Properties of Materials

Theme: Introduction

Lecture 0: The Intro

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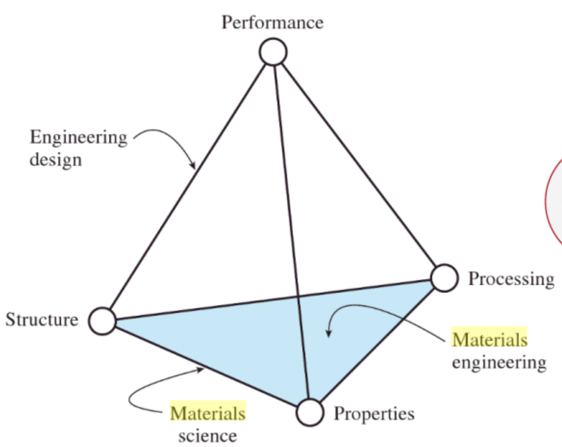
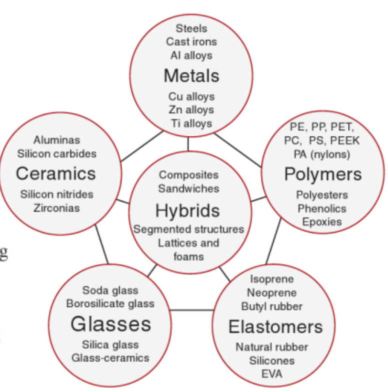
Materials





Future of Engineering Design is Materials

Materials

Process → Structure → Properties → Performance

Impact of processing on properties will become even more critical as Additive Manufacturing replaces Removal Manufacturing.

Image: Dragonfly, DESIGN OF MECHANICAL PARTS FOR ADDITIVE MANUFACTURING

What do we mean by properties?

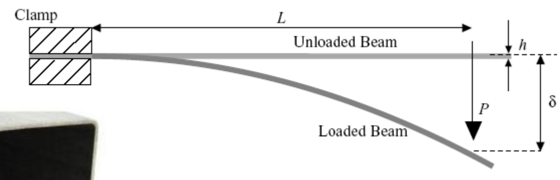
Heat flow
Thermal conductivity

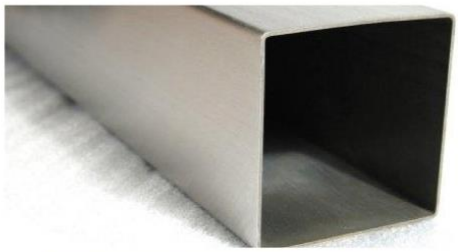
$$q = -k\nabla u$$

Light Bulb
Electrical resistivity

$$P = I^2R = I^2\frac{\rho l}{A}$$

What do we mean by properties?





$$\delta = \frac{1}{\boxed{E}} \boxed{\frac{PL^3}{3I}}$$

Material property (Modulus)

Geometry and loading

Properties

Secondary interest

Primary interest of this course

Lots to choose from

Table 1.1 Classes of Property

Class	Property
Economic and environmental	Price and availability
	Recyclability
	Sustainability
	Carbon footprint
General physical	Density
Mechanical	Modulus
	Yield and tensile strength
	Hardness
	Fracture toughness
	Fatigue strength
	Creep strength
	Damping
Thermal	Thermal conductivity
	Specific heat
	Thermal expansion coefficient
Electrical and magnetic	Resistivity
	Dielectric constant
	Magnetic permeability
Environmental interaction	Oxidation
	Corrosion
	Wear
Production	Ease of manufacture
	Joining
	Finishing
Aesthetic	Color
	Texture
	Feel

Themes

- Theme 1: Observed Properties
  - Empirically observed
  - Definitions
  - How we measure them
- Theme 2: Material Selection
  - Rational material selection
  - Ashby method
  - Material indices
- Theme 3: Structure
  - Atoms and bonding
  - Crystals and crystallography
- Theme 4: Polymers and composites
  - Structure
  - Viscoelasticity
  - Composites, foams and novel materials

Assessment 2017-18

- Why are we starting Materials in Week 9?
  1. Me
  2. Course evaluation 2016-17
- Materials component of STM1

  7% Materials Selection Group Assignment (T2)

  You will need you Lab data for this (T1)

  3% Online Materials Test (T1)

  2 Exam Questions (T3-4)

Due
Wednesday
January 31st
at 14:00

Reference Textbooks

M.F. Ashby, H. Shercliff, and D. Cebon.
Materials: Engineering, Science, Processing and Design.
Butterworth-Heinemann.

Supplementary reading:

W.D. Callister. Materials Science and Engineering: An Introduction. Wiley.

F.C. Campbell. Manufacturing Technology for Aerospace Structural Materials. Elsevier.

Properties of Materials

Theme: Observed Properties

Lecture 1: Elastic Behaviour

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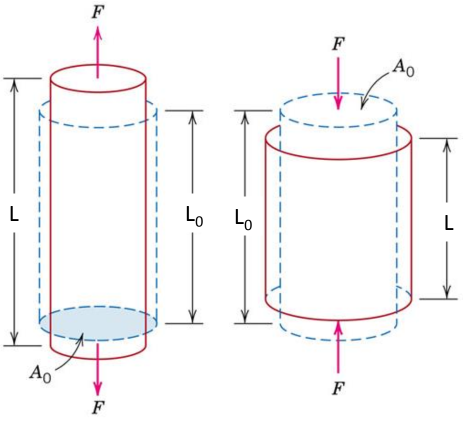
Intended Learning Objectives

Describe simple material properties in terms of desirable engineering characteristics

- Lecture 1:
  - Engineering stress/strain and mechanical testing
  - Elastic properties (modulus)
- Lecture 2:
  - True stress/strain
  - Plastic properties (yield, resilience, and strength)
- Lecture 3
  - Ductility and Resilience
- Lecture 4:
  - Toughness
- Lecture 5:
  - Hardness and wear resistance

Engineering Stress and Strain



- Tensile forces
  - Cause elongation
  - Reduction in area
- Compressive forces
  - Cause contraction
  - Increase in area
- Stress/strain
  - Normalise against dimensions

Eng. Stress:

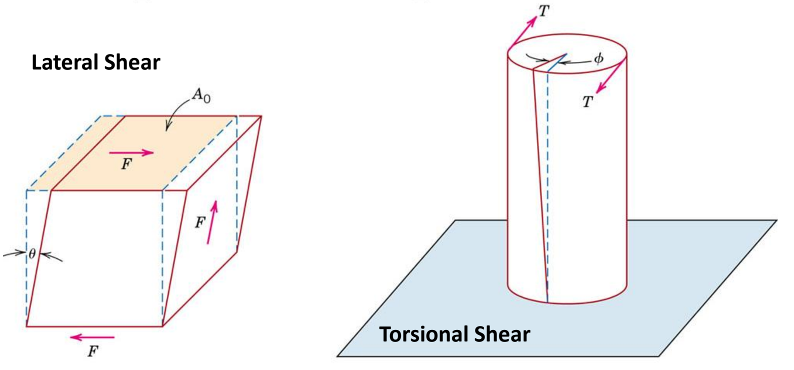
$$\sigma = \frac{F}{A_0}$$

Eng. Strain:

$$\varepsilon = \frac{L - L_0}{L_0} = \frac{\Delta}{L_0}$$

Shear Stress and Strain

- Shear causes change in shape but no change in area/volume



Shear Stress:

$$\tau = \frac{Force, F \text{ or } Torque, T}{Area, A_0}$$

Shear Strain:

$$\gamma = \tan(\theta)$$

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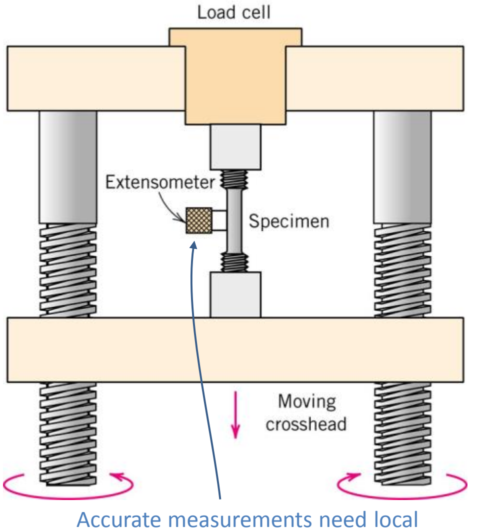
Tensile Testing

- Aim
  - To provide a standard method for obtaining key mechanical properties
- Stretch sample
  - Measure load
  - Measure deformation



Accurate measurements need local measures of deformation – or you measure deformation of machine too

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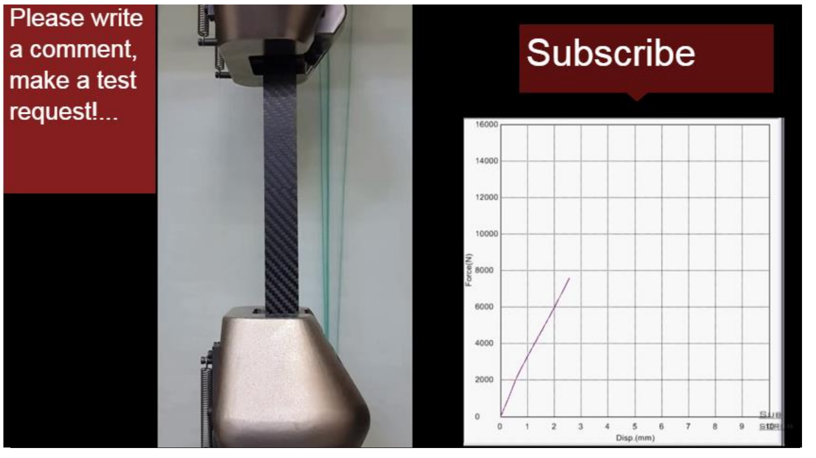
Tensile Test of a Carbon Fibre Composite



https://www.youtube.com/watch?v=aH9vcV7jzG0

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Tensile Test of a Metal

https://www.youtube.com/watch?v=5QaqwmZ7Sic

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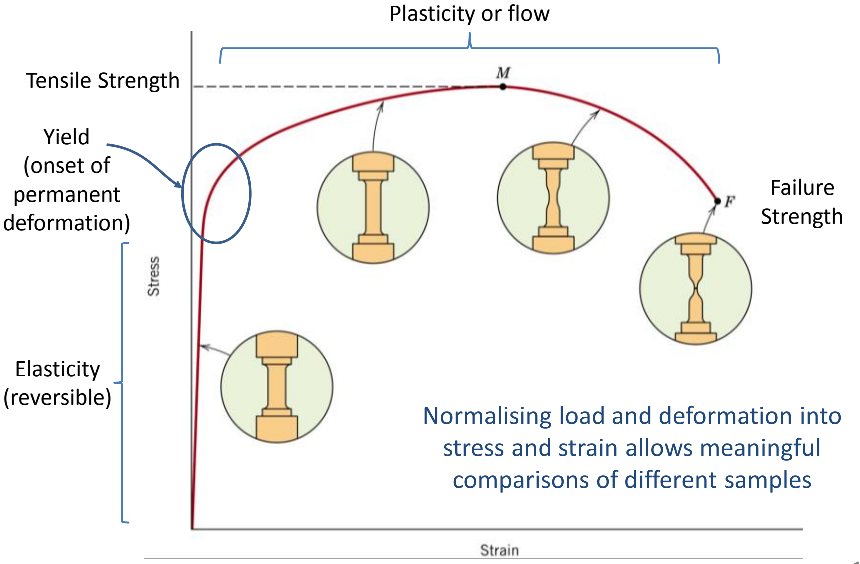
Tensile Behaviour of Metals



Normalising load and deformation into stress and strain allows meaningful comparisons of different samples

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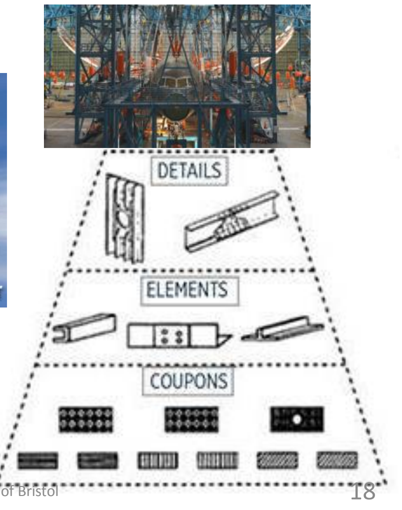
Building Block Approach

- Use of stress and strain eases comparison between tests and real structures



Good data at the coupon level provides a solid foundation for in-flight deflection estimates.

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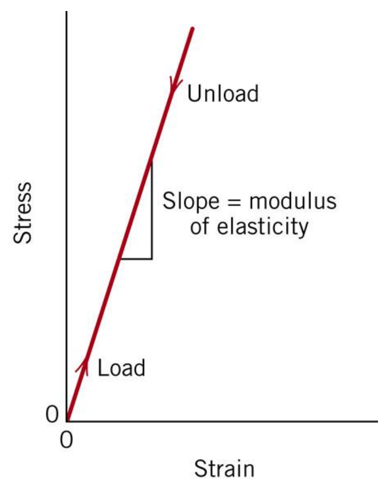
Modulus of Elasticity



- In the elastic regime
  - Strain is entirely recovered
  - Strain proportional to stress

Young's modulus

Stress → $\sigma = E\varepsilon$ ← Strain

Shear stress → $\tau = G\gamma$ ← Shear strain

Shear modulus

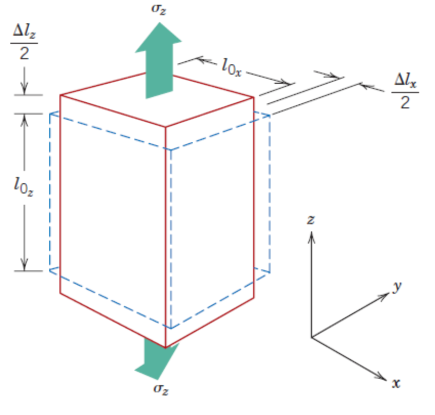
  - Only true for linear elastic materials

Poisson's Ratio, ν

- The amount a material shrinks inwards as a tensile load is applied

$$\upsilon = -\frac{transverse\ strain}{axial\ strain} = -\frac{\varepsilon_x}{\varepsilon_z}$$

Material	ν
Steel	0.30
Aluminum	0.33
Carbon fibre/epoxy	0.25
Rubber	0.48
Cork	0

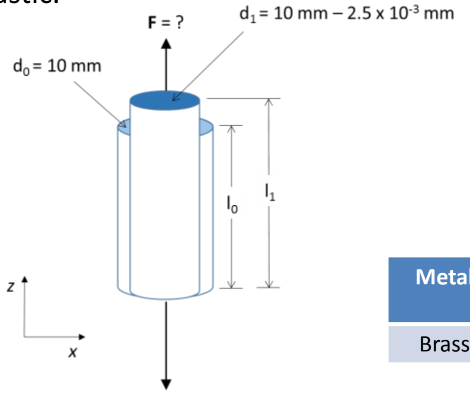


Relates Elastic and Shear Modulus:

$$E = 2G(1+\upsilon)$$

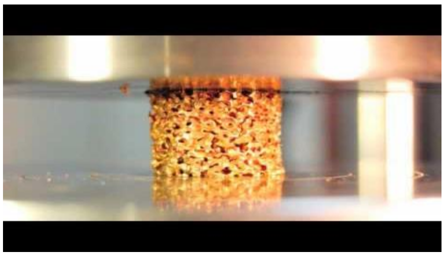
Example: Elastic Deformation

A tensile stress is applied to a brass rod that has a 10 mm diameter. In groups of 2-3, determine the load required to produce a 2.5 x 10^{-3} mm reduction in diameter if the deformation is purely elastic.



Metal	Young's Modulus	Shear Modulus	Poisson's Ratio
Brass	97 GPa	37 GPa	0.34

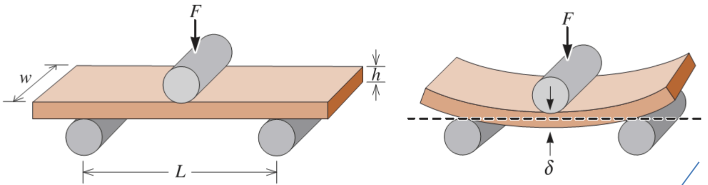
Compression tests



- Compression tests squash cylinders of material
  - Common for brittle materials (not used in tension)
  - Strength can be different in compression
  - No necking so max strain can be higher than for tension

Flexural Testing

- Useful for brittle materials
- Compressive stress above the mid-plane
- Tensile stress below the mid-plane
- Failure occurs in the half with lower strength
  - ➢Results are difficult to interpret

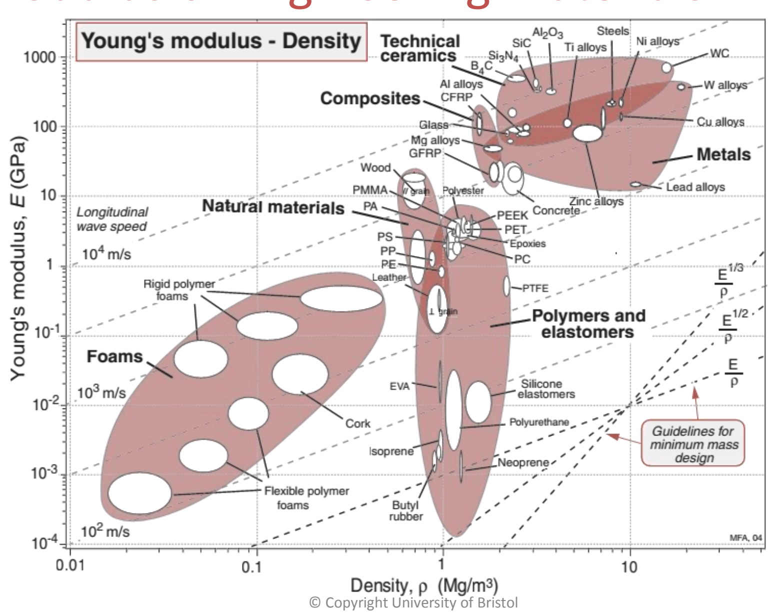


Failure load

Flexural modulus: $E_{bend} = \frac{L^3 F}{4wh^3\delta}$

Flexural strength: $\sigma_{bend} = \frac{3F_f L}{2wh^2}$

Modulus of Engineering Materials



Summary

- Stiffness
  - Resistance to **elastic** deformation
  - Stiff materials have high E (Young's Modulus)

Properties of Materials

Theme: Observed Properties

Lecture 2: Plastic Behaviour

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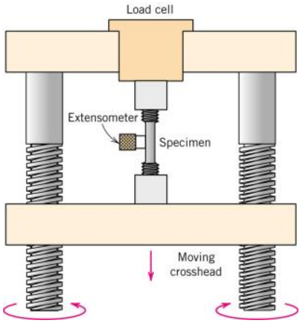
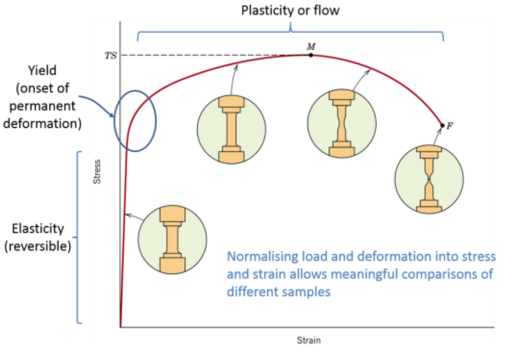
Previously

- Elastic deformation of materials
- Materials with a higher Young's Modulus (**E**) deform less when subject to the same stress





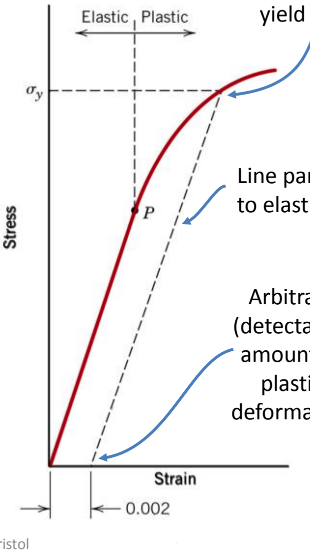
Yield Strength

- Definitions
  - First movement of dislocations
  - Proportional limit
  - Elastic limit
  - 0.2% offset

Needs TEM – not practical

Values are a function of the quality of your kit

Standard Method
Stress to achieve arbitrary quantity of plastic deformation



Intercept gives offset yield point

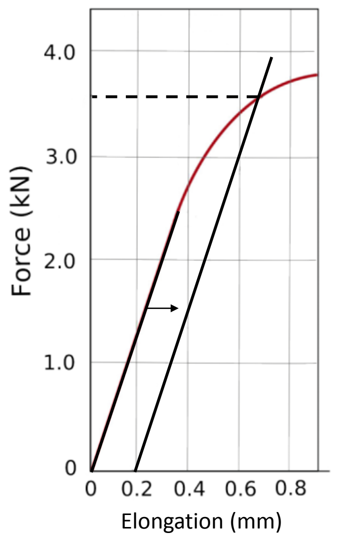
Line parallel to elastic

Arbitrary (detectable) amount of plastic deformation

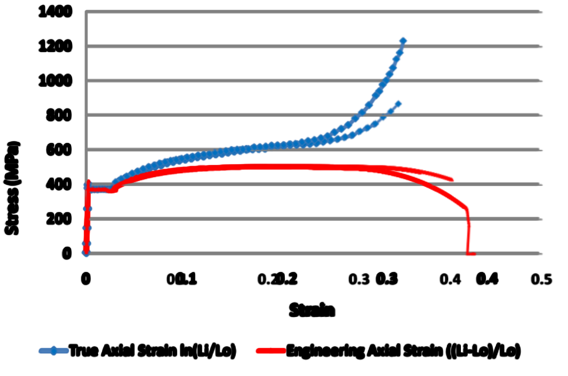
Example: Yield Strength Calculation

Diameter = 6 mm, Length = 100 mm

In groups of 2-3, calculate the 0.2% yield stress (sometimes called proof stress)

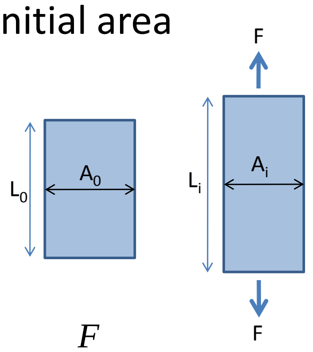


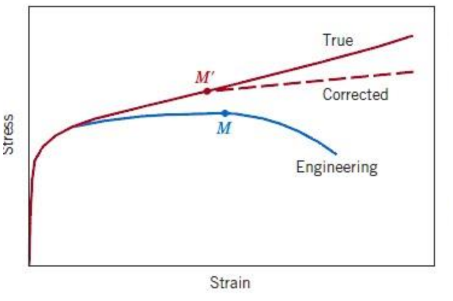
Engineering v. True Stress/Strain



True Stress, σ_T

- True stress is given by the actual area not the initial area





$$\sigma_T = \frac{F}{A_i}$$

Instantaneous area

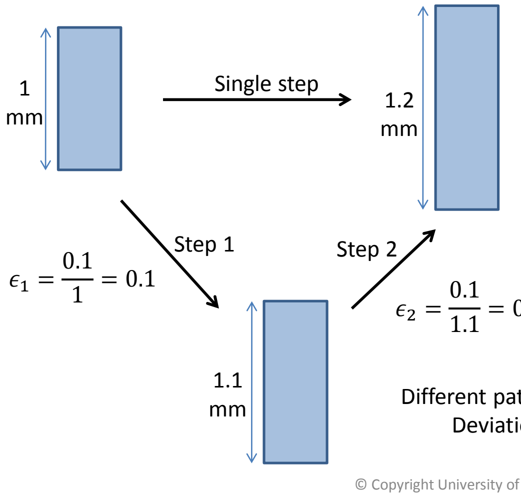
- If no volume change occurs

$A_iL_i = A_oL_o$

$$\sigma_T = \sigma(1+\varepsilon)$$

True Strain, ε_T

- Consider two tensile tests both resulting in a sample 20% longer



$$\epsilon_1 = \frac{0.1}{1} = 0.1$$

$$\epsilon_2 = \frac{0.1}{1.1} = 0.09$$

Single step

$$\varepsilon = \frac{\Delta L}{L_0} = \frac{0.2}{1} = 0.2$$

Two step

$$\varepsilon = \varepsilon_1 + \varepsilon_2 = 0.19$$

Different paths result in different calculated strains
Deviation from 'small strain assumption'

True Strain, ε_T

- When deformations are large we need an alternative measure

$$\varepsilon_T = \frac{L_1 - L_0}{L_0} + \frac{L_2 - L_1}{L_1} \cdots \frac{L_n - L_{(n-1)}}{L_{(n-1)}}$$

$$\varepsilon_T = \int_{L_0}^{L} \frac{dL}{L} = \ln(L) - \ln(L_0) = ln\left(\frac{L}{L_0}\right)$$

A tensile test is essentially lots of little increments of strain which must be integrated!
(Taylor Series)

- Define true strain in terms of engineering strain:

$$\varepsilon_T = ln\left(\frac{\Delta L + L_0}{L_0}\right) = \ln(1+\varepsilon)$$

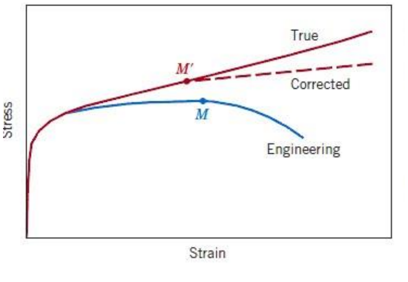
This works if deformation is uniform i.e. before a neck starts (after neck you must measure the length)

Corrected True Stress-Strain

- Accounts for the complex stress state in neck
- Valid until necking, M'

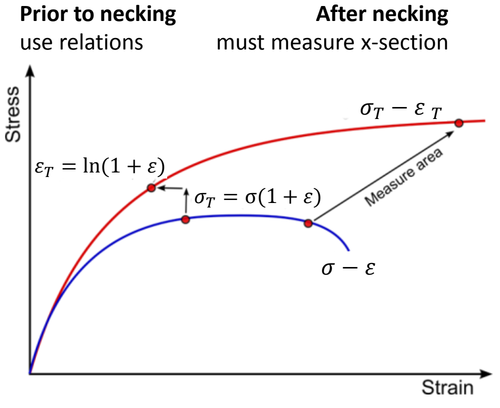
$$\sigma_T = \sigma(1+\varepsilon)$$

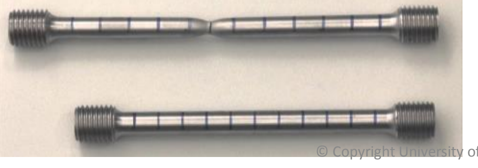
$$\varepsilon_T = \ln(1+\varepsilon)$$



- Non-axial stress state
- Corrected stress:
  - Actual load
  - Cross-sectional area
  - Gauge length measurements

Plastic Behaviour





- The stress in the neck follows the true stress-strain curve
- Drop in engineering stress is due to reduction in area
- Calculate area before necking
- Measure area after necking (video)

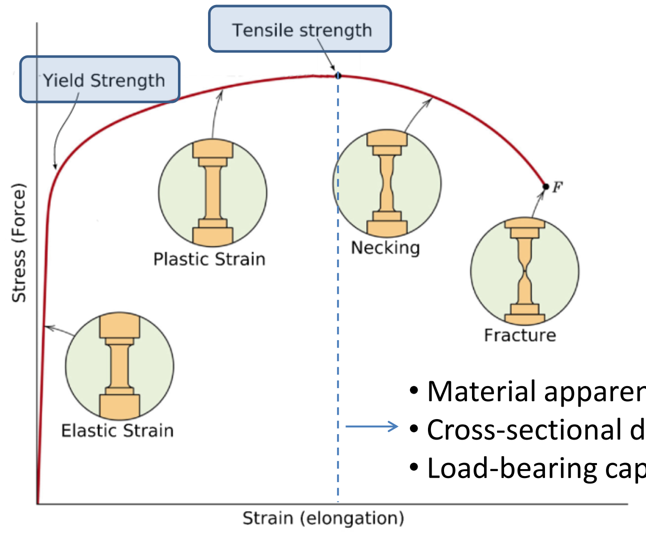
Example: True Stress-Strain

A cylindrical specimen of steel having an original diameter of 12.8 mm is tested in uniaxial tension to fracture. An engineering tensile fracture strength of 460 MPa and cross-sectional diameter of 10.7 mm is reported at fracture. In groups of 2-3, determine:

a) the true stress at fracture

b) the true strain at fracture

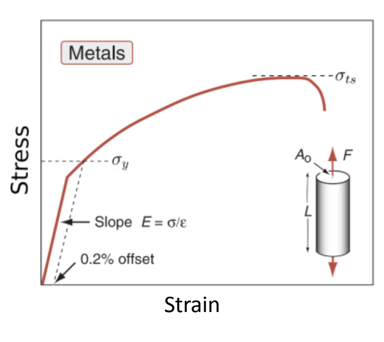
Tensile Strength

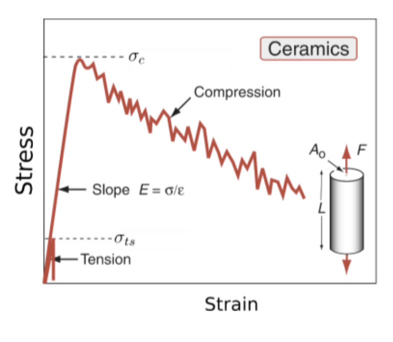


- Material apparently getting weaker
- Cross-sectional decreasing
- Load-bearing capacity increasing

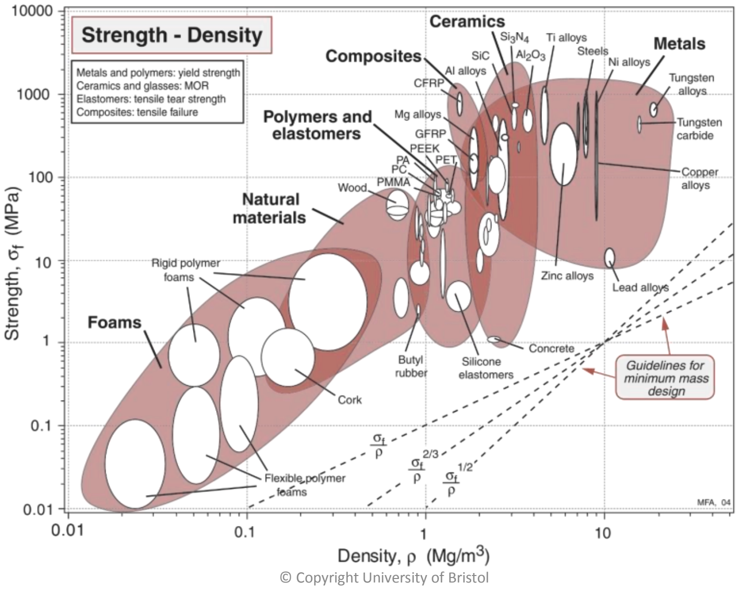
Strength

Maximum stress reported on the Engineering stress/ strain curve. Not normally used in metallic design because of the magnitude of plastic deformation. Can be used for some ceramics/ composites.





Strength of Engineering Materials



Summary

- Yield
  - Transition from Elastic to Plastic deformation
- Strength
  - Maximum stress sustained by a material

Materials 1: Properties of Materials

- Over the last 2 lectures, what new concept have you learned?

- As we end this lecture are there any aspects of elastic or plastic behaviour that are confusing to you?

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Properties of Materials

Theme: Observed Properties

Lecture 3: Ductility and Resilience

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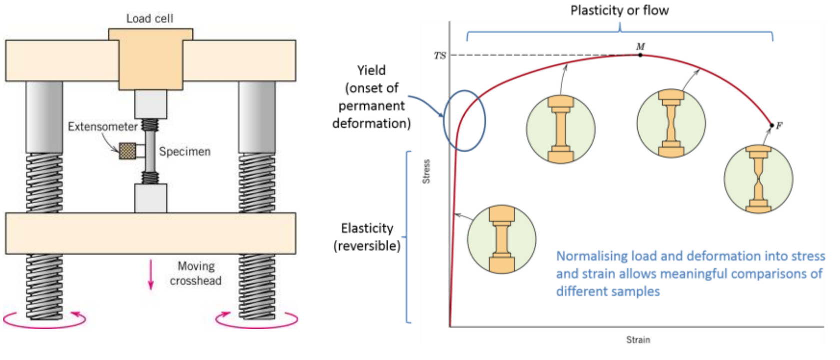
Previously

- Elastic and plastic deformation of materials
- Materials with a higher Young's Modulus (**E**) deform less when subject to the same stress



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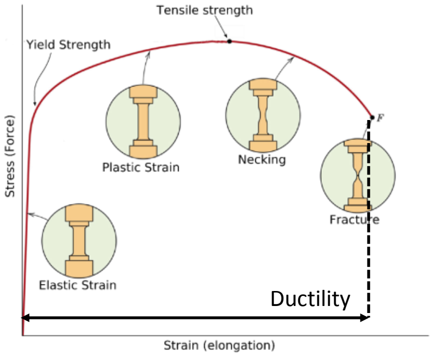
Ductility

Measure of the degree of plastic deformation that has been sustained at fracture.



- Two measures:

$$\%EL = \left(\frac{L - L_0}{L_0}\right) \times 100$$

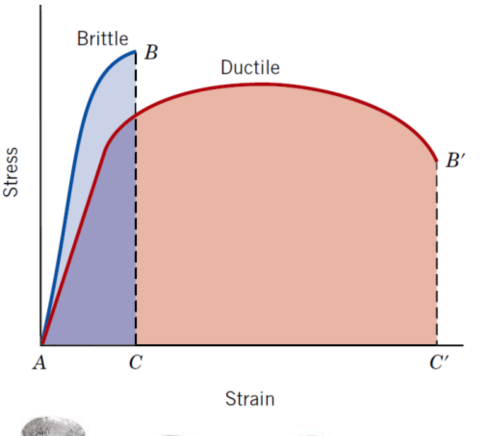
$$\%RA = \left(\frac{A_0 - A}{A_0}\right) \times 100$$

- Two measures give slightly different results

In design: structure deformation before fracture

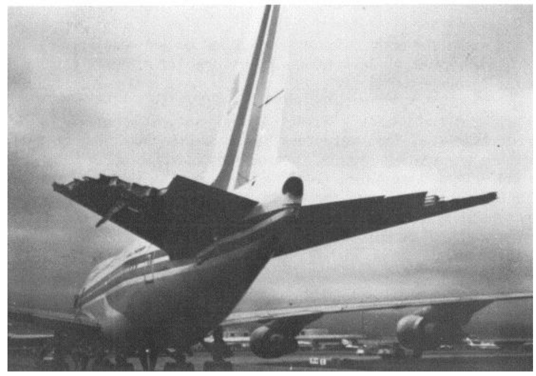
Ductility

- Arbitrary distinction into brittle vs ductile
  - Approx. 5% strain
- Ductile
  - Failure denoted by yield
- Brittle
  - Failure denoted by fracture



Example of In-service Ductility

- China Airlines 006
- February 1985
- Aircraft dropped 3140m in 33s
- Right wing down
- Vertical loading 5.1g
- Wings permanently deformed 50-75mm at wingtips

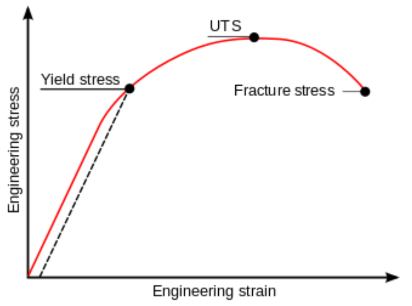


Resilience

- Capacity to store elastic energy
  - Loaded → Energy stored through deformation
  - Unloaded → Energy recovered

https://www.youtube.com/watch?v=00I2uXDxbaE

Modulus of Resilience, U_r

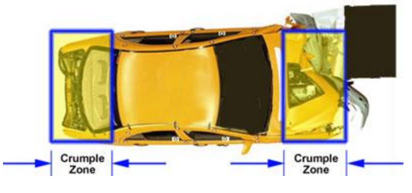


$$U_r = \frac{1}{2}\sigma_y \varepsilon_y = \frac{1}{2}\sigma_y\left(\frac{\sigma_y}{E}\right) = \frac{\sigma_y^2}{2E}$$

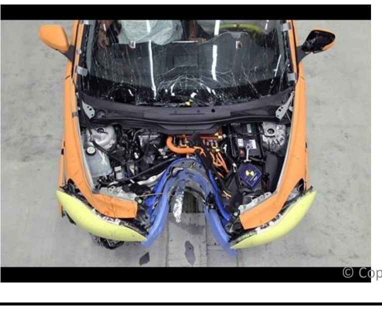
What material makes the best bumpers for low speed collisions?

Material	σ_y (MPa)	E (GPa)	u (MPa / MJm^{-3})
Steel	310	200	0.24
Aluminium	240	70	0.41
Rubber	20	0.05	4.0

Resilience in Automotive Impact

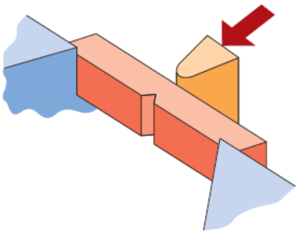


- Plastic collapse of metal is more important for safety
- Toughness/ductility

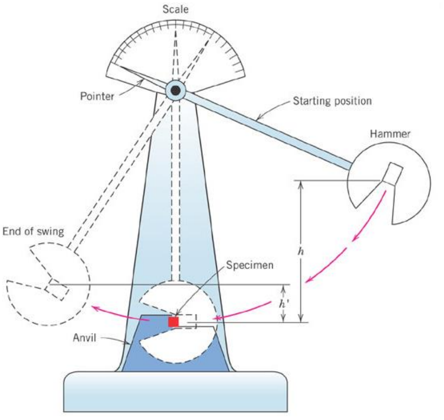


Impact Test

Charpy V-notch impact test



Sample: Square bar with notch



Energy absorbed is a measure of the difference in height of the hammer

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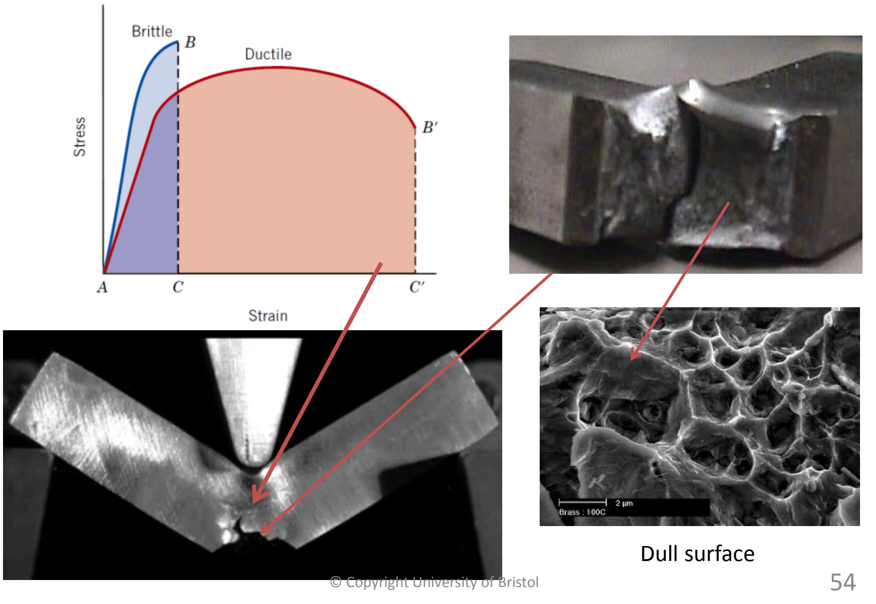
Impact Test: Ductile Material



Dull surface

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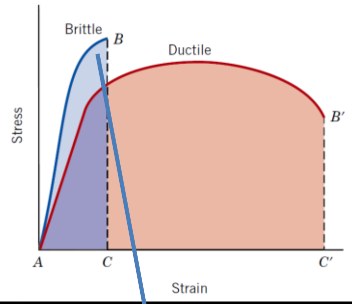
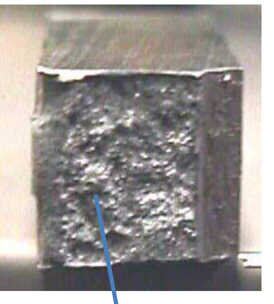
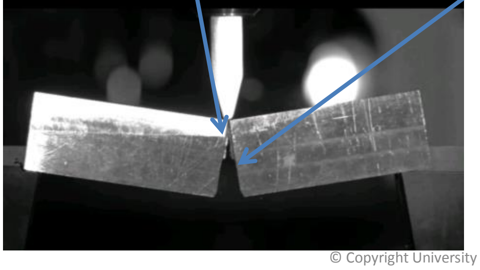
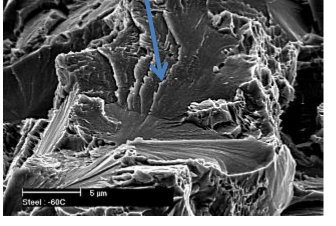
Impact Test: Brittle Material



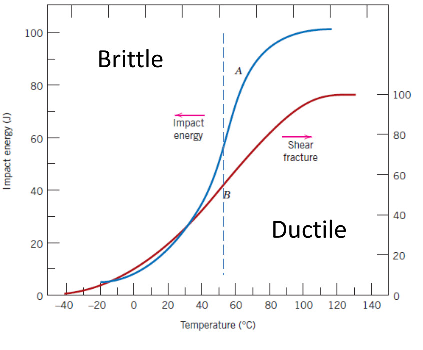






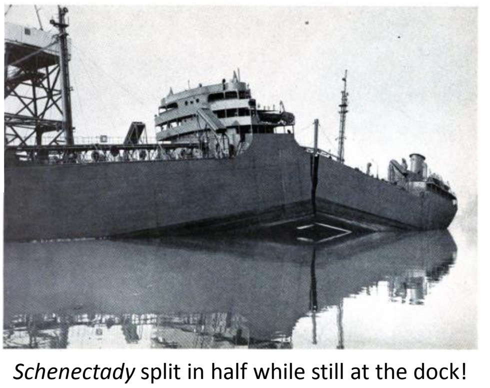
Shiny surface

Ductile to Brittle Transition Temperature



Testing needs to be performed at relevant service temperatures

The impact energy and the % shear fracture drop suddenly over a narrow temperature range



Schenectady split in half while still at the dock!

Summary

- Ductility
  - Highly desirable
  - Often only an issue for safety
- Resilience
  - Ability to absorb elastic energy

Properties of Materials

Theme: Observed Properties

Lecture 4: Toughness

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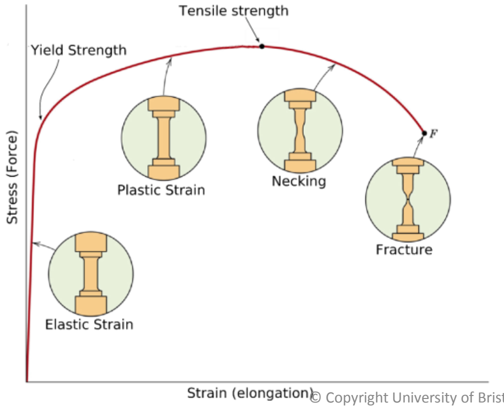
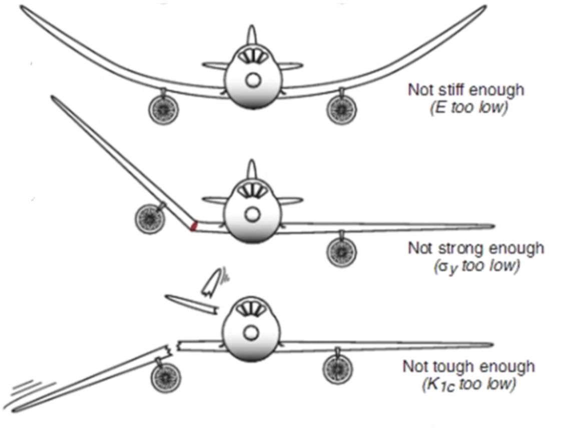
Previously

- Modulus: Deformation from an applied stress
- Strength: Plastic deformation
- Ductility: Strain at fracture



Today: Toughness
- Presence of flaws/cracks
- Measured performance lower than theoretical atomic bonding energy

Failure

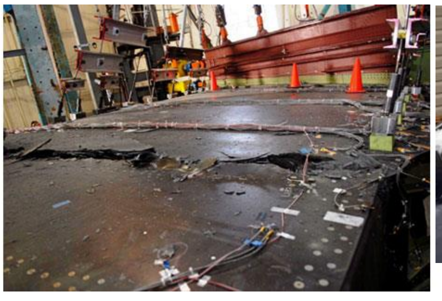


Structural engineering is the art of modelling materials we do not wholly understand, into shapes we cannot precisely analyse so as to withstand forces we cannot properly assess, in such a way that the public has no reason to suspect the extent of our ignorance.

(Dykes, 1978)

Toughness

- Multiple meanings
  - Capacity to absorb energy and plastically deform before fracture
  - Fracture Toughness: resistance to crack growth
  - Ability to tolerate impacts

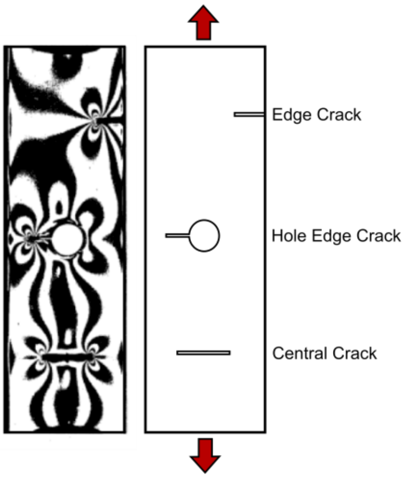


Hail impact damage

Boeing 787 composite wingbox fracture test

Fracture Toughness

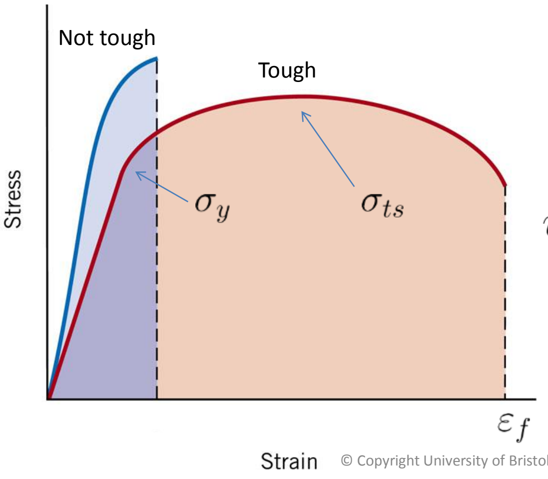
Clear plastic specimen with polarised light



- Tensile toughness
  - Easy to test but calculations difficult
- Fracture mechanics
  - Complex but good predictions
- Mathematical description of cracks
  - Characteristic strain pattern at cracks

Tensile Toughness

- Work required to cause failure
  - Area under stress strain curve up to fracture



$$u = \int_0^{\epsilon_f} \sigma d\epsilon$$

$$u \approx \varepsilon_f \left(\frac{\sigma_y + \sigma_{ts}}{2} \right)$$

Easy to determine but of restricted usefulness – comparative but hard to calculate useful numbers

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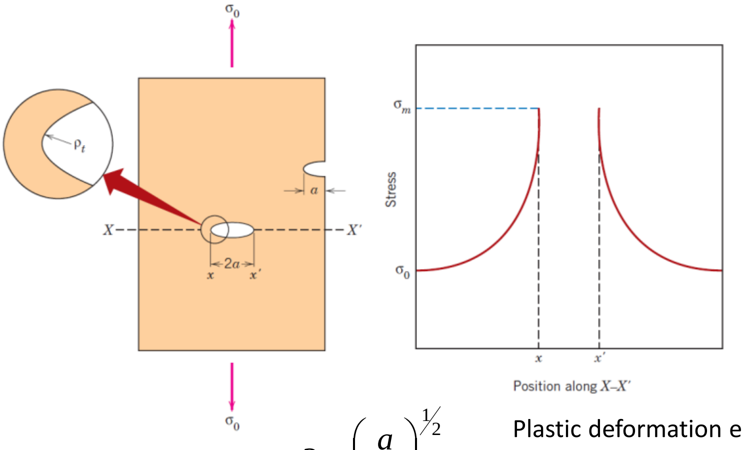
Stress Concentrations

- Applied stress amplified at the crack tip



Maximum stress $\sigma_m = 2\sigma_0 \left(\frac{a}{\rho_t} \right)^{1/2}$

Plastic deformation ensues when maximum stress exceed yield stress in ductile materials

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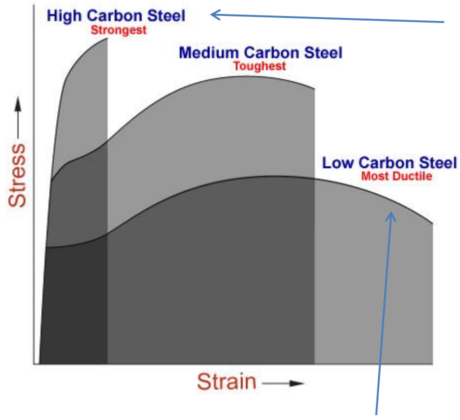
Brittle and Ductile Materials

- Is the material going to yield or fracture?



Brittle materials have high strength but this is limited by small cracks that always exist in all materials

Critical stress for crack growth in brittle materials:

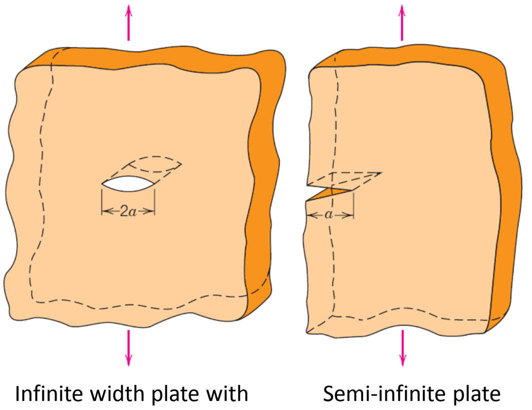
$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a} \right)^{1/2}$$

E = Young's modulus
γ_s = specific surface energy
a = half the length of internal crack

Ductile materials can tolerate these cracks so no effect on strength (yield first)

Fracture Toughness, K_c

- Measure of a material's resistance to brittle fracture when a crack is present



Infinite width plate with **central** crack
Y = 1.0

Semi-infinite plate with **edge** crack
Y ~ 1.1

$$K_c = Y\sigma_c\sqrt{\pi a}$$

Y = dimensionless parameter
Depends on:
- Crack length
- Specimen size
- Load application

Complex mathematical expressions for Y have been proposed for a variety of specimen geometries

Plain Strain Fracture Toughness, K_{Ic}

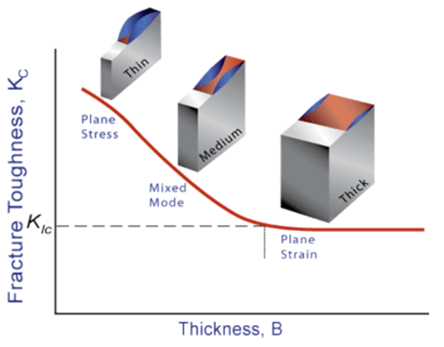
- If specimen thickness is much greater than crack dimensions, K_c becomes independent of thickness
- K_{Ic}, highest value of stress intensity that that a material can withstand without fracture under plane-strain conditions

Material property

$$\sigma_c \leq \frac{K_{Ic}}{Y\sqrt{\pi a}}$$

Critical design stress

Allowable flaw size in component



Example

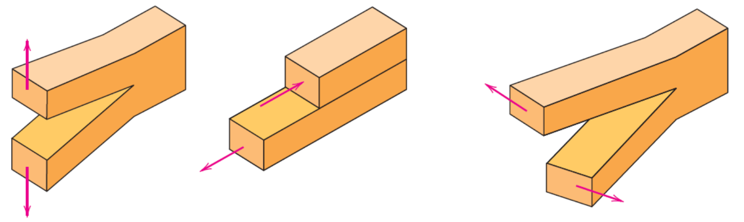
A structural steel tie is to be welded into place and then tested for internal defects using ultrasonic detection. Due to access restrictions and limits with on-site testing, it is felt that the minimum reliably detectable crack length (a) is 2mm. What is the maximum stress that can be applied to the joint if there must be a safety factor with respect to stress of 1.5? What if the safety factor applies to the crack length instead? Assume $K_{1C} = 77\text{MPa}\sqrt{\text{m}}$ *and Y=1.*

Smallest crack to design for

Extra margin of safety beyond estimated safe limit

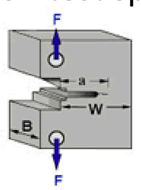
Fracture Toughness Testing

- Three modes of crack surface displacement

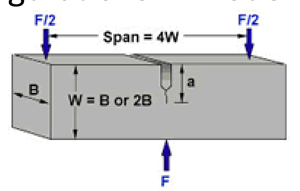


Mode I: Opening Mode II: Sliding Mode III: Tearing

- Common test specimen configurations in mode I



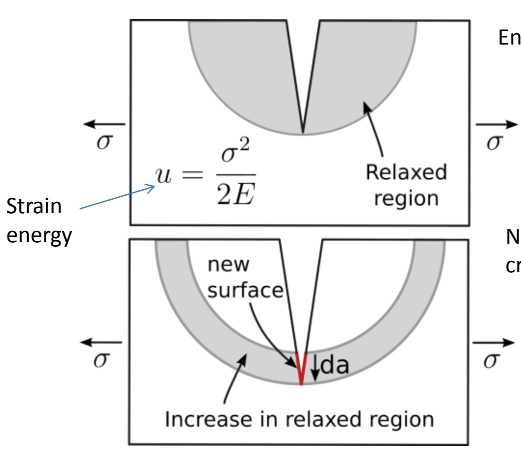
Compact Tension (CT)



Single Edge Notch Bending (SENB)

Critical Strain Energy Release Rate, G_c

- Energy absorbed in making a new crack surface



Energy release rate

$$G \geq 2\gamma$$

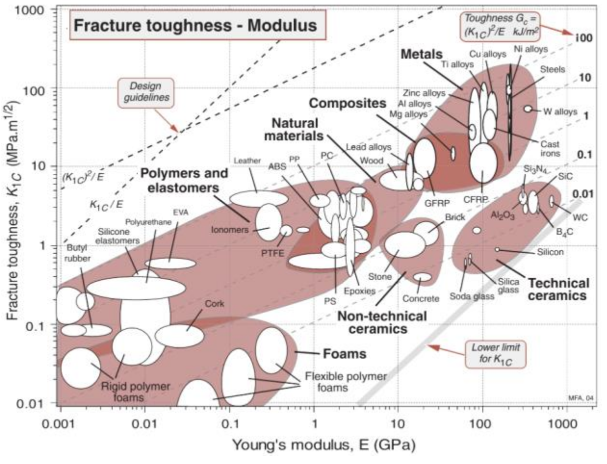
Number of crack sides

Interfacial energy (surface tension)

For linear elastic material:

$$G_c = \frac{K_c^2}{E} \quad \left[{kJ}/{m^2} \right]$$

Toughness Materials Index



Apparent critical energy release rate

Measured fracture toughness

$$G_C = \frac{K_{1C}^2}{E}$$

Measure elastic (Young's) modulus

First example of *material index* as function of 2 properties

Homework

Estimate the flaw size responsible for failure of a titanium fan blade that fractures at 900 MPa

Summary

- Toughness
  - Measure of work done to cause failure
  - Usually describes propensity for fracture
  - Brittle materials have low toughness

  G_c = toughness (sometimes: *critical strain energy release rate*); units kJ/m^2

  $K_{Ic} = (EG_c)^{1/2}$ = fracture toughness (sometimes: *critical stress intensity factor*); units $MN\ m^{-3/2}$

  $K = \sigma(\pi a)^{1/2}$ = stress intensity factor; units $MN\ m^{-3/2}$
- Cracks grow when $K = K_{Ic}$

Properties of Materials

Theme: Observed Properties

Lecture 5: Hardness and Wear

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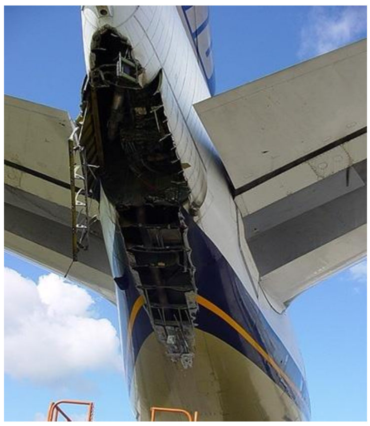
Wear

- Gradual accumulation of damage upon sliding contact of *two* surfaces

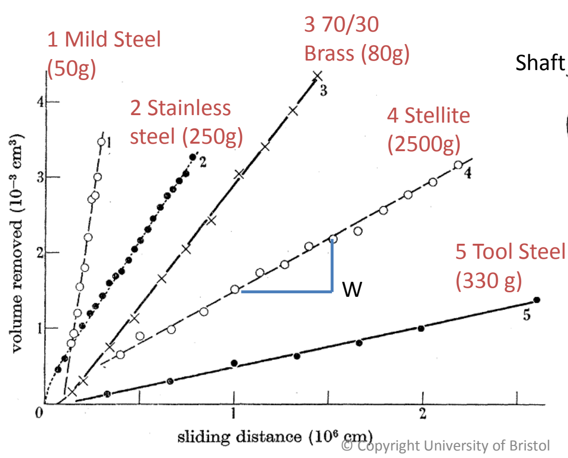


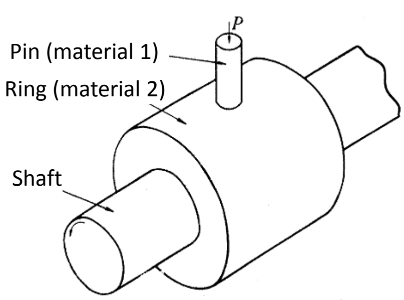
Tail-strike damage to a Singapore airlines B747

- Associated with friction and absence of lubrication
- Enormous impact on economics and productivity
  - Some estimates 5% lost GDP from wear and corrosion
- Tribology (science of surfaces) is *really* complex!
  - Chemistry, mechanics, physics

Wear Rate

$$W = \frac{\text{Volume of material removed}}{\text{Distance slid}}$$

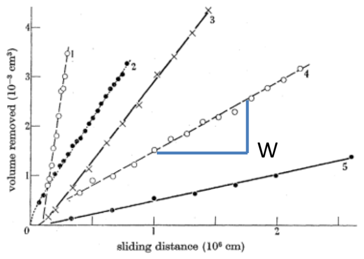




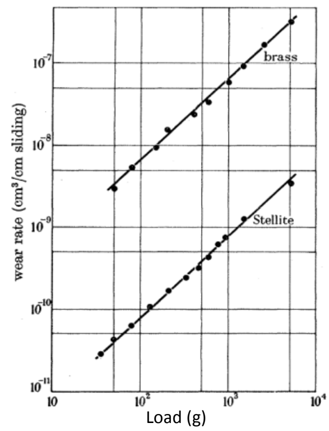
Graph for self wear (pin material = ring material) without lubrication

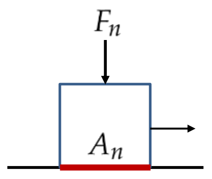
Other combinations have different rates (see friction)

Wear Rate



These experiments are very time consuming and sensitive to experimental error





Specific wear rate

$$\Omega = \frac{W}{A_n}$$

Wear rate

Nominal contact area

Wear rate

Specific wear rate

Wear rate constant

$$k_a = \frac{W}{F_n} = \frac{\Omega}{P}$$

Down force

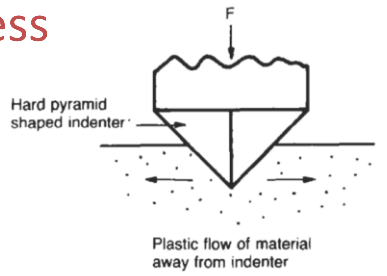
Down pressure (F_n/A_n)

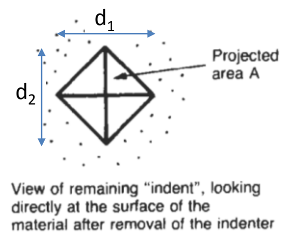
Hardness

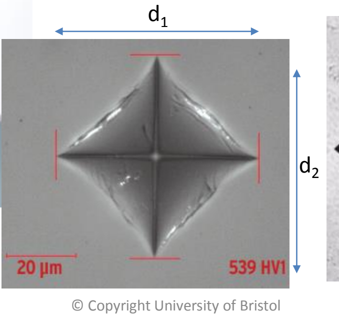
- Resistance to local plastic deformation
  - Meaning not as precise as strength or stiffness
- Excellent comparative measure

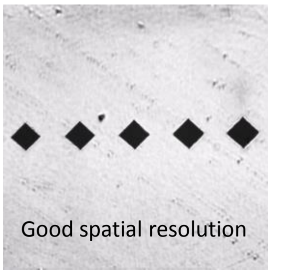
Origin in scratch test

Hardness









Hardness

$$HV = 1.854\frac{P[kg]}{d^2[mm^2]}$$

Present without units

Standard gravity (9.807)

$$HV = 1.854\frac{\overbrace{Pg}^{kgf \to N}}{\underbrace{1\times10^{-6}d^2}_{mm^2 \to m^2}} \times \underbrace{1\times10^{-6}}_{Pa \to MPa} = 18.19\frac{P}{d^2}[MPa]$$

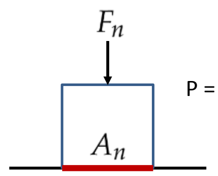
Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide	D, d	d	P	$HB = \frac{2P}{\pi D[D-\sqrt{D^2-d^2}]}$
Vickers microhardness	Diamond pyramid	136°	d_1, d_1	P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid	t; $l/b = 7.11$, $b/t = 4.00$	b, l	P	$HK = 14.2P/l^2$
Rockwell and superficial Rockwell	Diamond cone; $\frac{1}{16}$-, $\frac{1}{8}$-, $\frac{1}{4}$-, $\frac{1}{2}$- in.-diameter steel spheres	120°		60 kg, 100 kg, 150 kg: Rockwell; 15 kg, 30 kg, 45 kg: Superficial Rockwell	

Note load in obsolete kgf (use kg mass)

[a]For the hardness formulas given, P (the applied load) is in kg, whereas D, d, d_1, and l are all in mm.

Hardness and Wear

Properties acting on similar length scales



$P = F_n/A_n$

Max pressure on surface before yielding

Constant

Hardness of softer surface

$$P_{max} = CH$$

Specific wear rate

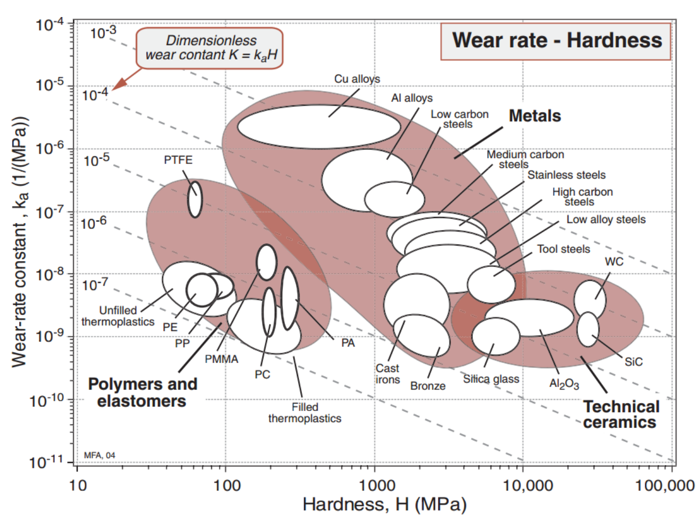
$$\Omega = k_a P = C\left(\frac{P}{P_{max}}\right) k_a H$$

Wear rate constant

Ratio of current pressure to max pressure

Hardness and Wear

Harder materials have a smaller wear rate



Summary

- Hardness
  - Resistance to local deformation
  - Cheap, non-destructive, easy
  - Physically challenging to interpret
- Wear resistance
  - Very difficult property to understand and quantify in industrially relevant manner
  - Typically assumed to correlate to hardness

Materials 1: Properties of Materials

- What are 1 or 2 things that supported your learning in these lectures?
- Please offer 1 or 2 suggestions that could have been done differently to support your learning.

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