failure
- However, energy is needed to ‘drive’ the crack
- So, both stress and energy are important in fracture
- In 1920 A.A. Griffiths proposed a thermodynamic explanation for fracture and started the science of ‘fracture mechanics’

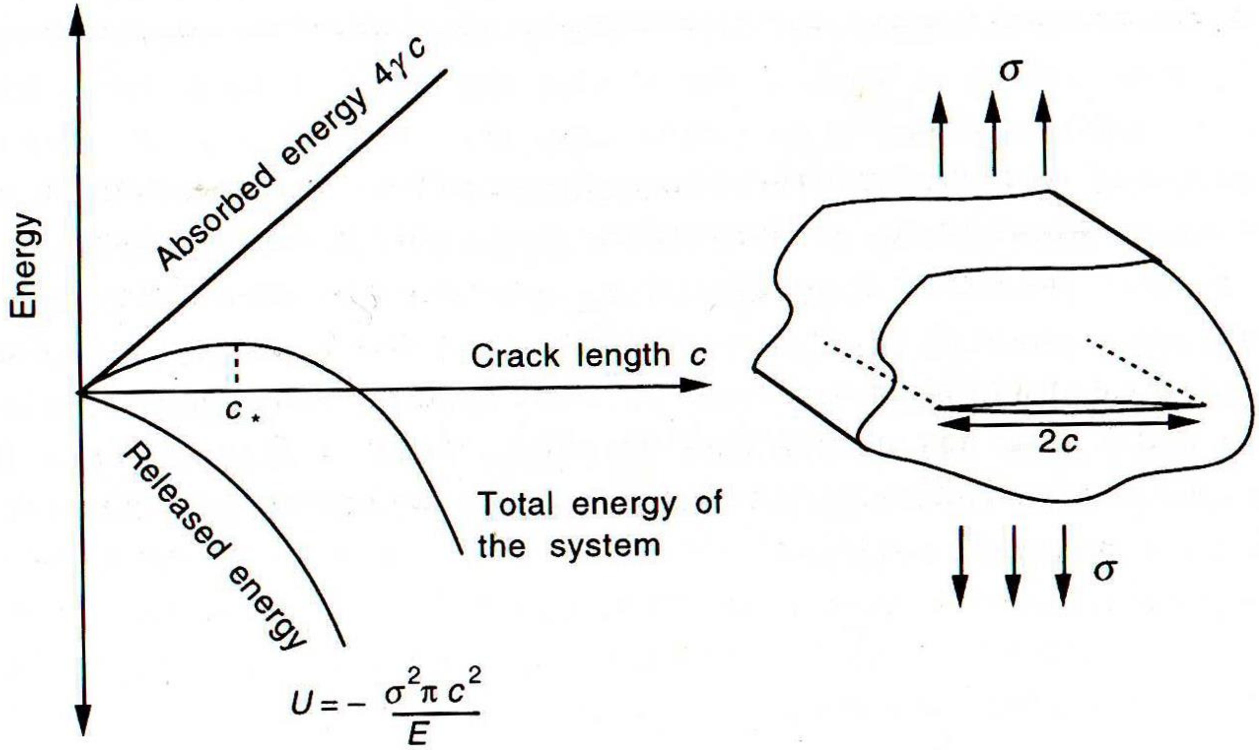


Fig. 9.1 Schematic plot of the two contributions to the energy associated with the presence of a crack in a brittle material, as a function of crack length. A crack of length c_* or larger will grow spontaneously, with a reduction in the total energy.

Griffiths and fracture mechanics

- Griffiths (1920) linked the failure stress (σ_F) of a material with the energy required to create new crack surfaces (surface energy for truly brittle material) and, a_c, the critical crack length (1)
- This was later extended to include tougher materials. In these, the surface energy term (γ_S) is supplemented by other energy absorption mechanisms (see later)
- The energy release rate, *G*, is derived from the Griffith's equation (2)
- The fracture energy (G_c) analogous to γ_S in the Griffith's equation (3)

$$\sigma_F = \left(\frac{2\gamma_S E}{\pi a_c} \right)^{1/2} \qquad (1)$$

E is Young's modulus

$2\gamma_S$ is the work of fracture
(γ_S is the surface energy)

$$G = \frac{\sigma^2 \pi . a}{E} \qquad (2)$$

$$\sigma_F = \left(\frac{G_C E}{\pi a} \right)^{1/2} \qquad (3)$$

Equivalence of stress based and energy based fracture criteria

A constant *K*, the *stress intensity factor* (units of MN $m^{-3/2}$) characterises the crack-tip stress-strain conditions:

$$G = K^2 / E$$ (in plane stress)

$$G = K^2 \left(1 - v^2\right) / E$$ (in plane strain)

Where: v is Poisson’s ratio

Stress concentrations - I

- Toughness may be regarded as the resistance a material possesses to the propagation of cracks or crack-like defects which might ultimately lead to failure
- Cracks may, for example, be macroscopic, ‘stress raisers’ such as bolted joints, or sharp changes in section, or alternatively pre-existing crack-like defects in the material itself. These cracks result in localised stress concentrations, the magnitude of which depend upon the size and shape of the crack

Stress concentrations - II

- If the stress concentrations are high enough, the material in the vicinity of the crack-tip may fail. Under certain conditions, a crack may propagate catastrophically, leading to sudden failure of the material
- The crack-tip may, therefore, be viewed as a mechanism whereby local stresses in the material are raised sufficiently for fracture to occur

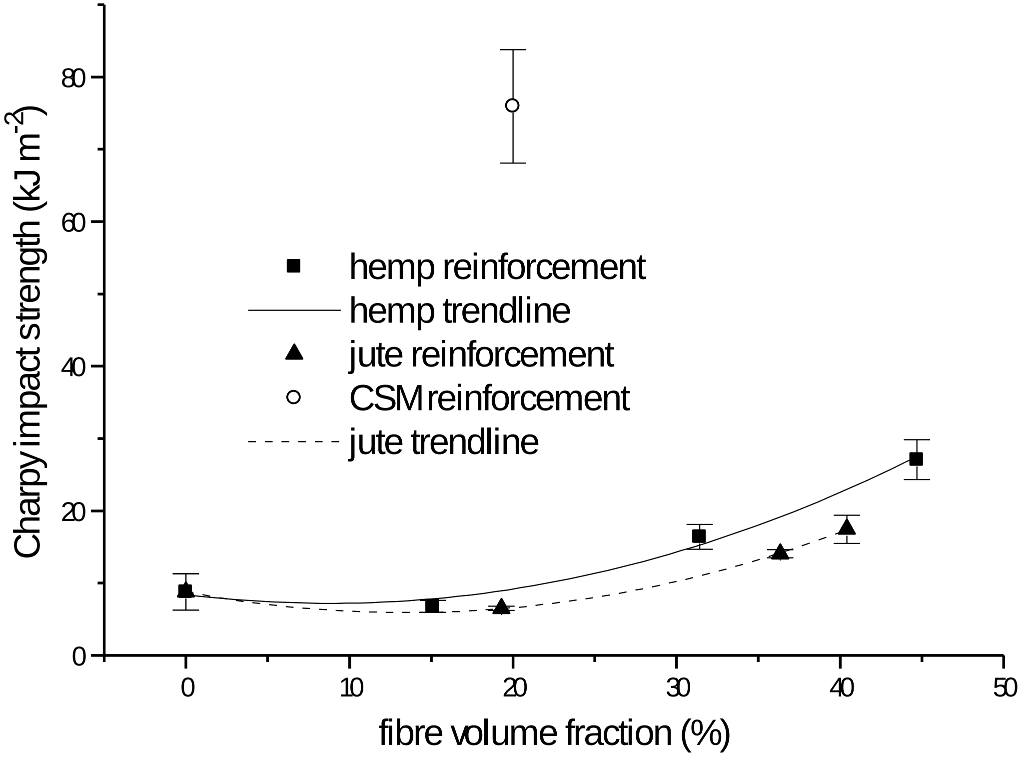
Energy absorption - I

- However, for the crack to propagate, it must be energetically favourable for it to do so
- The energy to drive the crack forward is provided by the release of stored **strain energy** in the material, together with any external work done by the loading system
- Therefore, a material that possesses mechanisms whereby significant amounts of energy can be absorbed as the crack advances or if, by some contrivance, the stress concentration at the crack-tip can be relieved, then the material is likely to be tough

Energy absorption - II

- Brittle materials such as glass have little means of energy absorption or crack-blunting and hence fail in a catastrophic manner, exhibiting low fracture energies of around 0.01 kJ/m^2
- Ductile metals such as mild steel, on the other hand, absorb large quantities of energy by plastic deformation. Typically, tough engineering materials such as steel exhibit fracture energies of around 100 kJ/m^2

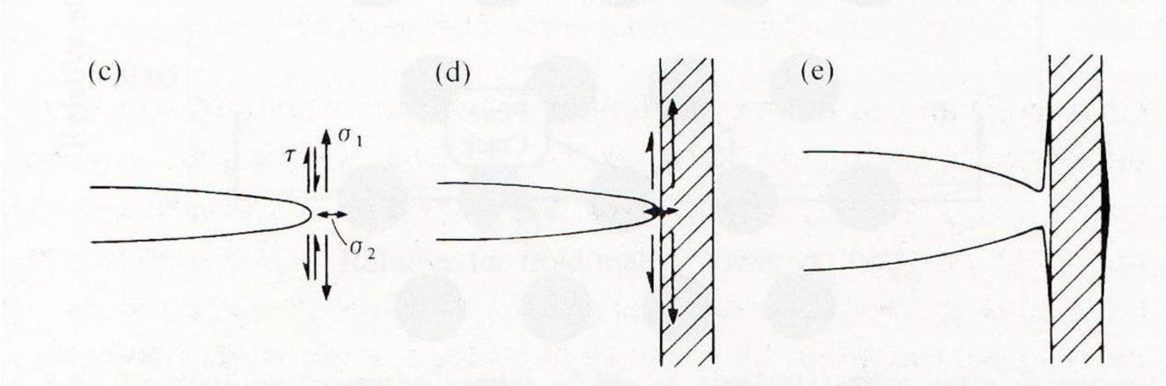
Toughness of natural fibre reinforced composites



Comparison of un-notched Charpy impact strength.
Jute, hemp and C.S.M. glass fibre reinforced laminates

The “Cook-Gordon” crack stopping/blunting/deflection mechanism

- Stress field ahead of advancing crack, “opens up” an interface
- Transverse stress about 20% of axial stress



(Cook and Gordon, 1964)

Energy absorbing processes in composites

- Several energy absorbing mechanisms have been identified. These are:
  - **Matrix deformation and fracture**
  - **Fibre fracture**
  - **Interfacial debonding**
  - **Frictional sliding and fibre pull-out**
- The contribution that each of the energy absorbing mechanisms makes to the overall toughness of the composite varies, depending upon the composite system involved and the properties of the phases

Matrix deformation & fracture

- With brittle thermoset polymers, the contribution from matrix deformation and fracture to the overall fracture energy of the composite is likely to be small. Typically, fracture energies of thermosetting polymers are of the order of 0.1 kJ/m^2
- The fracture energy of thermoplastic polymers such polypropylene, or polyethylene are greater

Fibre fracture I

- Brittle fibres such as glass exhibit very low fracture energies of the order 0.01 kJ/m^2. The contribution to the overall work of fracture of the composite is likely, therefore, to be small
- Wood fibres can, however, exhibit high works of fracture. It has been observed that wood fibres can deform in a ‘pseudo-plastic’ manner, due to the microfibril angle in the S2 layer. This results in shear failure in the fibre cell wall, leading to energy absorption. This mechanism is believed to account fro up to 90% of the work of fracture of wood across the grain (10-30 kJ/m^2)

Fibre fracture II

- The work of fracture of the wood cell wall material (i.e. not including the plastic deformation – the so-called “intrinsic toughness”) has been reported to be between <0.35 and 3.45 kJ/m^2 depending upon whether it is measured along or across the fibre axis
- Thus, fibre fracture could, potentially, contribute fairly significantly to the toughness of a wood fibre reinforced composite

Interfacial debonding

- The debonding energy in composites is generally quite small, ~0.01 kJ/m^2 and the resulting contribution to the overall work of fracture is generally low (~0.5 kJ/m^2). As discussed above
- If the interfacial fracture energy is increased too much, debonding is prevented (i.e. the interface becomes too strong) and this will lead to a reduction in the crack stopping / blunting capacity

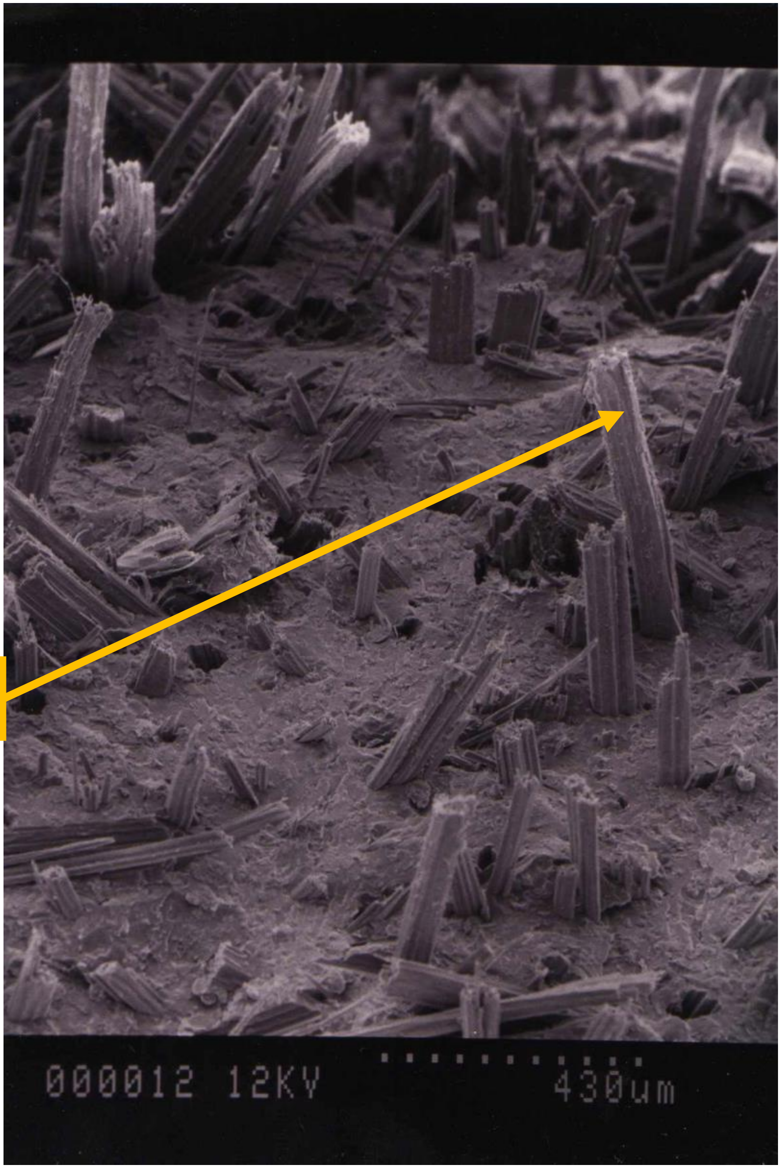
Fibre pull-out

- Frictional sliding and fibre pull-out as the fibre is withdrawn from the matrix socket during fracture
- Potentially, this mechanism can absorb large amounts of energy (of the order of 100 kJ/m^2 if the interfacial frictional forces are large and the pull-out length of the fibre are high as is the case in glass fibre reinforced composites)
- Frictional energy dissipation during pull-out is dependent upon interfacial roughness, contact pressure and sliding distance

Fracture surfaces

Natural fibre

Glass fibre



Fibre pull-out

Summary

- For engineering materials, adequate toughness is essential
- Cracks and crack-like defects raise local stresses that can lead to local failure
- Interfaces act as “crack-stopping” mechanisms
- If there is sufficient (strain) energy the crack can propagate unstably, leading to catastrophic failure
- Composites employ different energy absorbing mechanisms

Further reading & resources

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Further reading & resources

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