Mechanical Properties

Sections 1.2.1-1.2.6, 1.2.8-1.2.9†

† Mamlouk, M.S., and Zaniewski, J.P. (2006). *Materials for Civil and Construction Engineers*, 2nd ed., Prentice Hall

What we are going to talk about …

- Loading Conditions
- Stress
- Strain
- Stress-strain diagram
- Stiffness
- Ductile & brittle materials

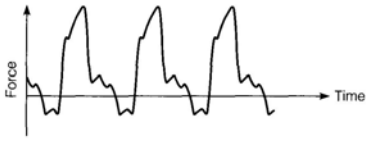
Loading Conditions

- **Static Loading** implies a sustained loading of the structure over a period of time.
  (Weight of the structure (Dead Load) and equipment in the structure).
- Loads that generate a shock or vibration in the structure are **Dynamic Loads**
  (a) Periodic load
  (b) Random Load
  (c) Transient Load

Loading Conditions (cont'd)

(a) Periodic load, such as a harmonic or sinusoidal load, repeats itself with time.

(EX. Rotating equipment in a building).

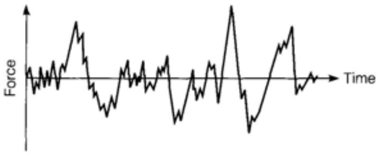


(a)

Loading Conditions (cont'd)

(b) Random Load, In random load, the load pattern never repeats.

(EX. Earthquakes)



(b)

Loading Conditions (cont'd)

(c) Transient Load is an impulse load that is applied over a short time interval after that the system returns to rest.

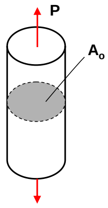
(EX. Bridges must be designed to withstand the transient loads of trucks).

(c)

Stress

- Amount of load a material carries *per unit of cross-sectional area*

$$\sigma = \frac{P}{A_o}$$



Units of Stress

- SI Units

$$1 \text{ Pa} = \frac{\text{N}}{\text{m}^2} \qquad 1 \text{ MPa} = 10^6 \text{ Pa} = \frac{\text{N}}{\text{mm}^2}$$

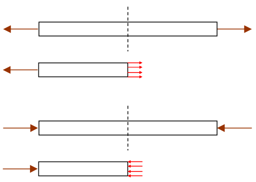
- U.S. Customary Units

$$1 \frac{\text{lb}}{\text{ft}^2} \text{ (psf)} = 47.88 \text{ Pa}$$

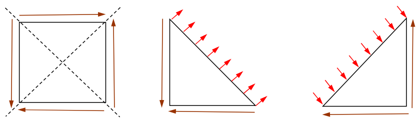
$$1 \frac{\text{lb}}{\text{in}^2} \text{ (psi)} = 6.895 \text{ kPa}$$

Types of Stresses

- Normal
  - Tension
  - Compression



- Shear



Example 1

- We want to suspend a 7.7 kg bowling ball from a 1.5 m long piece of steel. There are 2 options:
  - Piano wire of 0.40 mm diameter
  - Threaded rod of 6.4 mm diameter
- We conduct an experiment and find out that the piano wire breaks. Why?

Same material, same length, but …

Example 1 (cont'd)

Different diameter → different cross-sectional area

$$A_0 \text{ (wire) } = \frac{\pi d^2}{4} = 0.126 \text{ mm}^2$$

$$A_0 \text{ (rod) } = \frac{\pi d^2}{4} = 32.2 \text{ mm}^2$$

A_0 (rod) ~ 255 A_o (wire)

Example 1 (cont'd)

$$\sigma \text{ (wire) } = \frac{P}{A_0} = 611 \text{ MPa}$$

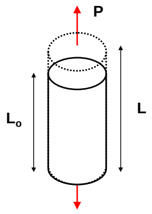
$$\sigma \text{ (rod) } = \frac{P}{A_0} = 2.4 \text{ MPa}$$

- By increasing the diameter of the bar, we decrease the stress for a constant P
- Increasing the load, increases the stress for a constant A_0

Strain

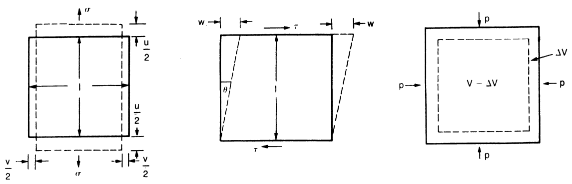
- Material's deformation *per unit length*

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



Types of Strain

$$\varepsilon_n = \frac{u}{l} \qquad \gamma = \frac{w}{l} = \tan\theta \qquad \Delta = \frac{\Delta V}{V}$$



Tensile Strain **Shear Strain** **Dilation**

Units of Strain

- Dimensionless
- Often expressed as:
  - m/m
  - radians

Example 2

- Suppose our wire in fact did not break, but stretched to 1.53 m. What is the strain?

$$\varepsilon\text{ (wire) } = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0}$$
$$= \frac{1.53 - 1.50}{1.50} = 0.02\text{ (m/m)}$$
$$= 2\%$$

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Engineering Stress & Strain

- Based on original dimensions A_o & L_o
- At small strains, these values are adequate descriptions of the deformation

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True Stress & Strain

- Since area changes as specimen deforms, engineering stress is not a correct measure of stress at higher strains
- True stress & strain represent *actual* area and incremental change in length

$$\sigma_t = \frac{P}{A}$$
$$\varepsilon_t = \int_{L_0}^{L} \frac{1}{L} dL = \ln \frac{L}{L_0}$$

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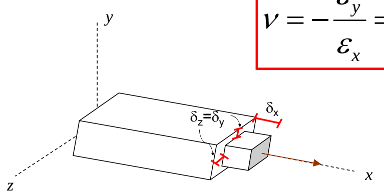
Poisson's Ratio



$$\nu = -\frac{\varepsilon_y}{\varepsilon_x} = -\frac{\varepsilon_z}{\varepsilon_x}$$

Isotropic material $0 \le \nu \le 0.5$

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Poisson's Ratio (cont'd)

$$\varepsilon_{transverse} = -\nu\, \varepsilon_{longitudinal}$$

- For most construction materials, ν ranges from 0.15 to 0.4
  - Concrete 0.1 - 0.2
  - Steel 0.27 - 0.3

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Stress-Strain Diagram

- Defines how a material will respond to load without regard for material's physical size or shape
- Obtained from testing in tension or compression
- From σ-ε curve, we can find a number of important mechanical properties

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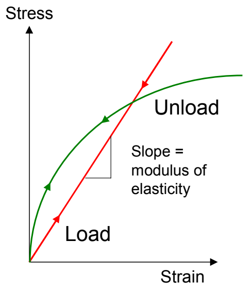
Elastic Behaviour

- Elastic deformation is recoverable
- In most materials, elastic deformation is linear
- In *some* materials, elastic deformation is non-linear



Modulus of Elasticity

$$E = \frac{\sigma}{\varepsilon} \quad \text{(Pa)}$$

- Three moduli corresponding to 3 stresses:
  - Tension } Young's modulus
  - Compression } Young's modulus
  - Shear → Modulus of rigidity

$$\tau = G\gamma \qquad G = \frac{E}{2(1+\nu)} \text{(Pa)}$$

Table 1.1 Typical Modulus and Poisson's Ratio Values (Room Temperature)

TABLE 1 . 1	*Typical Modulus and Poisson's Ratio Values (Room Temperature)*	
Material	*Modulus GPa (psi x 10^6)*	*Poisson's Ratio*
Aluminum	69-75 (10-11)	0.33
Brick	10-17 (1.5-2.5)	0.23-0.40
Cast iron	75-169(11-23)	0.17
Concrete	14-40(2-6)	0.11-0.21
Copper	110(16)	0.35
Epoxy	3-140 (0.4-20)	
Glass	62-70(9-10)	0.25
Limestone	58 (8.4)	
Rubber (soft)	0.001-0.014 (0.00015-0.002)	0.49
Steel	207(30)	0.27
Tungsten	407 (59)	0.28
Wood	6-15 (0.9-2.2)	

Example 2

- A rod made of aluminum alloy, with a gauge length of 100 mm, diameter of 10 mm, and yield strength of 150 MPa, was subjected to a tensile load of 5.85 kN. If the gauge length was changed to 100.1 mm and the diameter was changed to 9.9967 mm, calculate the modulus of elasticity and Poisson's ratio.

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Example 3

- A series of steel specimens are being tested in tension for possible use as a structural component. A strain gauge on one of the specimens measures a strain of 0.00032 at a time when the load cell on the test frame indicates a load of 5.2 kN. At the start of the test, the strain gauge reads 0.00001 while the load cell reads 0.102 kN. The test specimen has a cross-section of 3×25 mm and a length of 152 mm. Calculate the **elastic modulus**.

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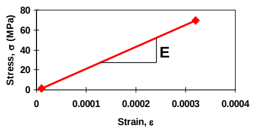
Example 3 (cont'd)

$$A = 3\times 25 = 75\ \text{mm}^2$$

ε	P (kN)	σ (MPa)
0.001%	0.102	1.36
0.032%	5.2	69.3

$$E = \frac{69.3-1.4}{0.00032-.00001} = \frac{67.9}{3.1\times 10^{-4}} = 219\ \text{GPa}$$



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Hooke's Law

- Most engineering structures are designed to undergo relatively small deformations → *linear elastic behaviour*

$$\sigma = E\varepsilon$$

- Robert Hooke (17th century, England)
  - found that the elongation of a spring was proportional to the applied force

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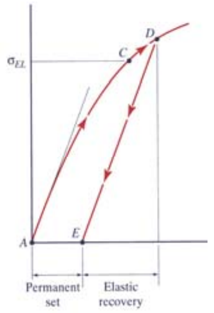
Plastic Behaviour

- Non-recoverable deformation



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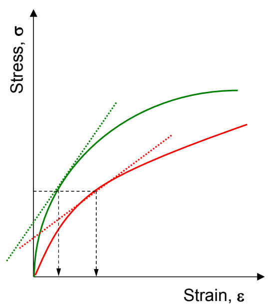
Stiffness

- Relative measure of deformability of a material under load
- Measured by the rate of stress with respect to strain
  - slope of σ-ε curve



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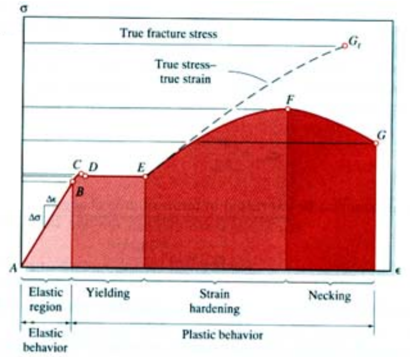
Steel σ-ε Curve



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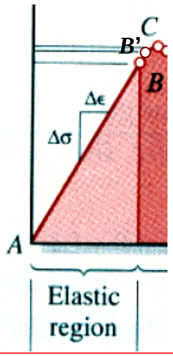
Elastic Region

- σ_B → proportional limit

  (max. stress below which σ/ε is constant)
- $\sigma_{B'}$ → elastic limit

  (max. stress under which material remains elastic)
- B & B' usually assumed to be the same



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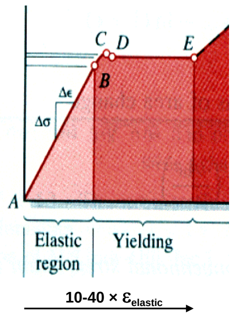
Yielding

- σ_C → yield stress or yield point σ_Y
- Deformation beyond C is permanent → plastic deformation
- Often 2 values define σ_Y:
  - upper yield point, C
  - lower yield point, D
- D-E → perfectly plastic material



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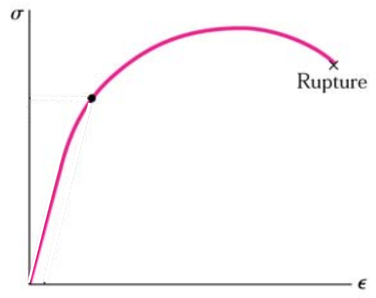
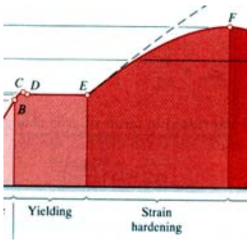
Yield Point – Offset Method



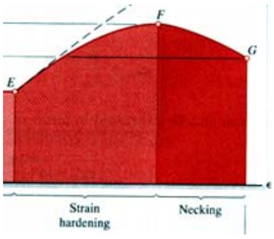
Strain Hardening

- Stress begins to increase at E
- σ_F → ultimate stress σ_u
- E-F → strain hardening zone

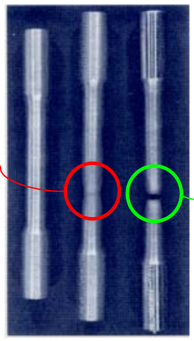


Necking

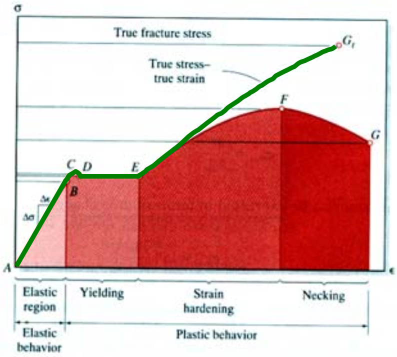
- At F the stress begins to drop as the specimen begins to "neck down."
- σ_G → fracture stress σ_f



Necking (cont'd)



Steel True σ- True ε Curve



Ductile Materials

- Undergo large strains before fracture
- Chosen for design because:
  - they are capable of absorbing shock or energy
  - if overloaded, they exhibit large deformation before failing
- Ductility measured as:
  - % elongation
  - % reduction of area

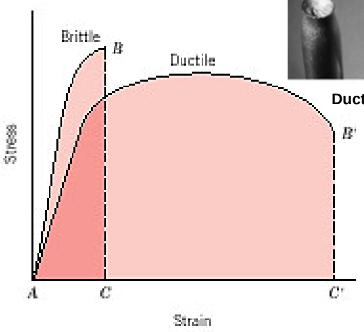
$$\frac{L_f - L_o}{L_o} \times 100$$

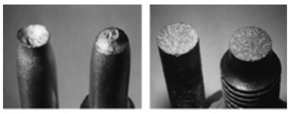
$$\frac{A_o - A_f}{A_o} \times 100$$

Brittle Materials

- Materials that exhibit little or no yielding before failure

Ductile vs. Brittle Materials

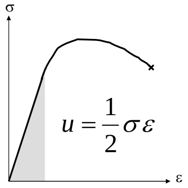




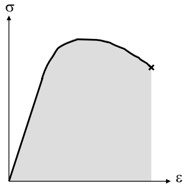
Ductile Brittle

Resilience - Toughness

- Ability to absorb energy without any permanent damage
- Ability to absorb energy before fracture

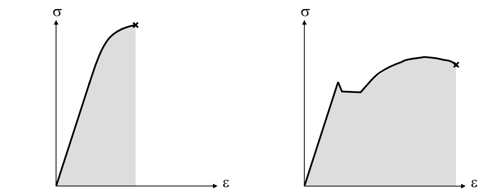


Modulus of resilience



Modulus of toughness

Strength vs. Toughness



High-carbon steel — high strength, low toughness, brittle

Low-carbon steel — lower strength, higher toughness, ductile

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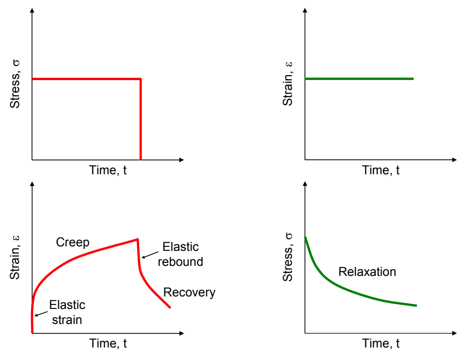
Time-Dependent Response



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Fatigue

- Gradual reduction in a material's strength due to repeated *cycles* of stress or strain
- Fracture occurs at a stress level lower than material's yield stress
  - connections or supports for bridges
  - railroad wheels & axles
  - steam or gas turbine blades, …

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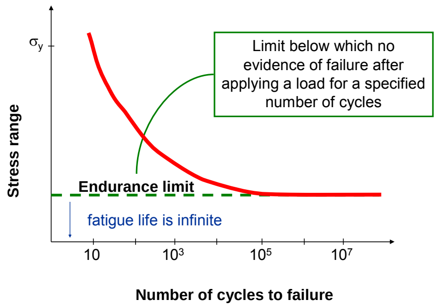
Fatigue



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