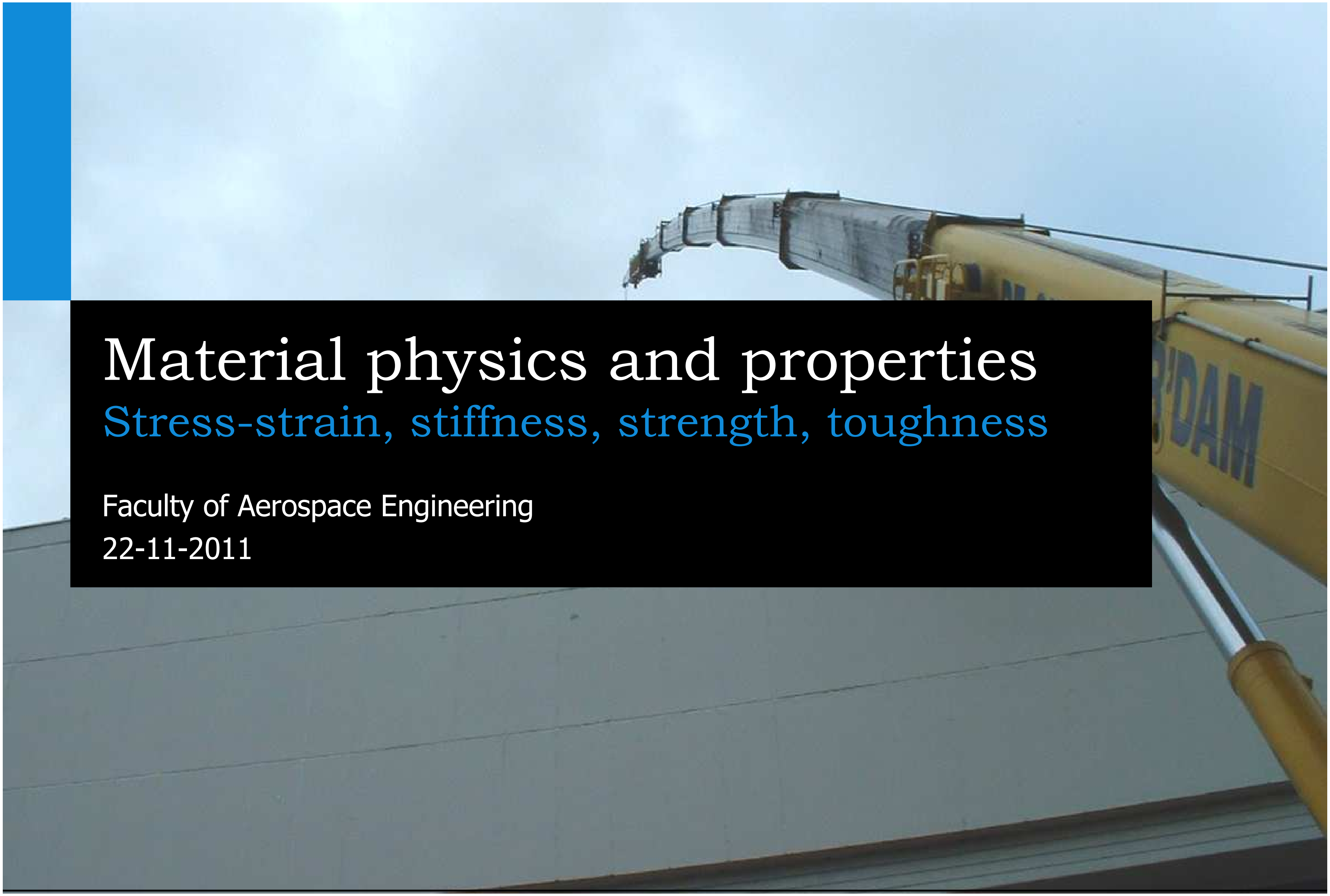
Introduction to Aerospace Engineering

Lecture slides



Material physics and properties

Stress-strain, stiffness, strength, toughness

Faculty of Aerospace Engineering

22-11-2011

TU Delft
Delft University of Technology

Introduction

Outline of lectures/lecturer

- 15/11 Material physics & properties / environment
- 22/11 Structures
- 29/11 Loads
- 6/12 Materials & manufacturing
- 13/12 Selection of materials & structures / space
- 20/12 Design & certification / fatigue & durability

- 6/1 Manufacturing & joining

- Lecturer
  - Name: R.C. Alderliesten
  - Room: NB0.45
  - Email: R.C.Alderliesten@tudelft.nl

Learning objectives

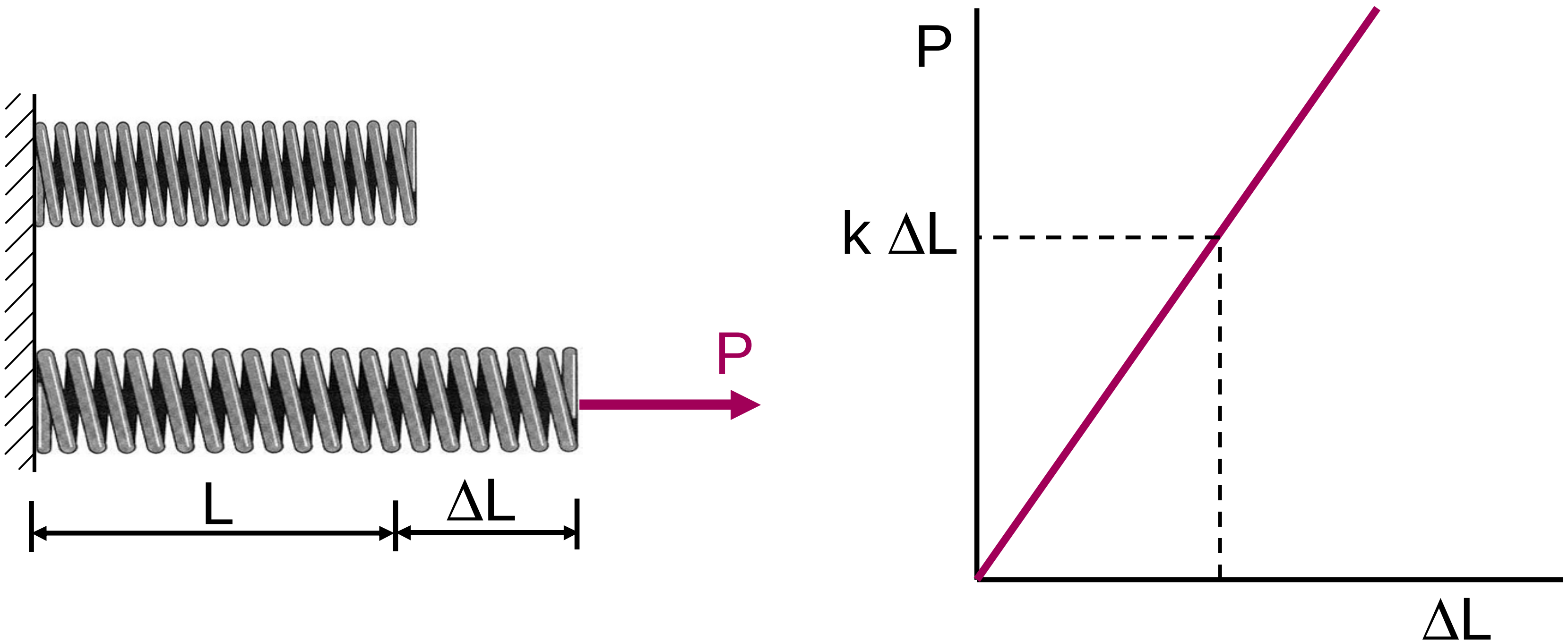
Student should be able to…

- Describe the concept of stress and strain
- Describe the definitions of
    - Strength
    - Stiffness
    - Toughness
    - Uni-axial & bi-axial loading
    - Isotropy and anisotropy

Stress and strain

Definitions

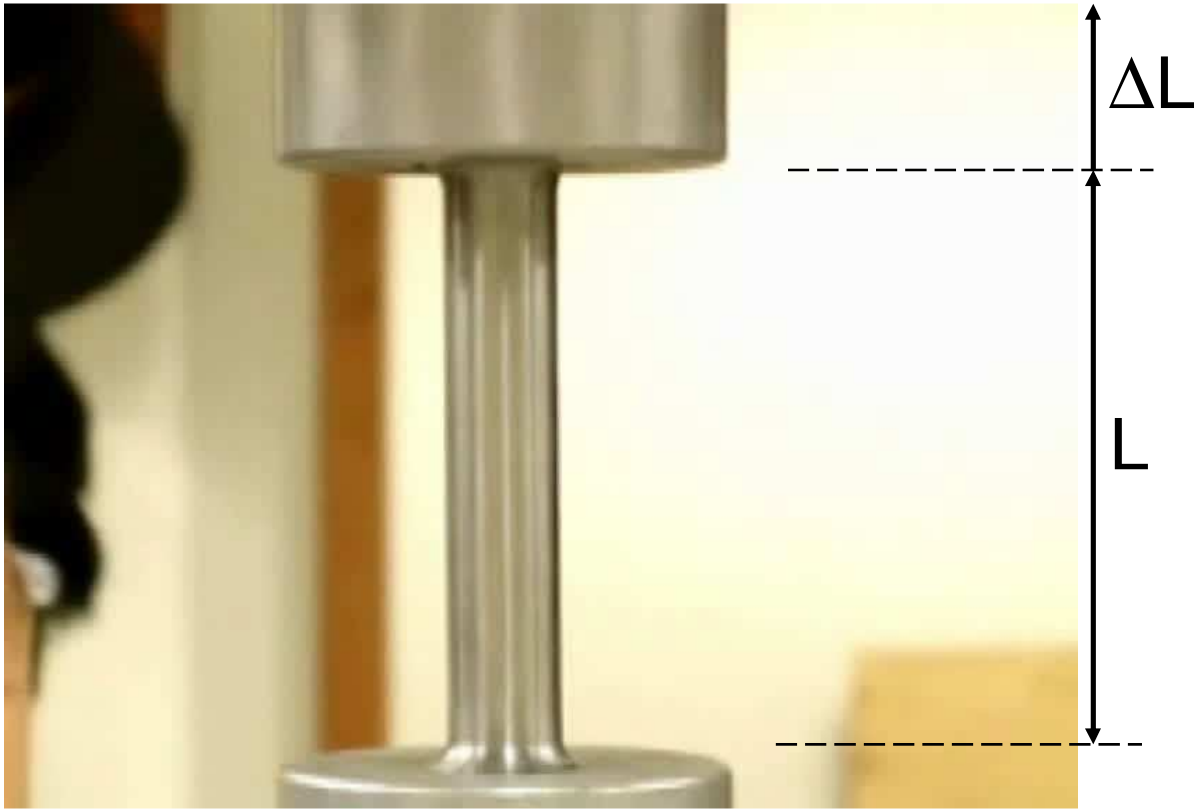
- Consider a spring
  - The resistance against loading is given by the spring constant *k*



Stress and strain

Definitions

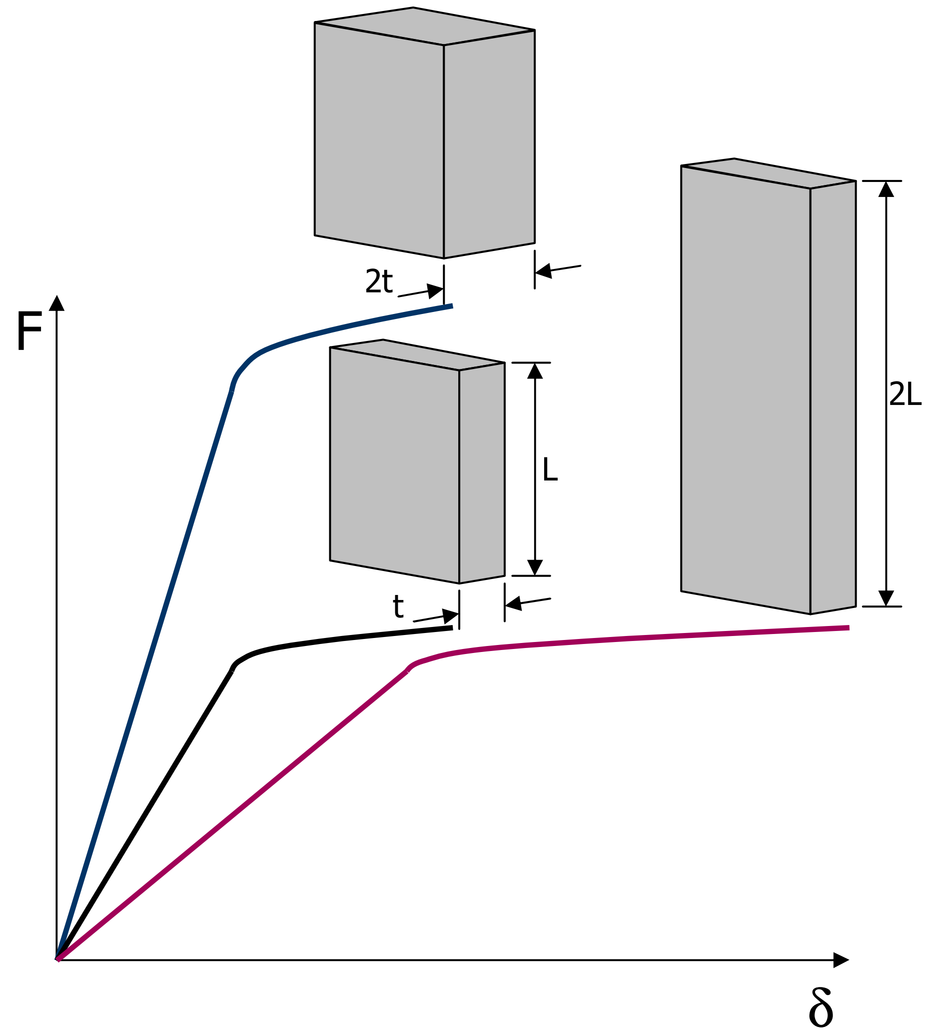
- Loading a material…



Stress and strain

Definitions

- Loading a material…

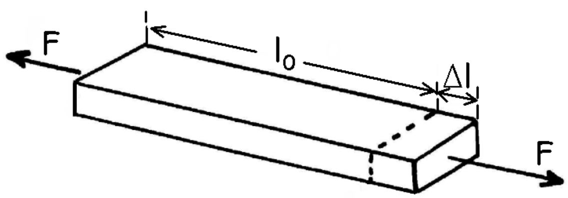


Stress and strain

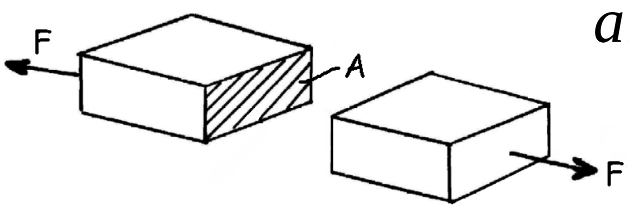
Definitions

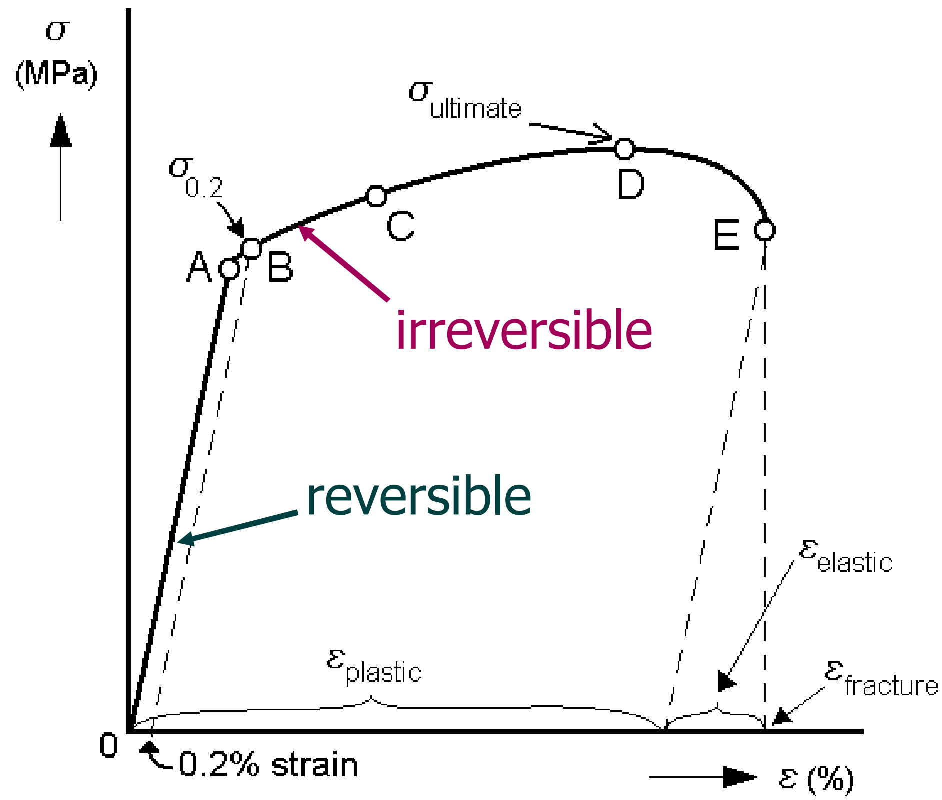
- Material acts as spring

$$strain\ \varepsilon \equiv \frac{elongation\ \Delta l}{initial\ length\ l_0}$$



$$stress\ \sigma \equiv \frac{force\ F}{area\ A}$$

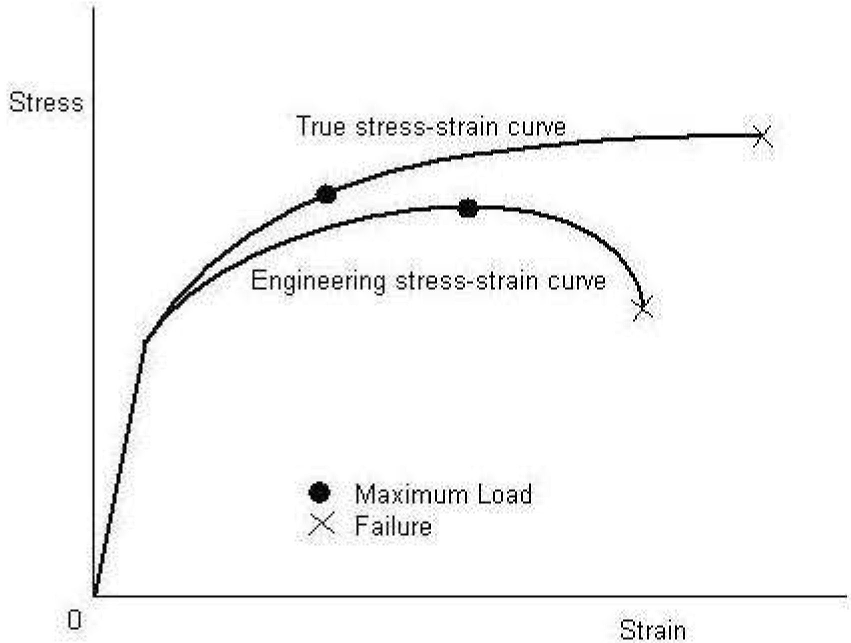




Stress and strain

Definitions

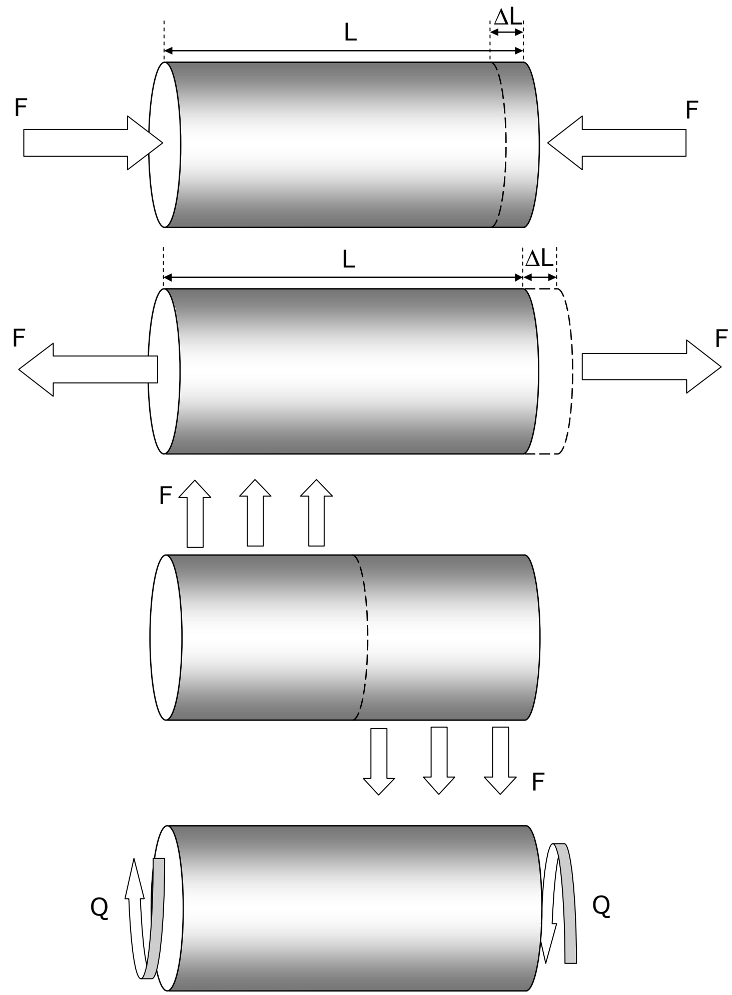
- Engineering stress and true stress
  - Engineering stress = load/nominal cross section
  - Necking: reduction in cross-section -> increase or true stress



Stress and strain

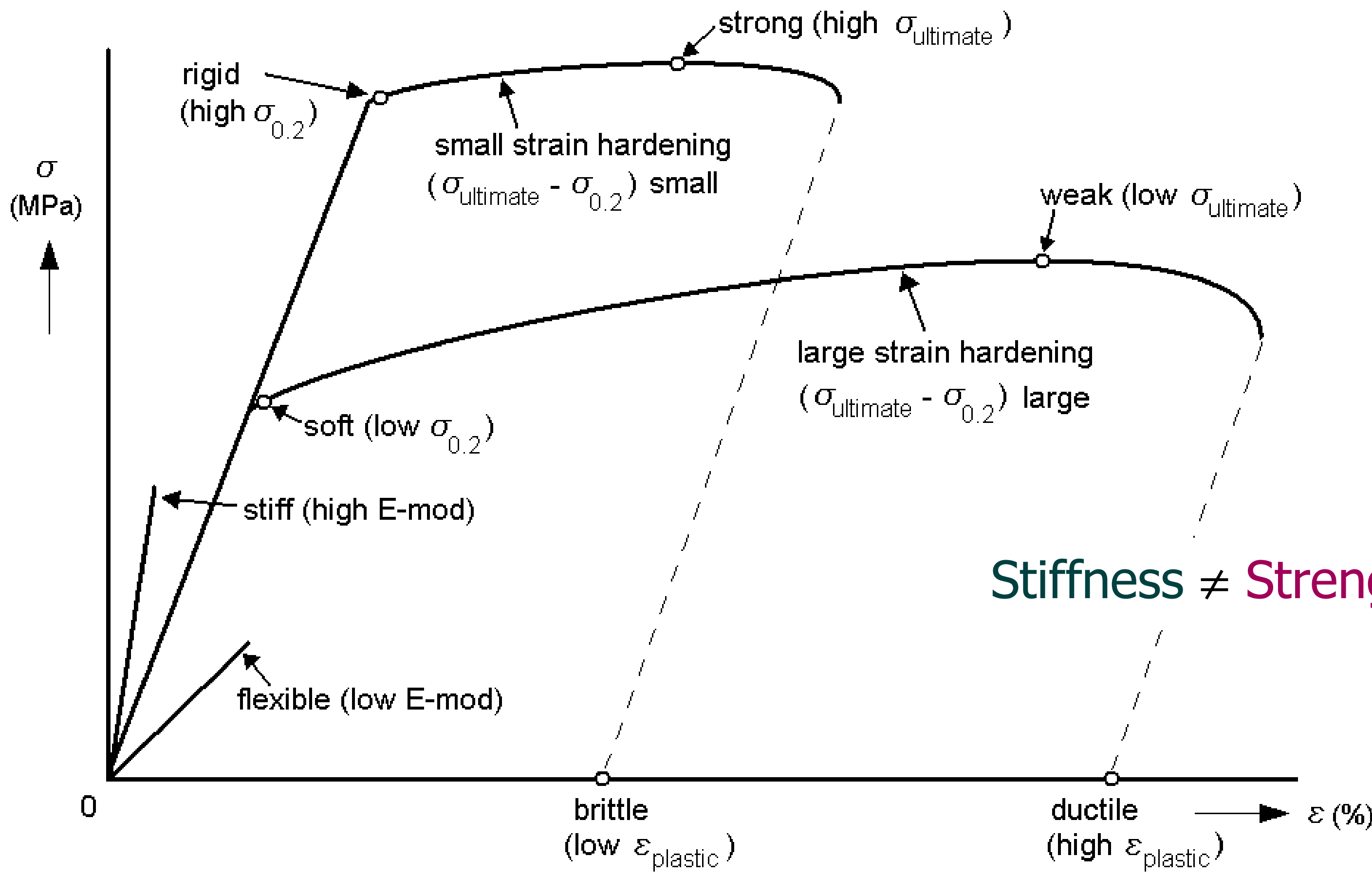
Categories

- Compression
- Tension
- Shear
- Torsion



Stress – strain diagram

Engineering terminology

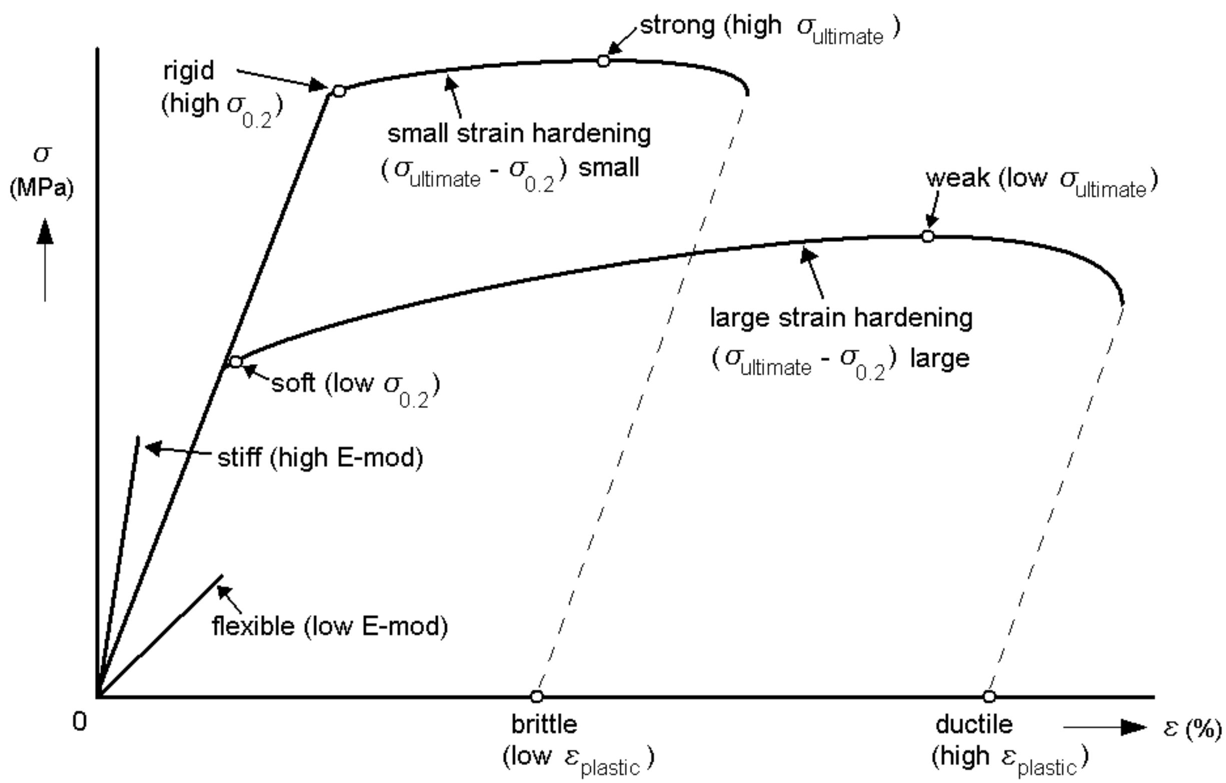


Stiffness ≠ Strength !!

Stiffness & Strength

Example: Helios

Stiffness ≠ Strength !!



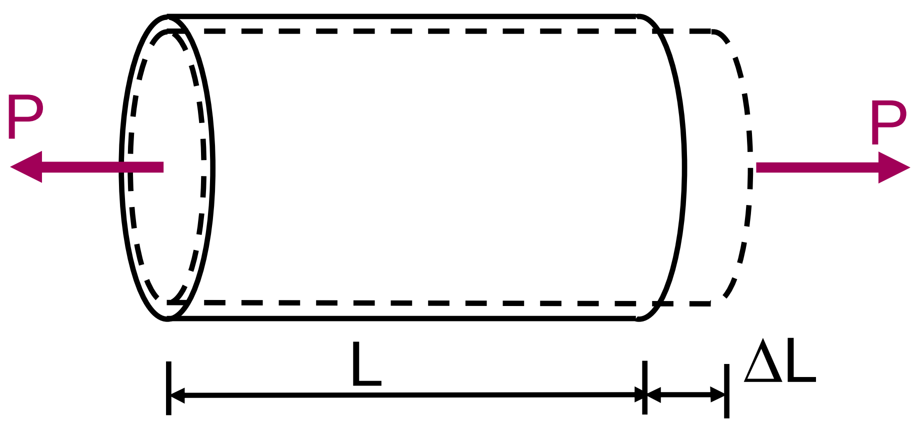
Normal stresses

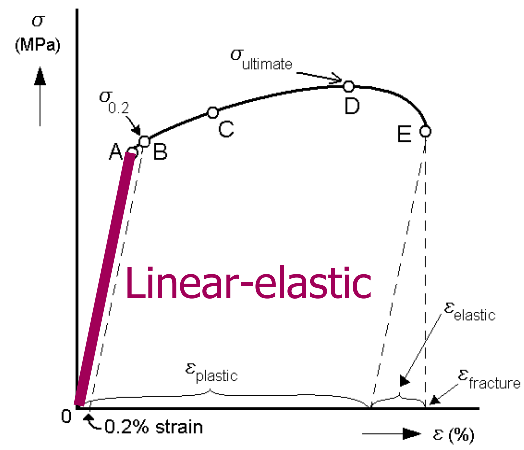
Tension & compression

- Linear-elastic uni-axial stress-strain condition in structure

$$\sigma_l = \frac{F}{A} \qquad \varepsilon_l = \frac{\sigma_l}{E}$$

- Consider elongating rubber





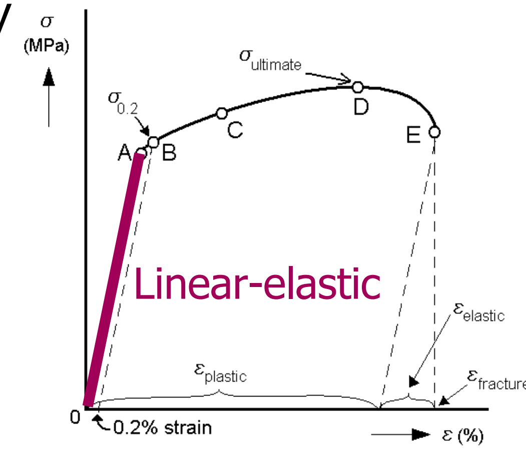
Normal stresses

Tension & compression

- Linear-elastic uni-axial stress-strain condition in structure

$$\sigma_l = \frac{F}{A} \qquad \varepsilon_l = \frac{\sigma_l}{E}$$

  - E is Young's modulus, is a measure for material resistance against imposed elastic deformation, modulus of elasticity



- In transverse direction

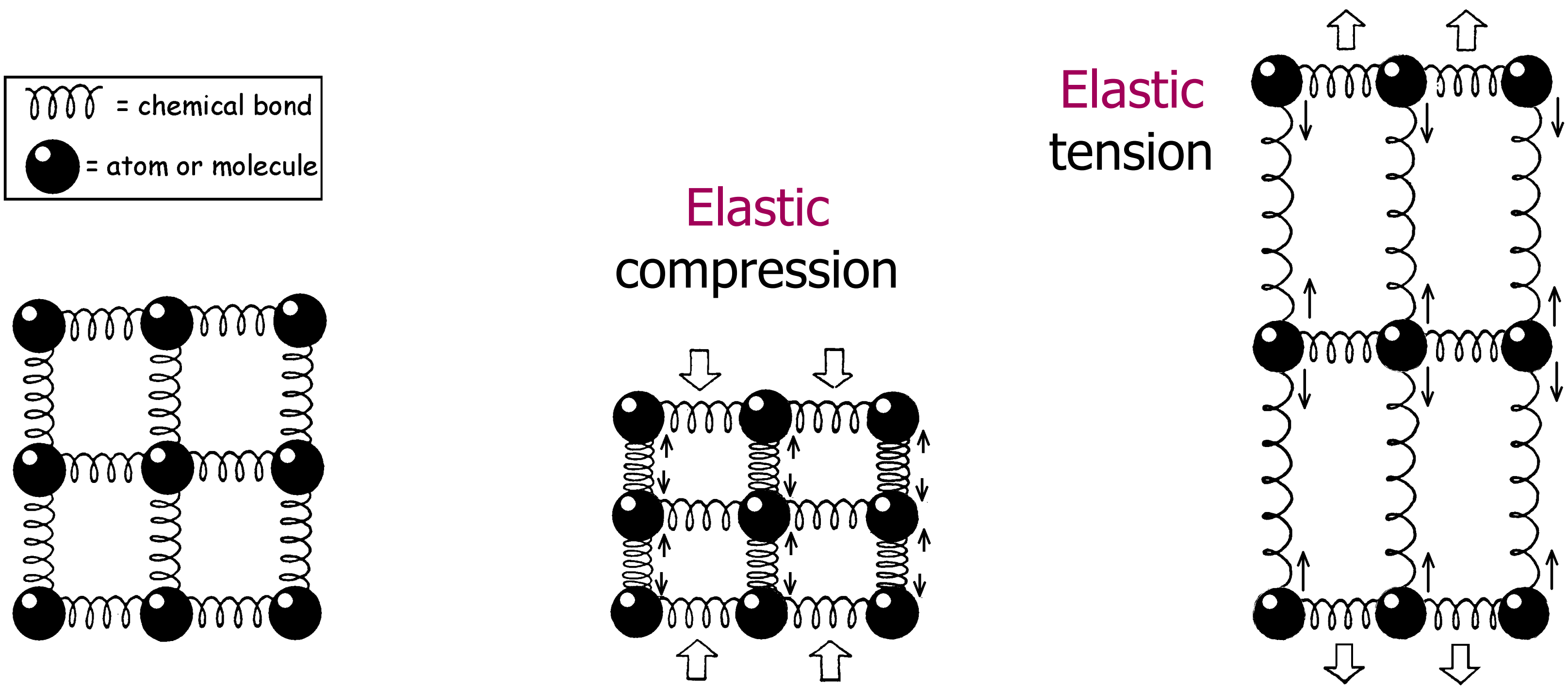
$$\varepsilon_t = -\nu\varepsilon_l = -\nu\frac{\sigma_l}{E}$$

  - ν is Poisson's ratio (transverse contraction)
  - ν and E characterize the linear elastic behavior of a material

Normal stresses

Chemical bonds

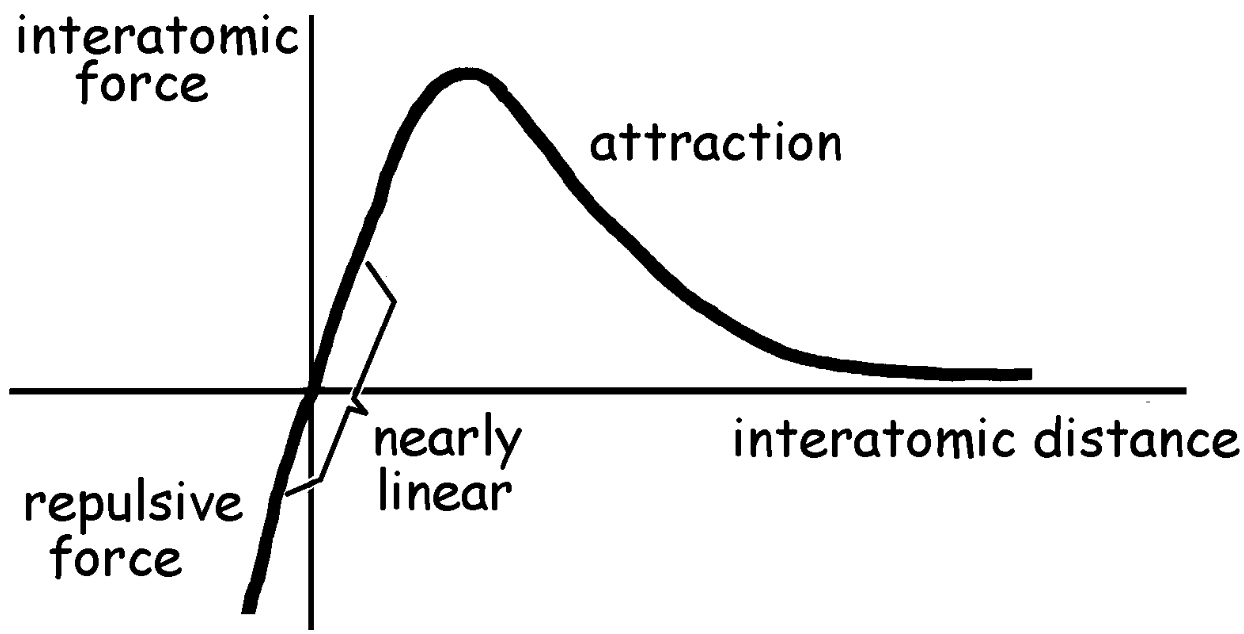
- All materials deform under a load, although deformations can be very small



Normal stresses

Chemical bonds

- Elastic ⇒ stretching of chemical bond (reversible)
- Plastic ⇒ breaking the chemical bond (irreversible)



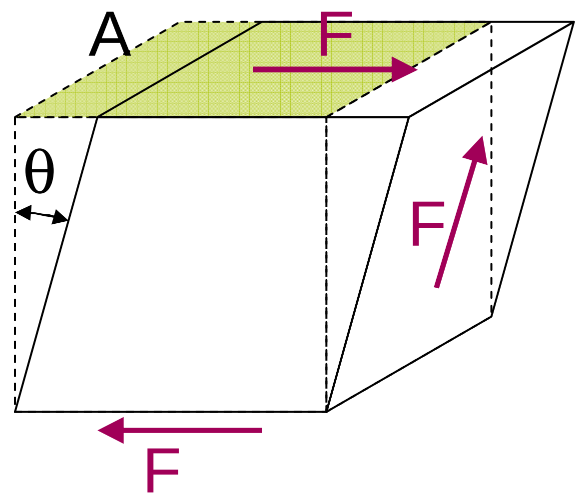
Shear stresses

Element deformation

- Elastic uni-axial stress-strain condition in structure

$$\tau = \frac{F}{A} \qquad \gamma = \frac{\tau}{G}$$

  - F is force to upper and lower area A
  - γ is engineering (total) shear strain (equal to $\tan\theta$)



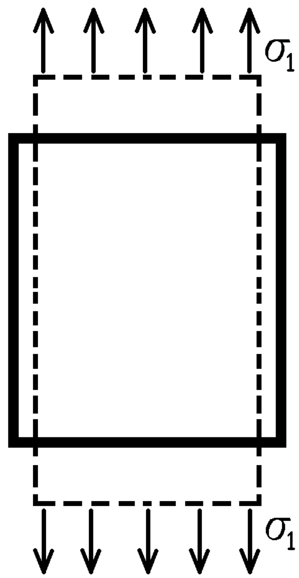
Normal stresses

Sheet material

- Longitudinal loading

$$\varepsilon_l = \frac{\sigma_l}{E}$$

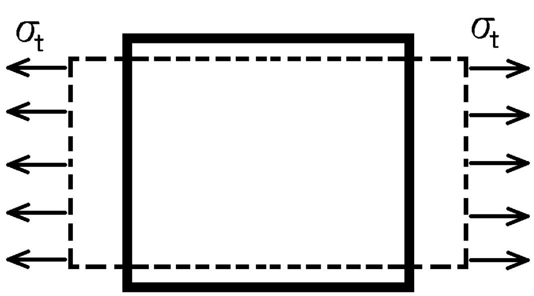
$$\varepsilon_t = -\nu \frac{\sigma_l}{E}$$



- Transverse loading

$$\varepsilon_t = \frac{\sigma_t}{E}$$

$$\varepsilon_l = -\nu \frac{\sigma_t}{E}$$



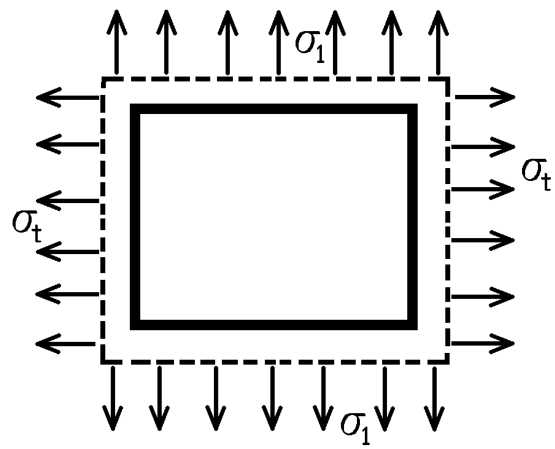
Normal stresses

Sheet material

- Biaxial loading
  - Superposition of stress or strain

$$\varepsilon_l = \frac{\sigma_l}{E} - \nu \frac{\sigma_t}{E}$$

$$\varepsilon_t = \frac{\sigma_t}{E} - \nu \frac{\sigma_l}{E}$$



⇒ Hooke's law for biaxial stress condition

Normal stresses

Sheet material

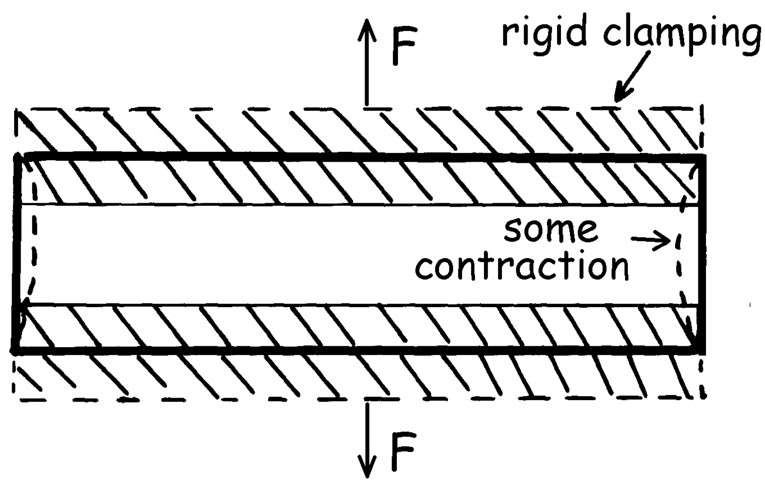
- Stiffness and apparent stiffness
  - Tension on a sheet with large width: rigid clamping hinders the transverse contraction: $\varepsilon_t = 0$

$$\varepsilon_t = \frac{\sigma_t}{E} - \nu \frac{\sigma_l}{E} = 0$$

  - A transverse stress is introduced

$$\sigma_t = \nu \sigma_l$$

with σ_l is applied stress

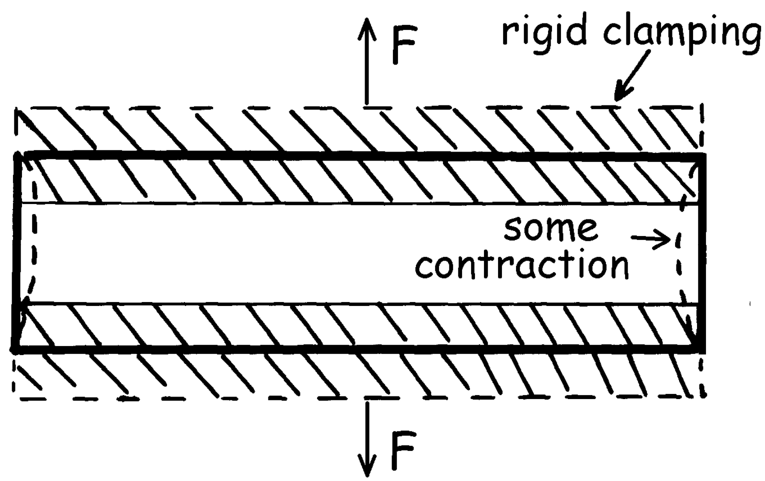


Normal stresses

Sheet material

- Stiffness and apparent stiffness
  - Strain in loading direction

$$\varepsilon_l = \frac{\sigma_l}{E} - \nu \frac{\sigma_t}{E} = \left(1-\nu^2\right)\frac{\sigma_l}{E}$$



  - Strain in a regular tensile test

$$\varepsilon_l = \frac{\sigma_l}{E}$$

  - Apparent stiffness is about 10% higher

$$E' = \frac{1}{1-\nu^2} E$$

Isotropic sheet material

Sheet deformation

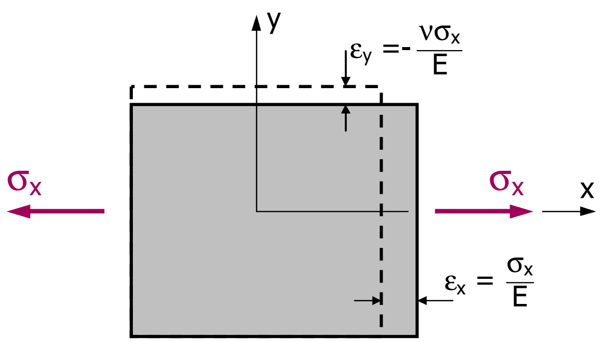
- Recall

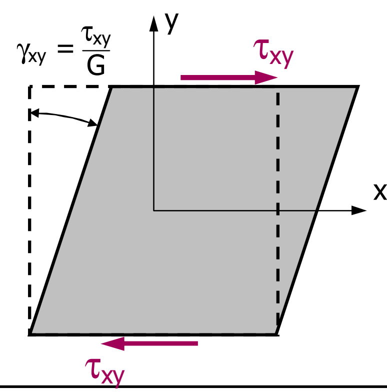
$$\varepsilon_l = \frac{\sigma_l}{E} - \nu \frac{\sigma_t}{E}$$

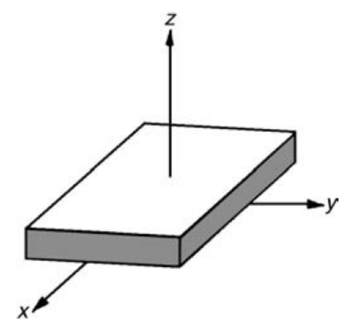
$$\varepsilon_t = \frac{\sigma_t}{E} - \nu \frac{\sigma_l}{E}$$

$$\gamma = \frac{\tau}{G}$$

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix} = \begin{bmatrix} \frac{1}{E} & \frac{-\nu}{E} & 0 \\ \frac{-\nu}{E} & \frac{1}{E} & 0 \\ 0 & 0 & \frac{1}{G} \end{bmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix}$$



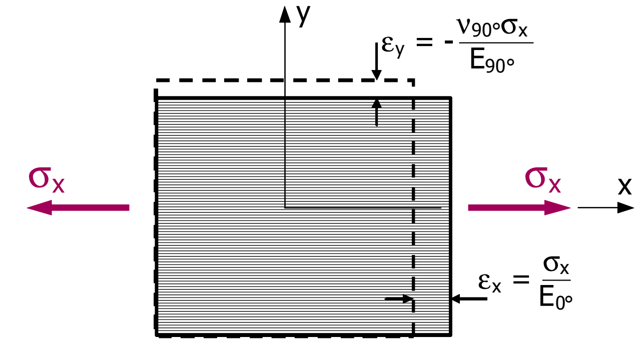


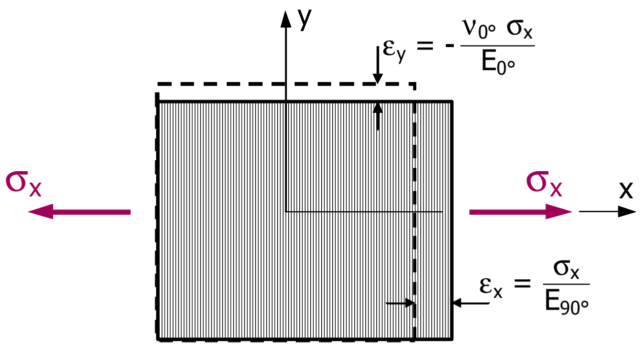


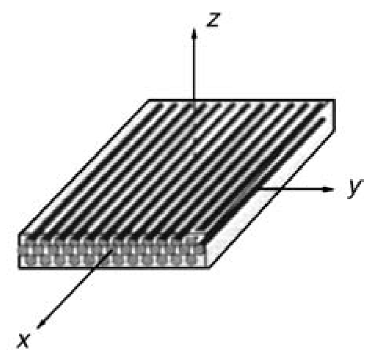
Anisotropic sheet material

Sheet deformation

- Recall







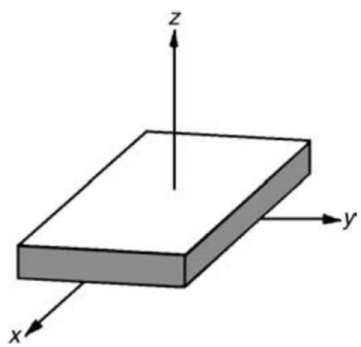
Anisotropic sheet material

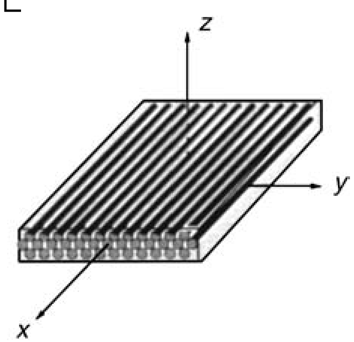
Sheet deformation

- Recall

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix} = \begin{bmatrix} \frac{1}{E} & \frac{-\nu}{E} & 0 \\ \frac{-\nu}{E} & \frac{1}{E} & 0 \\ 0 & 0 & \frac{1}{G} \end{bmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix}$$

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix} = \begin{bmatrix} \frac{1}{E_x} & \frac{-\nu_{yx}}{E_y} & 0 \\ \frac{-\nu_{xy}}{E_x} & \frac{1}{E_y} & 0 \\ 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix}$$



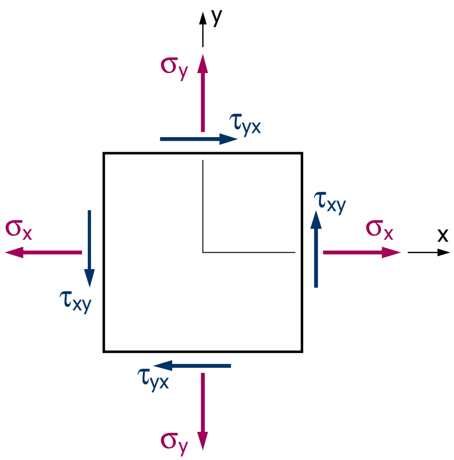


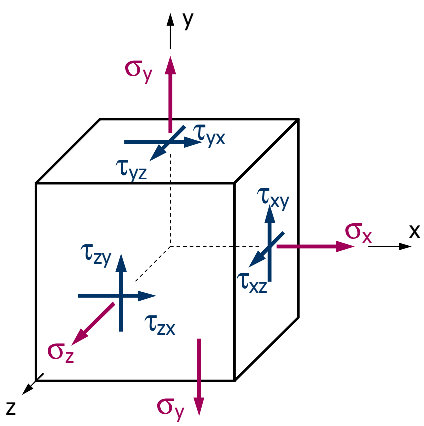
Anisotropic sheet material

Sheet deformation

- UD-properties

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix} = \begin{bmatrix} \frac{1}{E_x} & \frac{-\nu_{yx}}{E_y} & 0 \\ \frac{-\nu_{xy}}{E_x} & \frac{1}{E_y} & 0 \\ 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix}$$



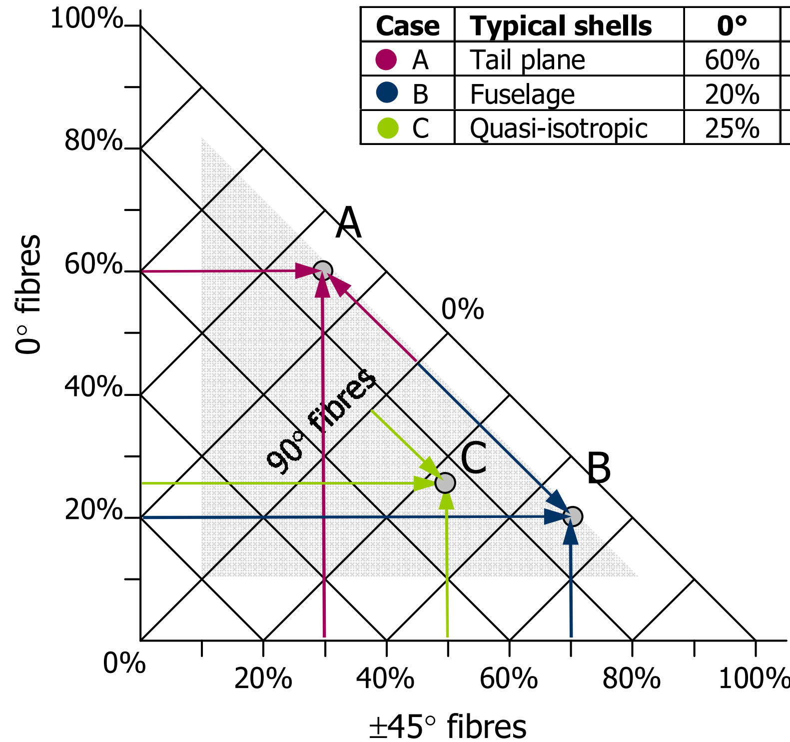


Material	E_x	E_y	$\sigma_{U\,x}$	$\sigma_{U\,y}$
	[kN/mm^2]	[kN/mm^2]	[N/mm^2]	[N/mm^2]
E-glass epoxy UD-60%	45	8	1020	40
HM carbon epoxy UD-60%	220	10	760	40

Anisotropic sheet material

Sheet deformation

- Aircraft structures are designed with cross-ply composites !
- Example
  0°, 90°, ±45° only
- Definition of quasi-isotropy
  - Approximation of isotropy by orienting plies in different directions

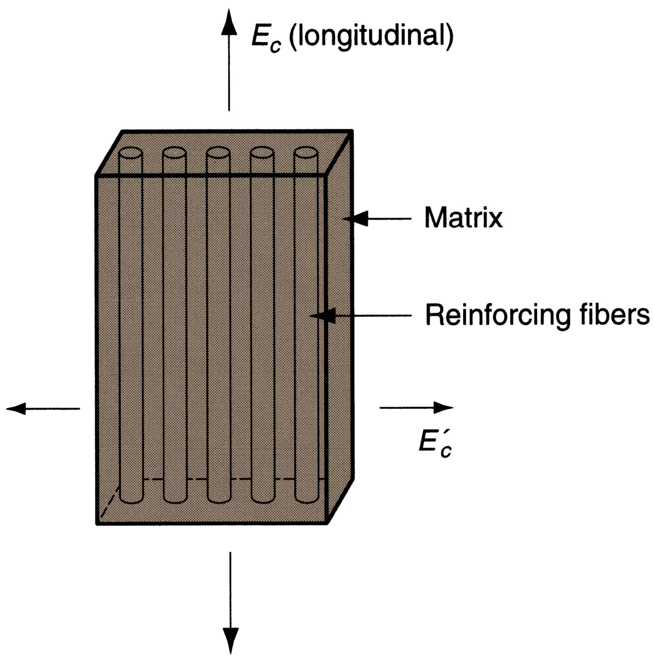


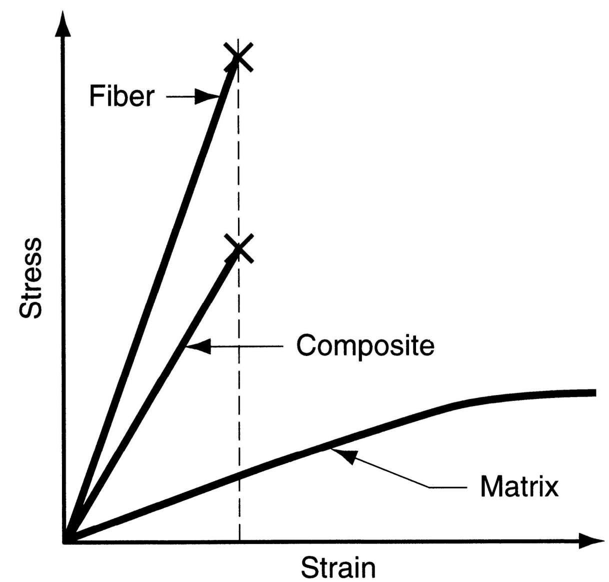
Case	Typical shells	0°	±45°	90°
A	Tail plane	60%	30%	10%
B	Fuselage	20%	70%	10%
C	Quasi-isotropic	25%	50%	25%

Anisotropic sheet material

Sheet deformation

- Stress-strain
  - Young's modulus determined by both fibre & matrix
  - Strain to failure determined by fibre

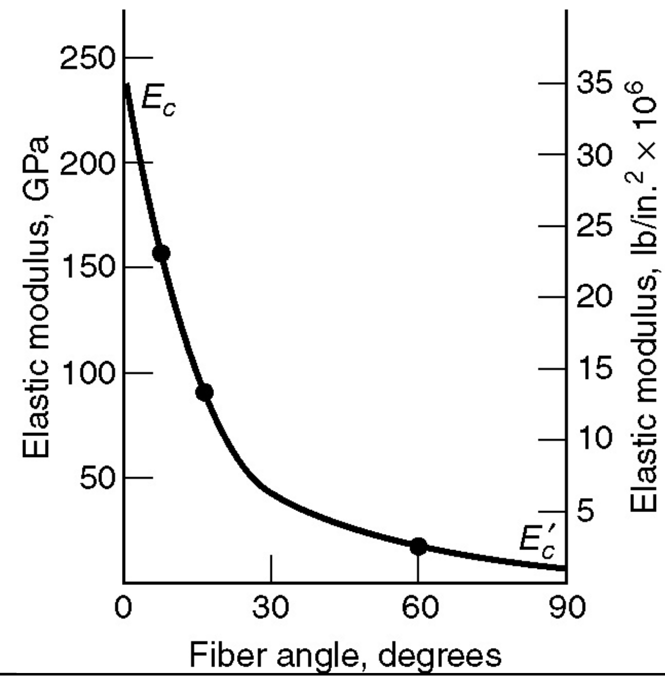


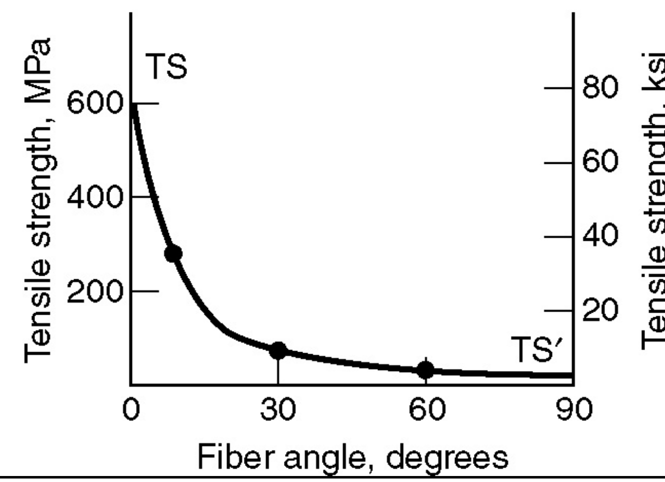


Anisotropic sheet material

Sheet deformation

- Stress-strain
  - Young's modulus and strength measured with respect to longitunial axis of UD carbon-fibre composites

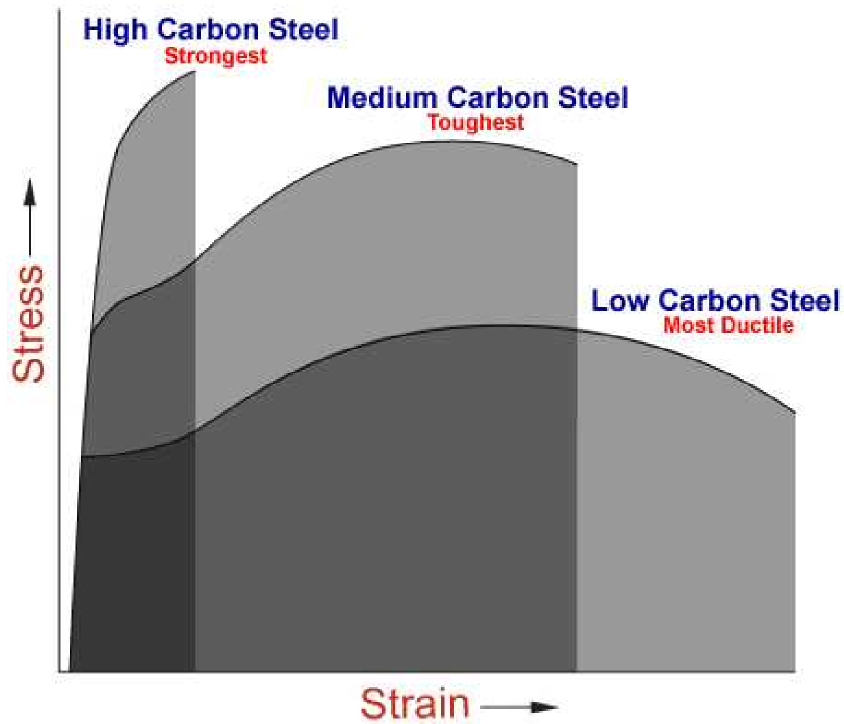




Toughness

Definitions

- Toughness
    - Area under stress-strain curve

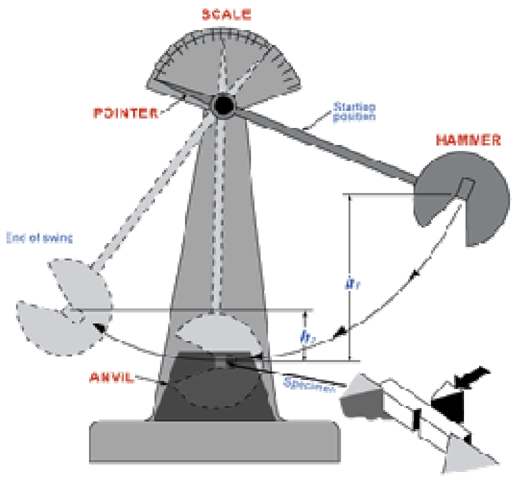


Toughness

Definitions

- Toughness
  - Area under stress-strain curve

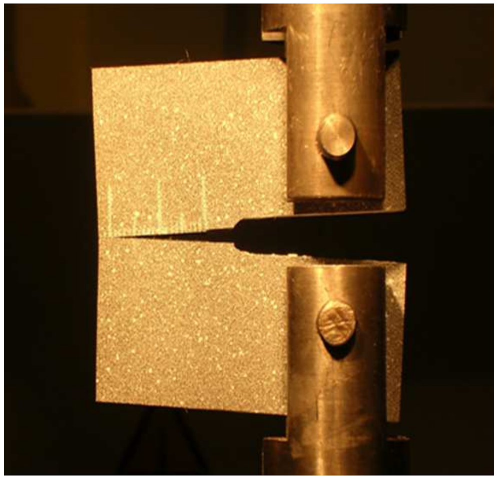
- Impact toughness
  - Energy to fracture a notched specimen

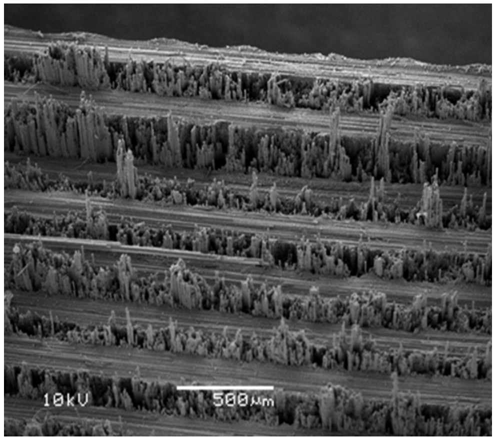


Toughness

Definitions

- Toughness
  - Area under stress-strain curve
- Impact toughness
  - Energy to fracture a notched specimen
- Fracture toughness
  - Measure of energy to fail a specimen containing a crack





Overview of properties

Some typical aerospace materials

Material		Density	E-modulus	Yield strength	Ultimate strength	Maximum strain
		[kg/dm^3]	[kN/mm^2]	[N/mm^2]	[N/mm^2]	[%]
Metals	Carbon steel (norm.)	7.8	207	375	590	28
	HS steel (OQ-Temp)	7.8	207	1620	1760	12
	Pure aluminium (O)	2.7	69	34	90	40
	Al2024-T351	2.8	72	325	470	20
	Al7075-T6	2.8	71	505	572	11
	Pure Titanium (An.)	4.5	103	170	240	30
	Ti-6Al-4V (A.)	4.5	114	830	900	14
Composites	Epoxy (TS)	1.25	2.4	--	60	4.5
	Polyetherketone (PEEK) (TP)	1.31	1.1	91	100	75
	E-glass epoxy UD-60%	2.1	45	--	1020	2.3
	HM carbon epoxy UD-60%	1.7	220	--	760	0.3

Summary

Mechanical properties of materials

- Stress = load/area
- Tension/Compression/Shear/Torsion
- Lateral contraction (Poisson)
- Isotropic and anisotropic material behaviour
- Toughness