
Mechanical Properties

Sections 1.2.1-1.2.8[†]

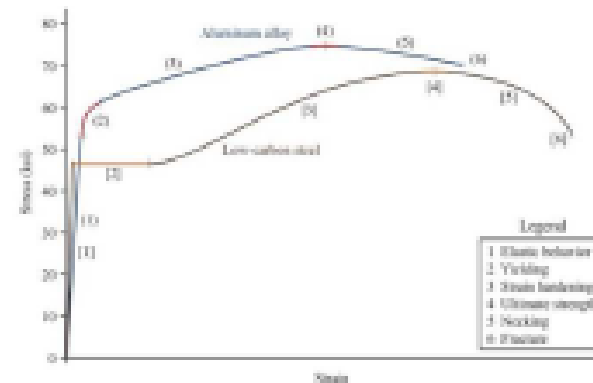
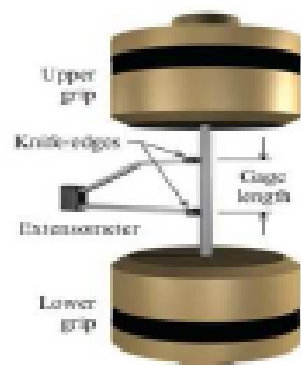
[†] Mamlouk, M.S., and Zaniewski, J.P. (2011). *Materials for Civil and Construction Engineers*, 3rd ed., Prentice Hall

What is a perfect/ideal material?

- Can resist the load
- Deforms but not excessively
- Can absorb energy
 - Absorb and recover?
 - Absorb and deform beyond recovery?

Introduction

- To determine the "mechanical" properties of materials we use simple laboratory tests.
 - Example: steel test
 - but fixed dimensions... what to do to eliminate the dependency on dimension



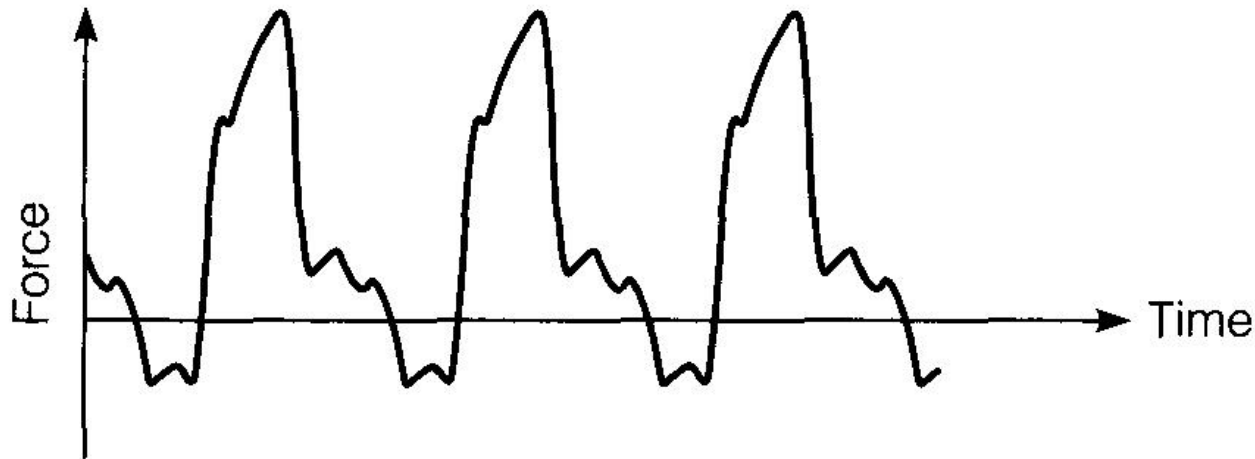
Loading Conditions

- **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).

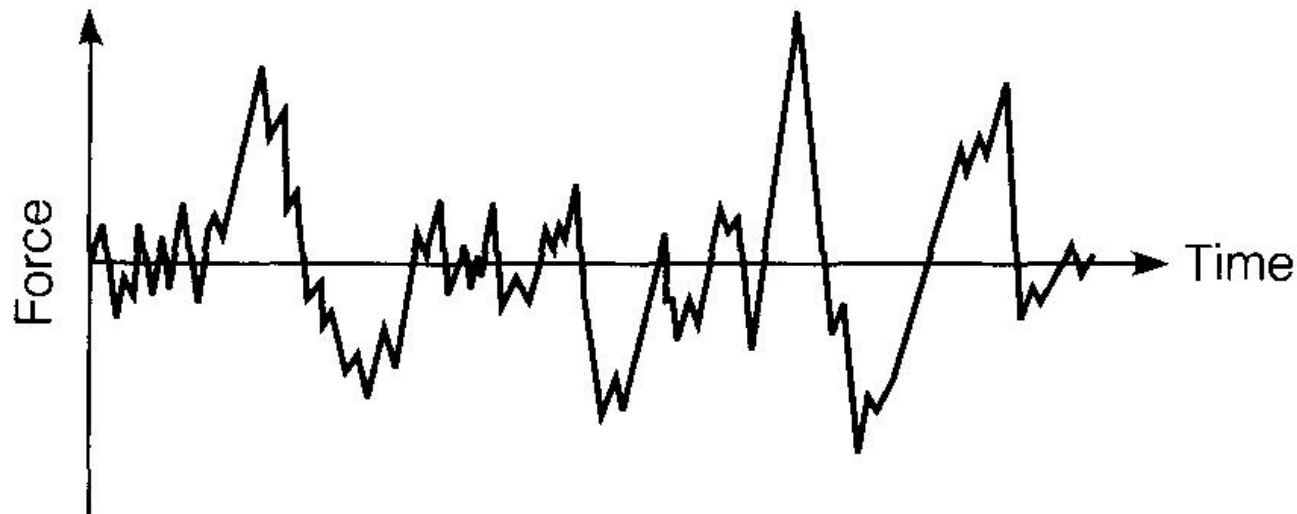


(a)

Loading Conditions (cont'd)

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

(EX. Earthquakes)

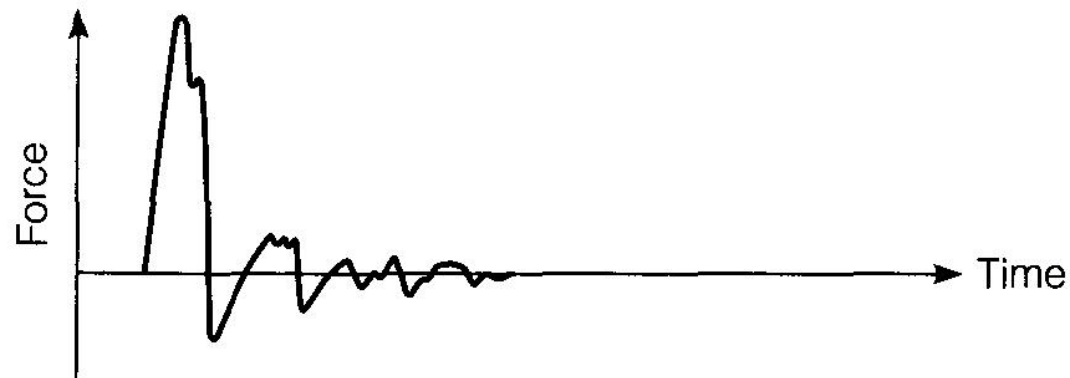


(b)

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

All solid materials deform under load but need to **normalize** the effect of dimension

- stress is like force with the size factored out so that we can directly compare different sizes, so: **stress = force / area**
- Stress is like the ``**intensity**`` of the force

Units of Stress

- SI Units

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

- U.S. Customary Units

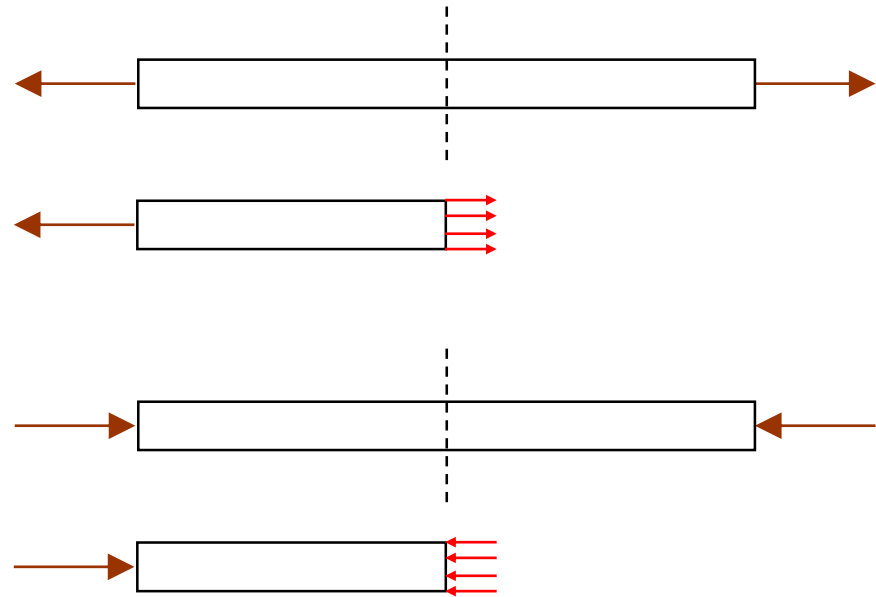
$$1 \frac{\text{lb}}{\text{ft}^2} \text{ (psf)} = 47.88 \text{ Pa}$$

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

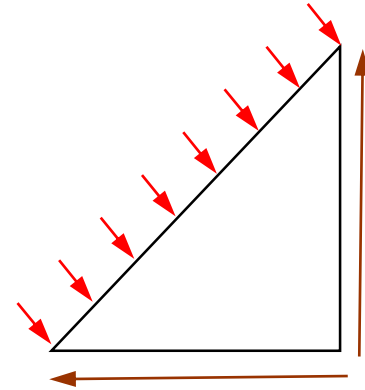
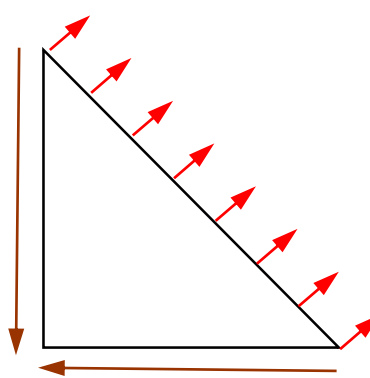
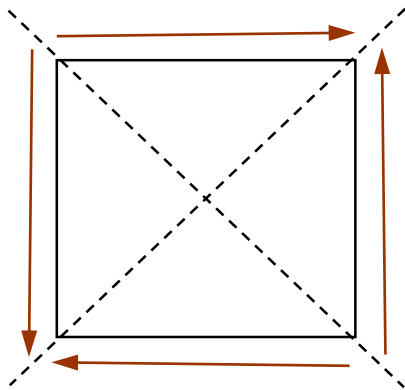
Types of Stresses

■ Normal

- Tension
- Compression



■ Shear



Strain

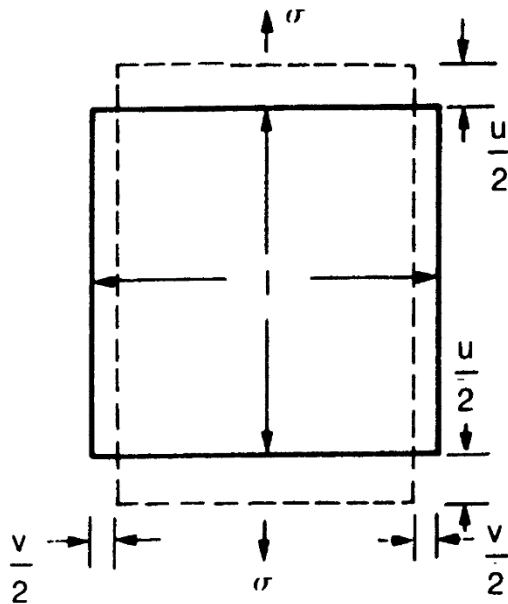
- All solid materials deform under load.
- Hence stress (force) will be accompanied by strain (deformation)
- Strain is *deformation per unit length*
- strain is like deformation with the size factored out, so: $\text{strain} = \text{deformation} / \text{original length}$

Types of Strain

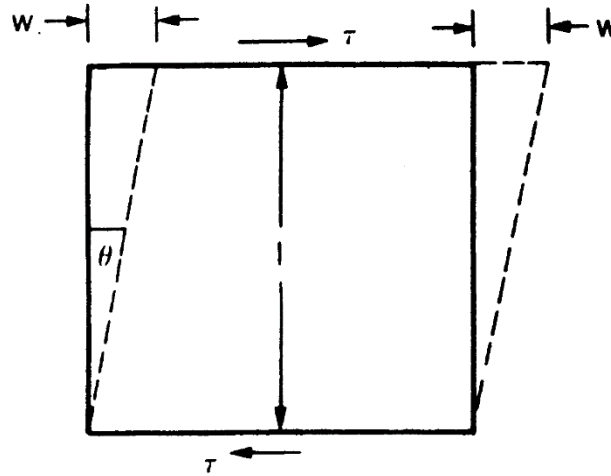
$$\epsilon_n = \frac{u}{l}$$

$$\gamma = \frac{w}{l} = \tan \theta$$

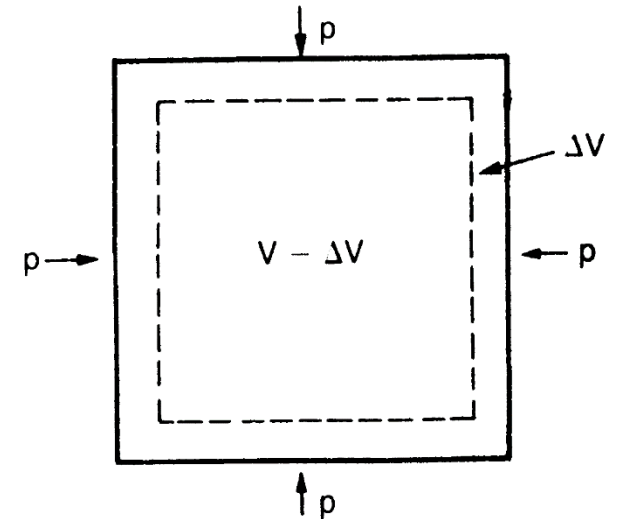
$$\Delta = \frac{\Delta V}{V}$$



Tensile Strain



Shear Strain



Dilation

Units of Strain

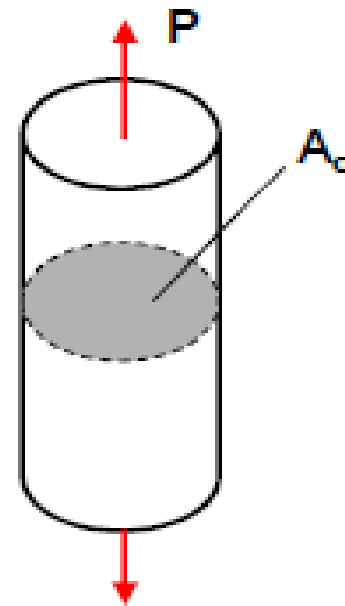
- Dimensionless
- Often expressed as:
 - m/m
 - %
 - radians

Axial stress and strain

- Axial stress is normal stress
- Amount of load a material carries *per unit of cross-sectional area*

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

- P = load
- A_0 = cross-sectional area

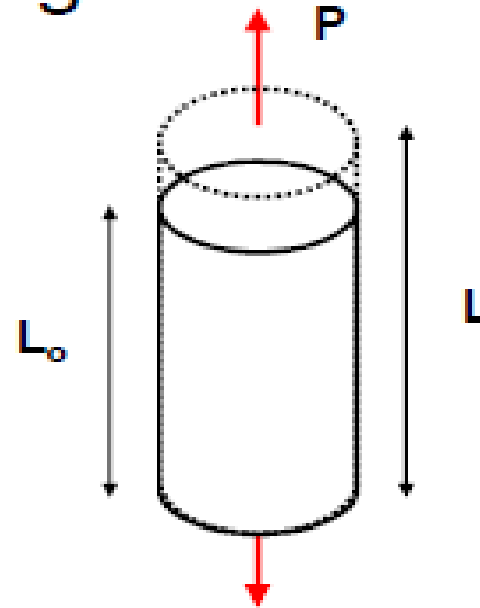


Axial strain

- Axial strain is normal strain
- Deformation per unit length

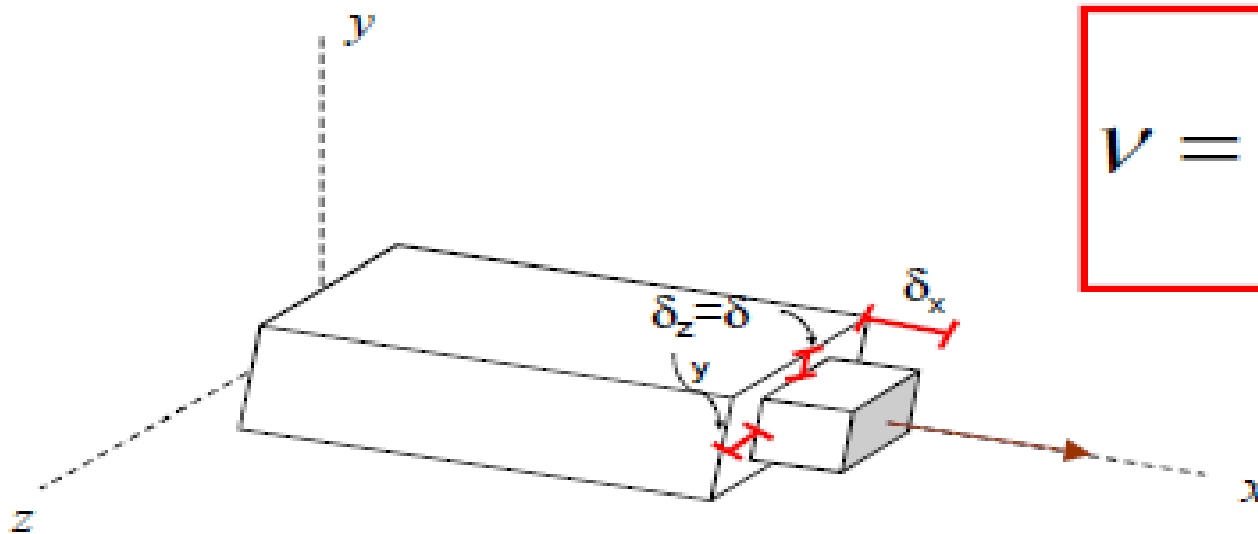
$$\varepsilon = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0}$$

- $\Delta L = L - L_0$
- $L_0 = \text{Original length}$



Poisson's Ratio ν

- Relates lateral strain, ϵ_y , to axial strain, ϵ_x
- As material is stretched the cross section shrinks and vice versa for compression
(*hence the negative sign*)



$$\nu = -\frac{\epsilon_y}{\epsilon_x} = -\frac{\epsilon_z}{\epsilon_x}$$

Poisson's Ratio (cont'd)

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

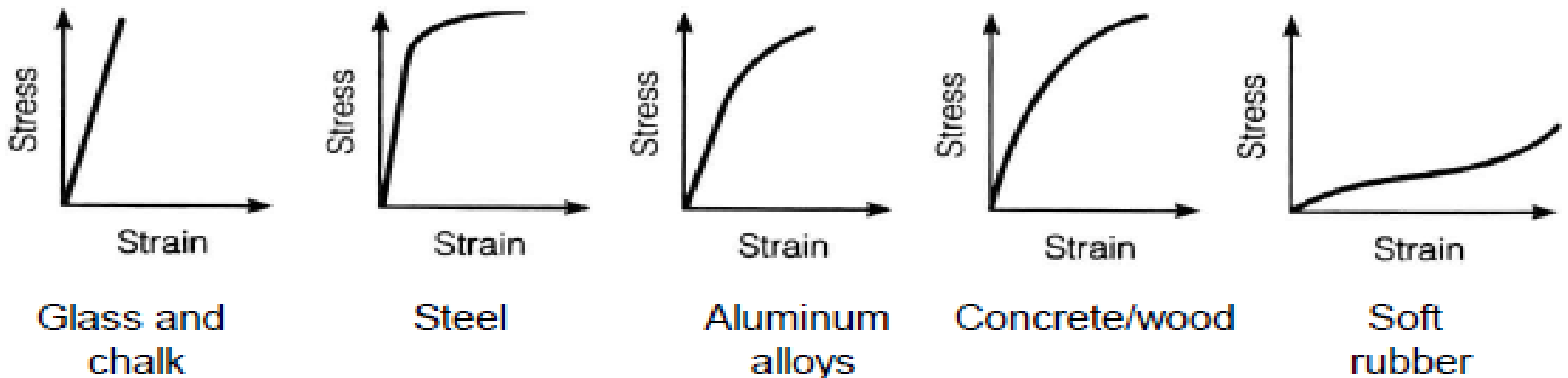
- For most construction materials, ν ranges from 0.15 to 0.4
 - Concrete 0.1 - 0.2
 - Steel 0.27 - 0.3
 - Wood 0.3 – 0.45

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**

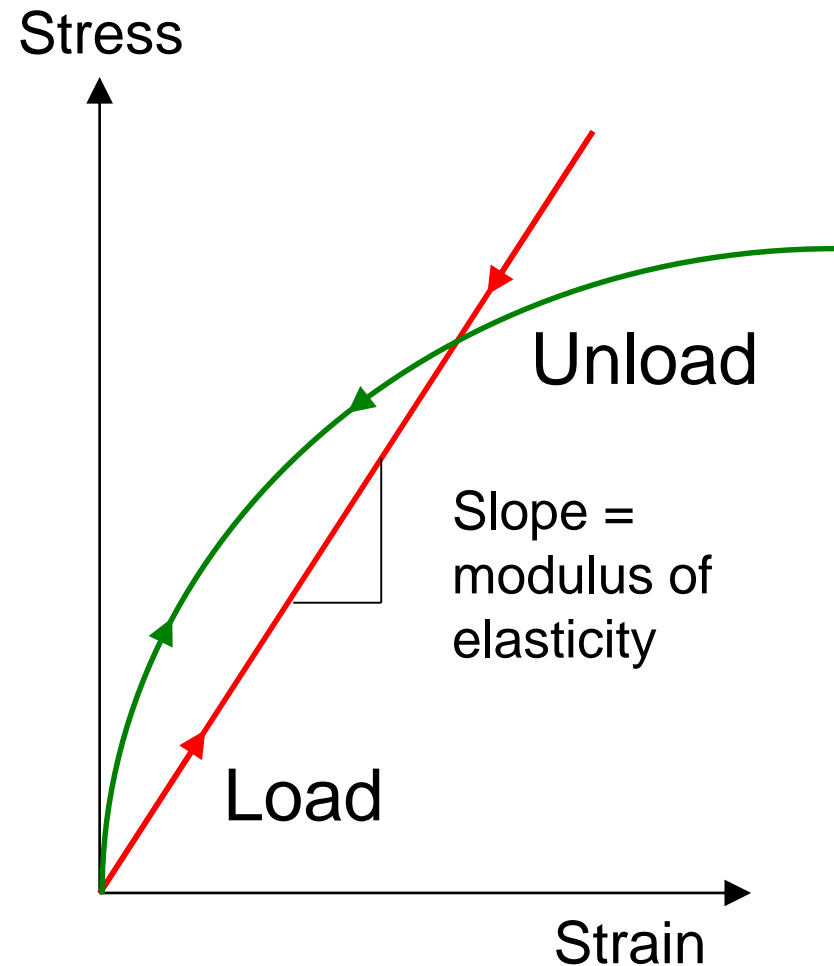
Stress-Strain Diagram

- $\sigma - \epsilon$ is usually linear in the low stress range but transforms into non-linear
- Important to be able to recognize material behavior



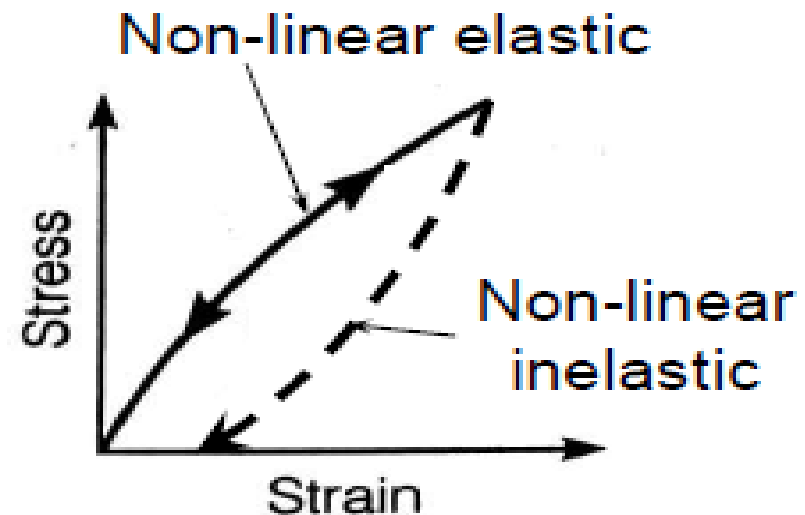
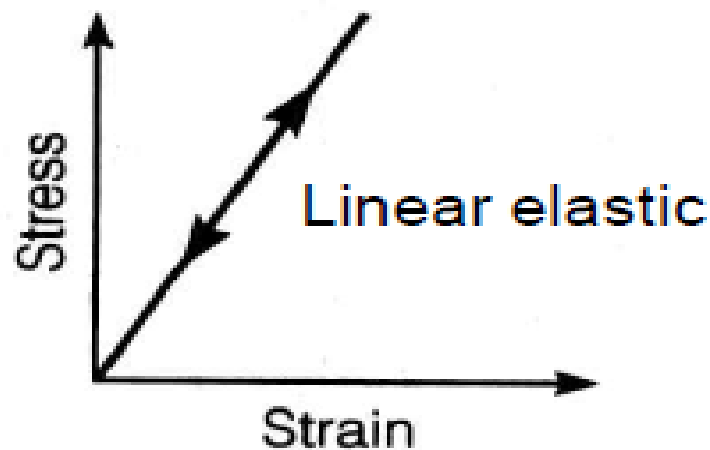
Elastic Behaviour

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



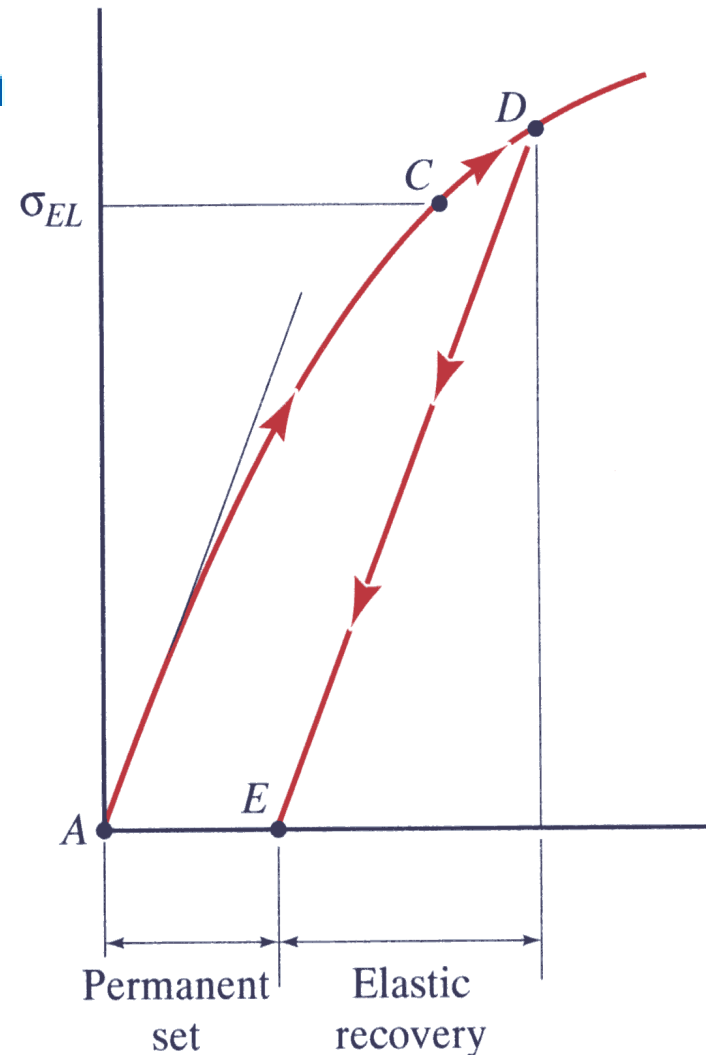
Linear and non-linear Behaviour

- A **linear** material has a **straight** line stress-strain graph
- In most material elastic deformation is linear (**linear elastic**)



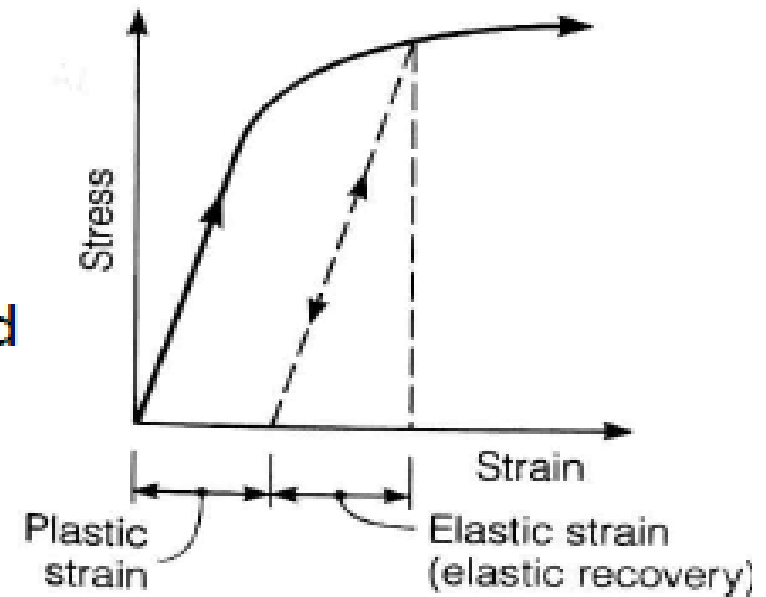
Plastic Behaviour

- Non-recoverable deformation
- Atomic bonds slip past each other and rearrange
- Permanent deformations (does not spring all the way back)



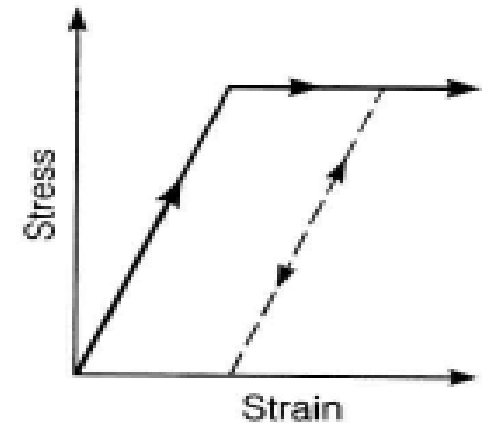
Elastoplastic Behaviour

- When unloaded, rebound parallel to the linear portion with some remaining plastic deformation
 - stretched bonds return, rearranged ones don't
- when reloaded, follows the rebound line and then original curve

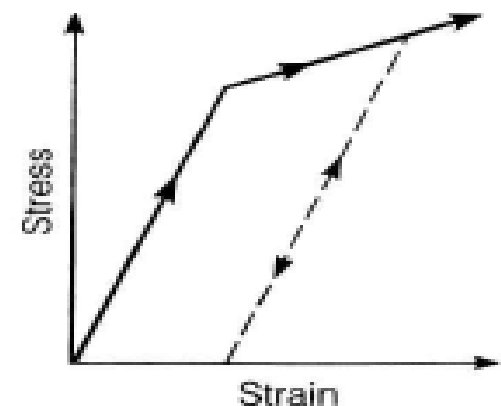


Elastoplastic Behaviour (idealized)

- Elastic-perfectly plastic
- strain hardening
 - stress increases during plastic deformation
 - reloading returns to previous peak stress



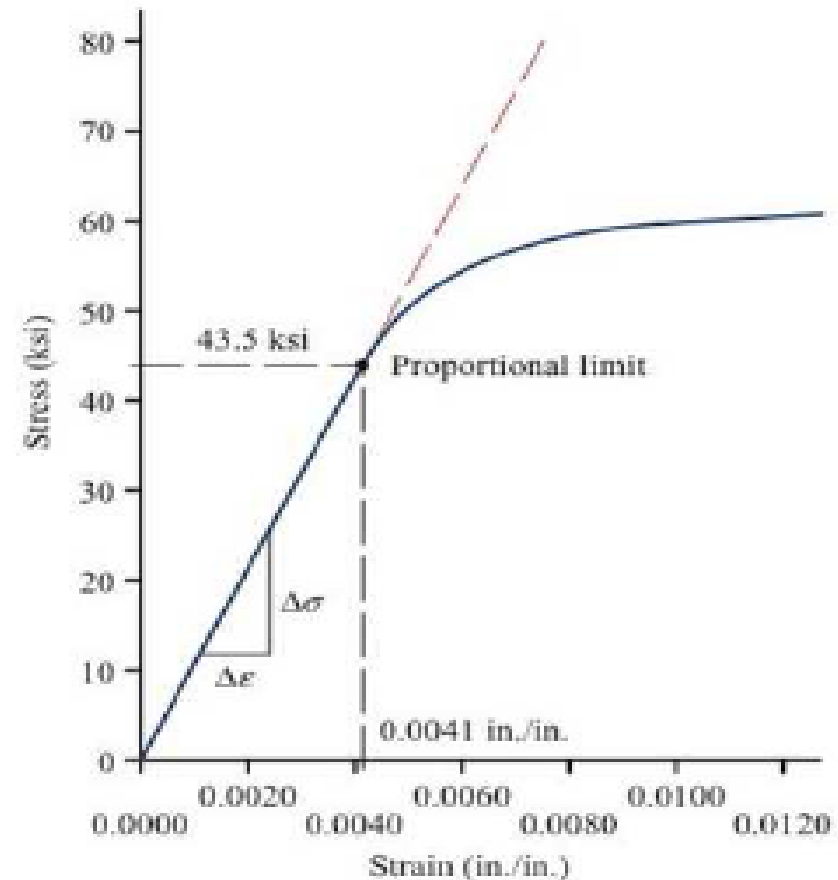
Elastic-perfectly plastic



Strain hardening

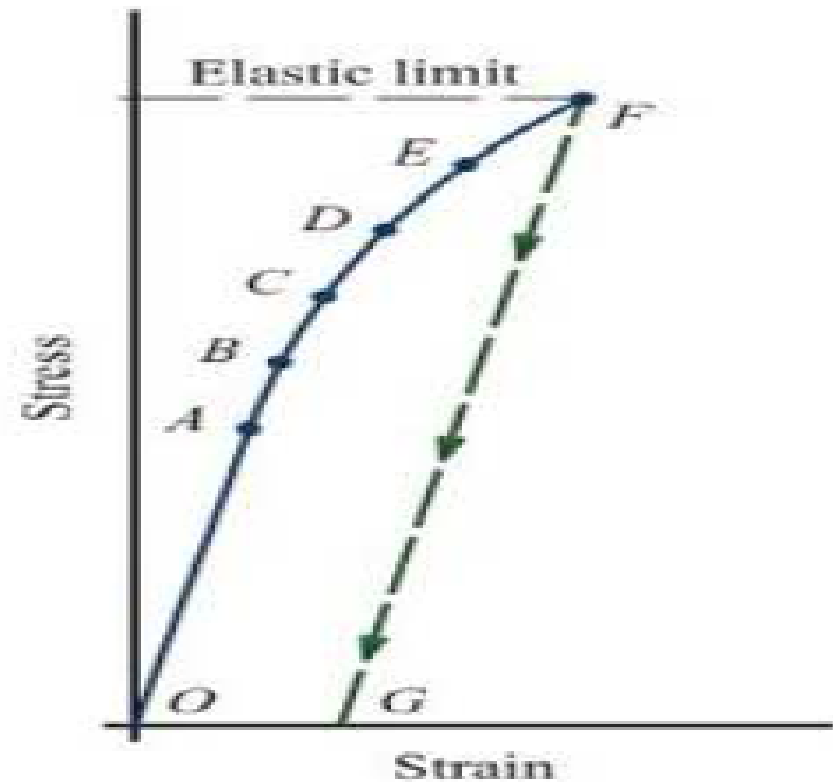
Proportionality limit

- The stress at which the stress-strain plot changes from **linear** to **non-linear**



Elastic Limit

- The stress at which the deformation will change from **elastic** to **plastic**
- The **elastic limit** is the largest stress that a material can withstand without permanent deformation



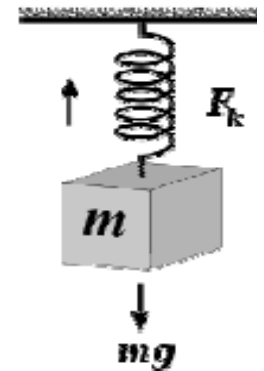
Elastic Limit

- How does ***Elastic limit*** differ from ***Proportional limit*** ?
 - For most common materials the elastic limit is indistinguishable to the proportional limit.
 - However some materials have non-linear elastic behavior in which case the elastic limit could be substantially greater than the proportional limit.

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

Modulus of Elasticity

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

- Three moduli corresponding to 3 stresses:

- Tension
 - Compression
 - Shear → Modulus of rigidity
- } Young's modulus

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

Material	Modulus, E (GPa)
Aluminum	70
Concrete	14 - 40
Steel	200
Wood	8 - 15

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 ...

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

Example 2

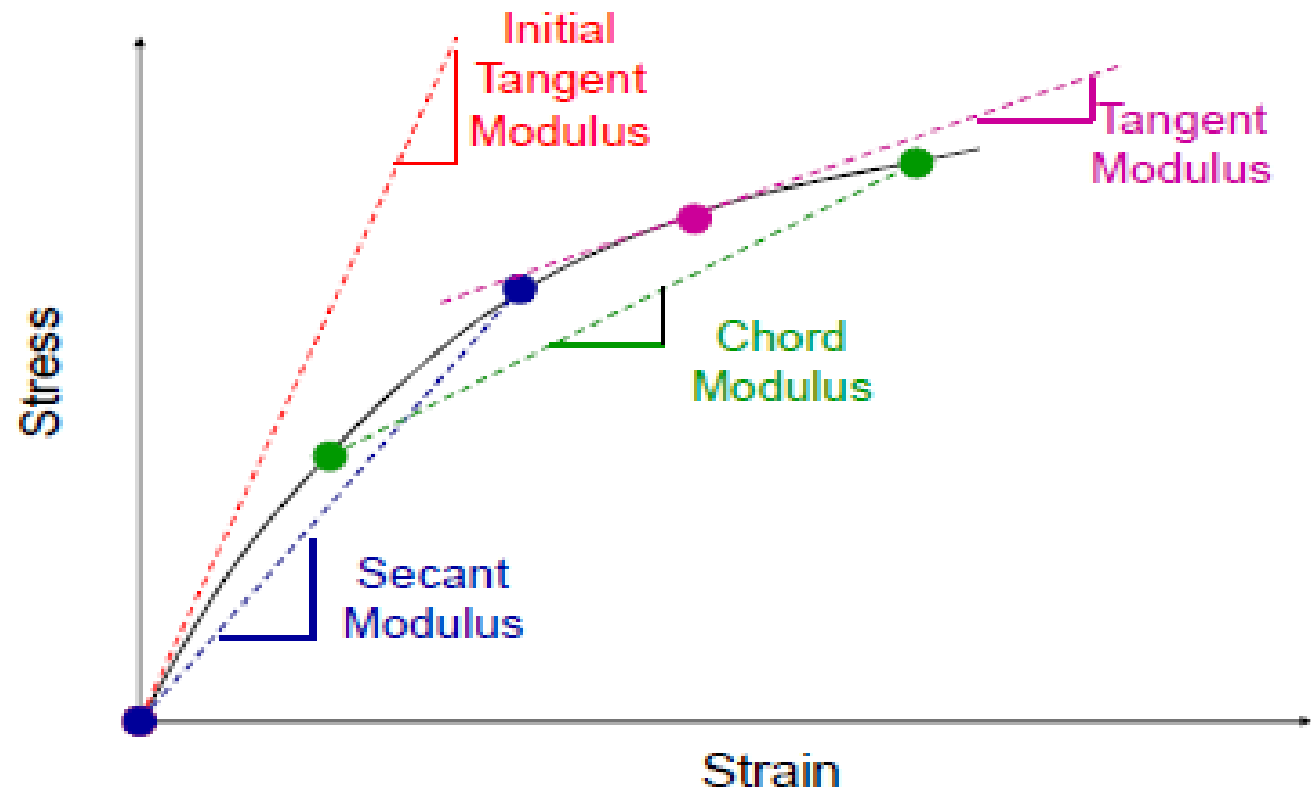
- A series of steel specimens are being tested in tension for possible use as a structural component. A strain gauge on one of the specimens measures a strain of 0.00032 at a time when the load cell on the test frame indicates a load of 5.2 kN . At the start of the test, the strain gauge reads 0.00001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

Example 3

- 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.

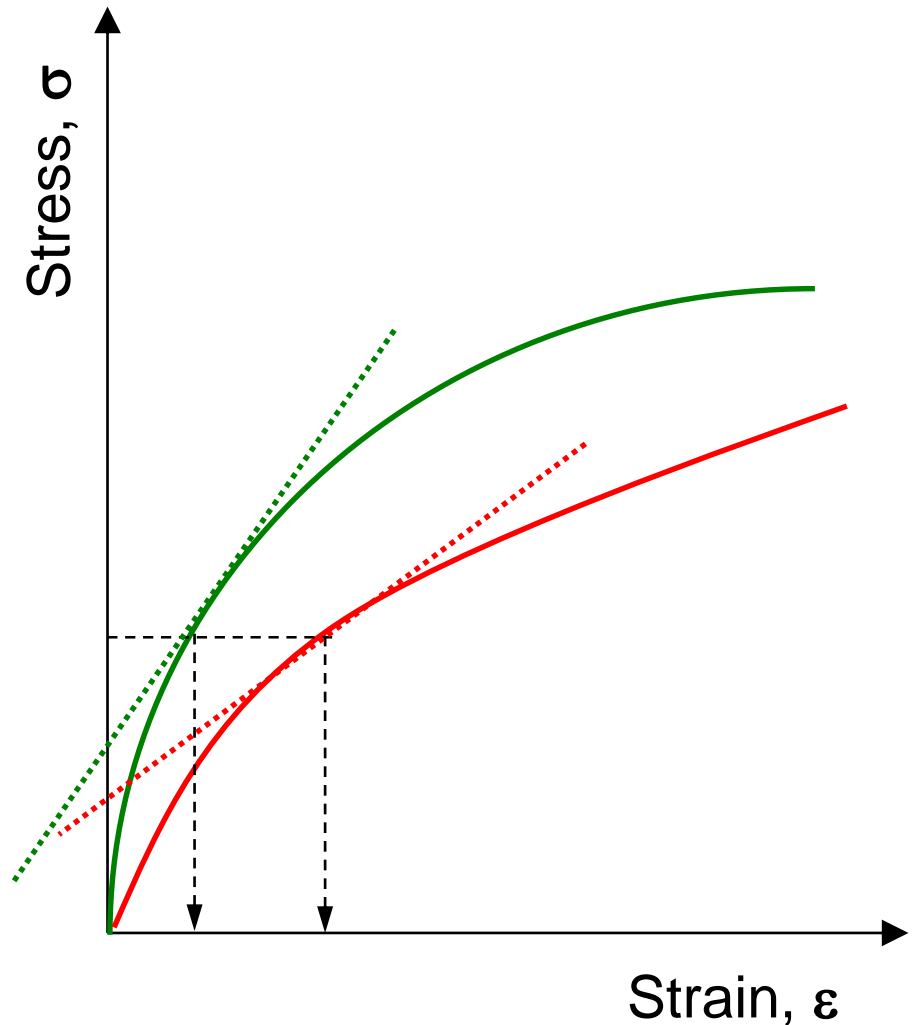
Non-linear response

- What if response is non-linear in elastic region?
- How do we find the slope (Modulus of Elasticity)?

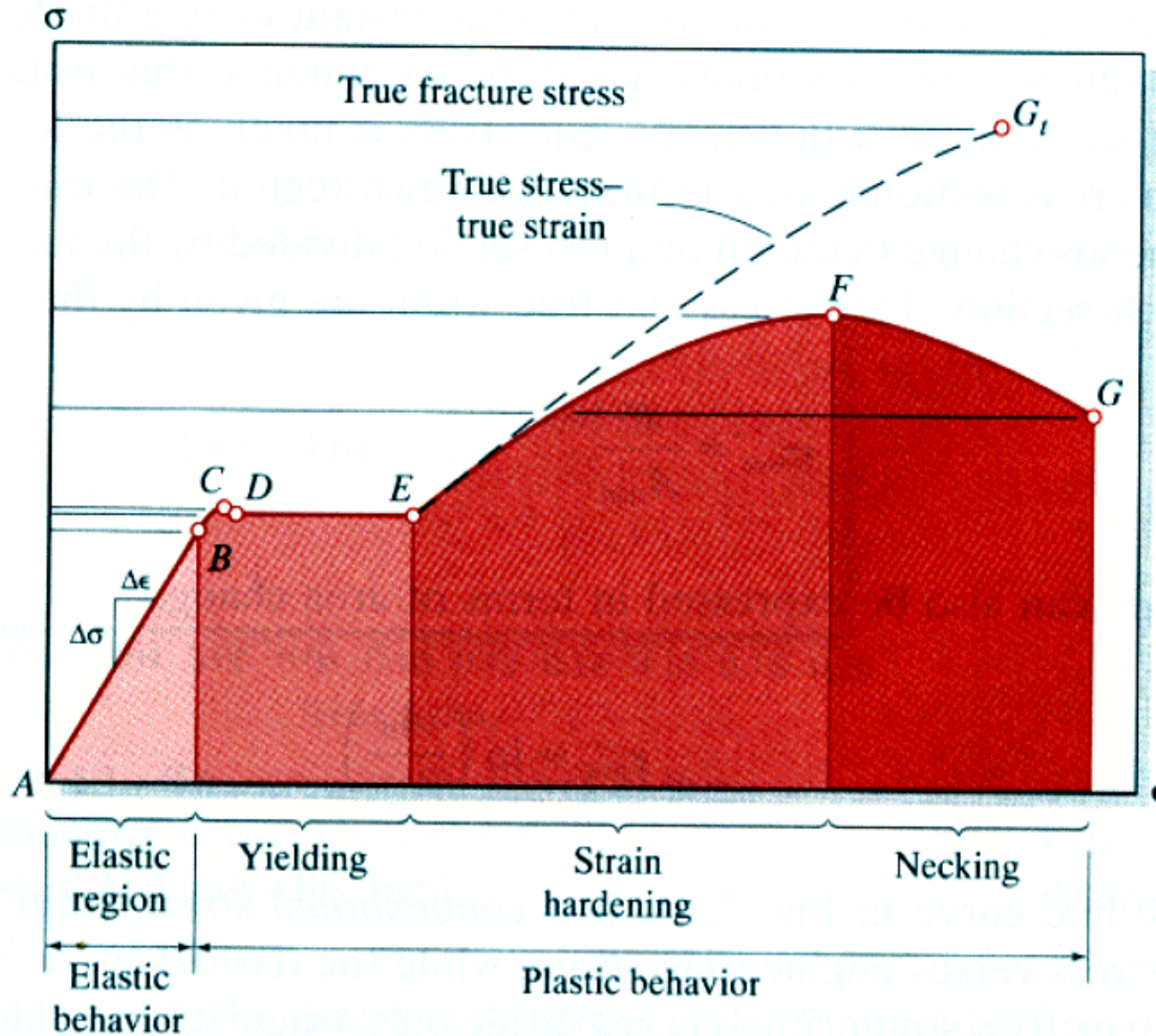


Stiffness

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

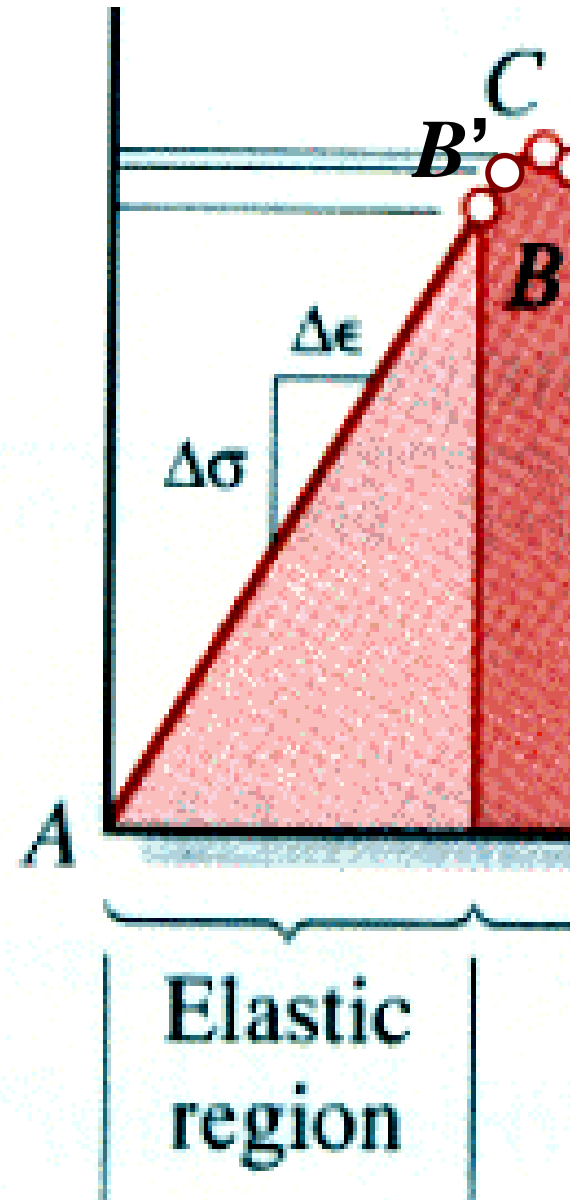


Steel σ - ϵ Curve



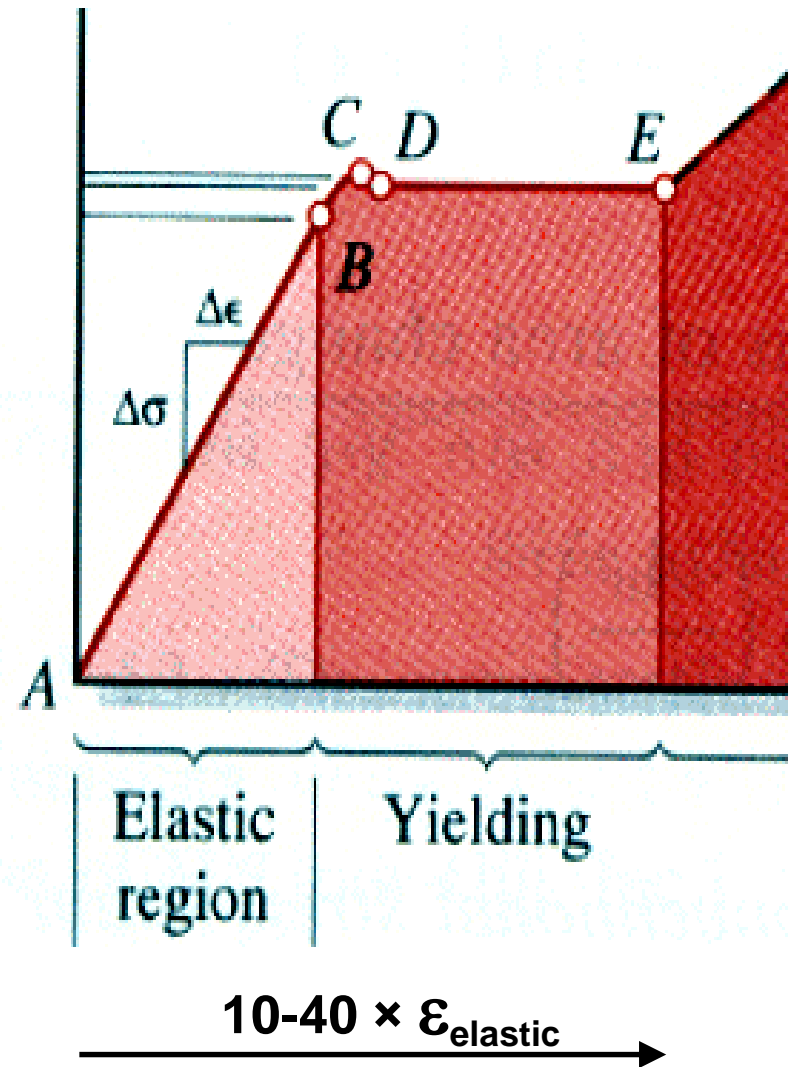
Elastic Region

- $\sigma_B \rightarrow$ **proportional limit**
(max. stress below which σ/ϵ is constant)
- $\sigma_{B'} \rightarrow$ **elastic limit**
(max. stress under which material remains elastic)
- B & B' usually assumed to be the same



Yielding

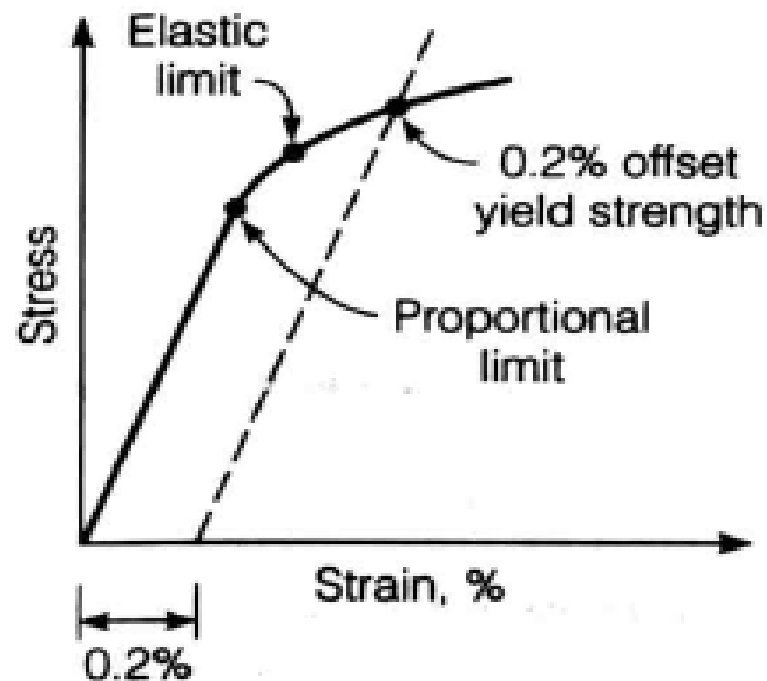
- $\sigma_C \rightarrow$ yield stress or yield point σ_Y
- Deformation beyond C is permanent \rightarrow plastic deformation
- Often 2 values define σ_Y :
 - upper yield point, C
 - lower yield point, D
- D-E \rightarrow perfectly plastic material



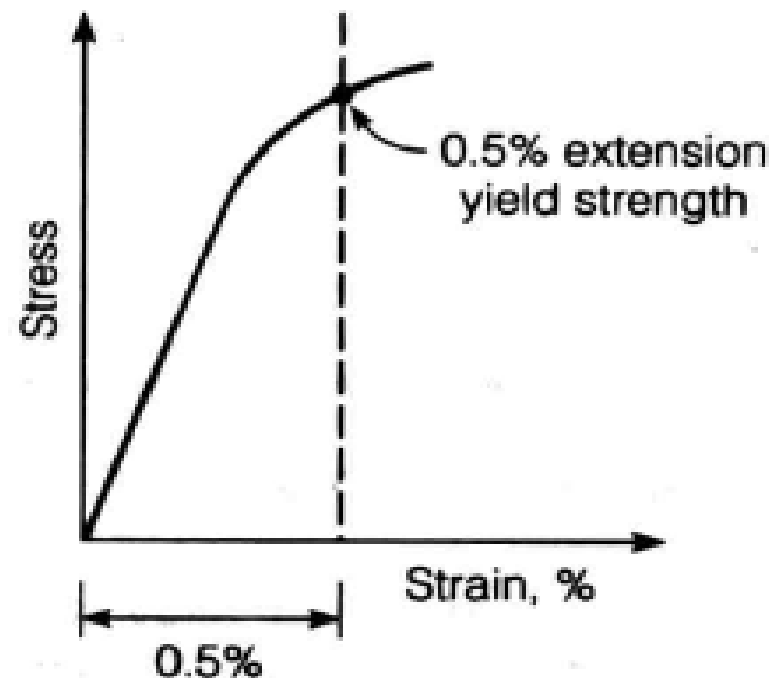
Yield Point – Offset Method

- What if there's no clear transition point?

Offset method

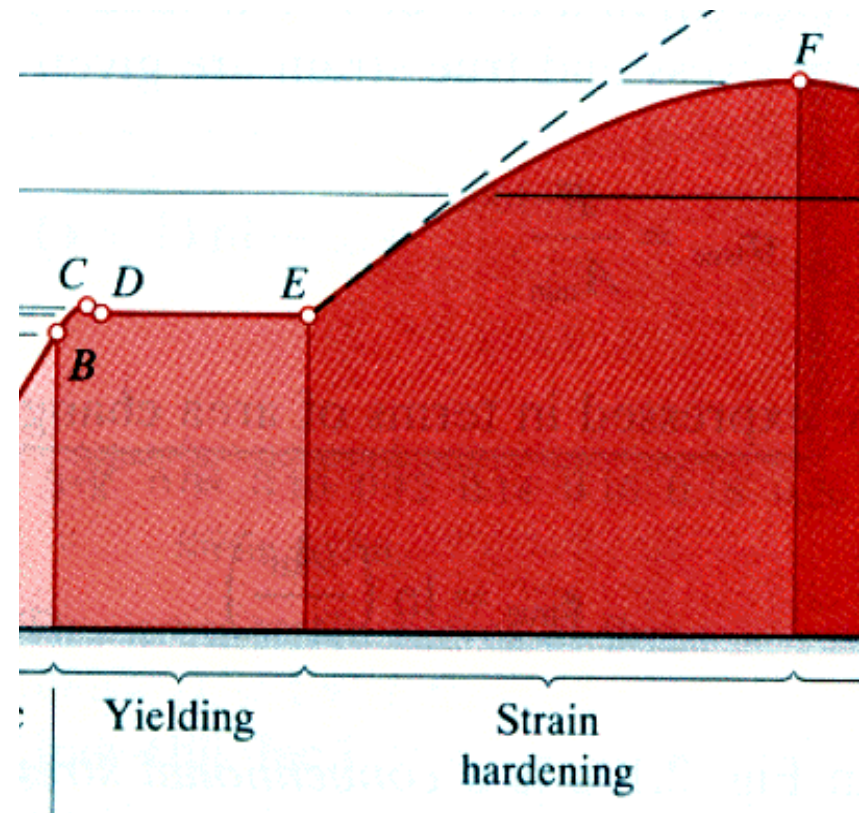


Extension method



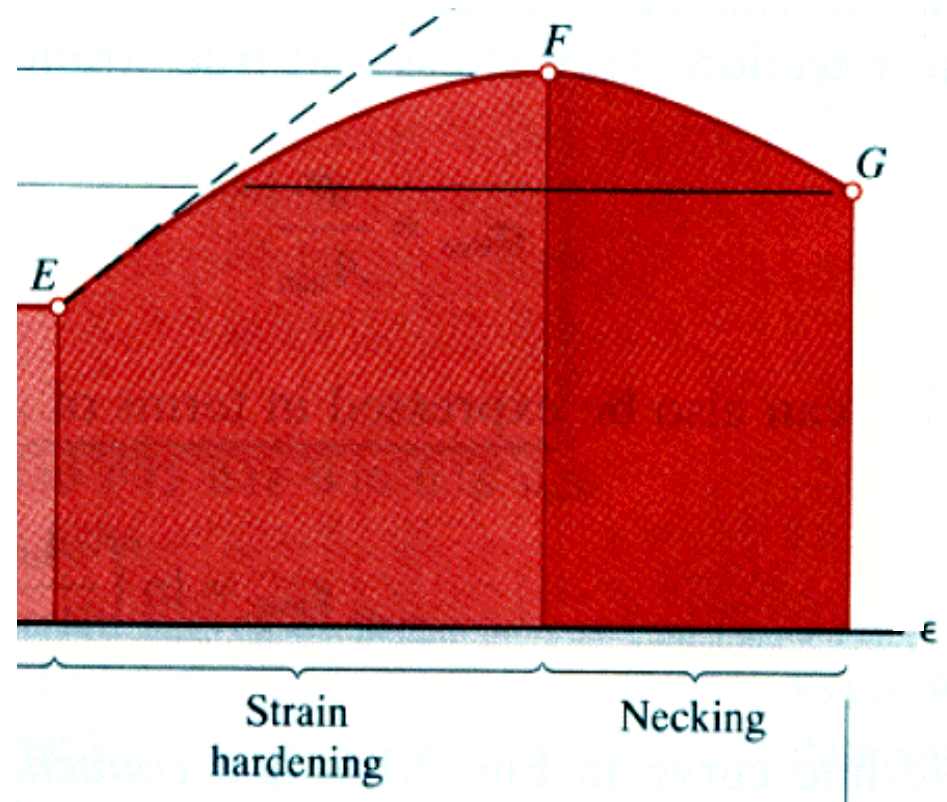
Strain Hardening

- Stress begins to increase at E
- $\sigma_F \rightarrow$ ultimate stress σ_u
- E-F \rightarrow strain hardening zone

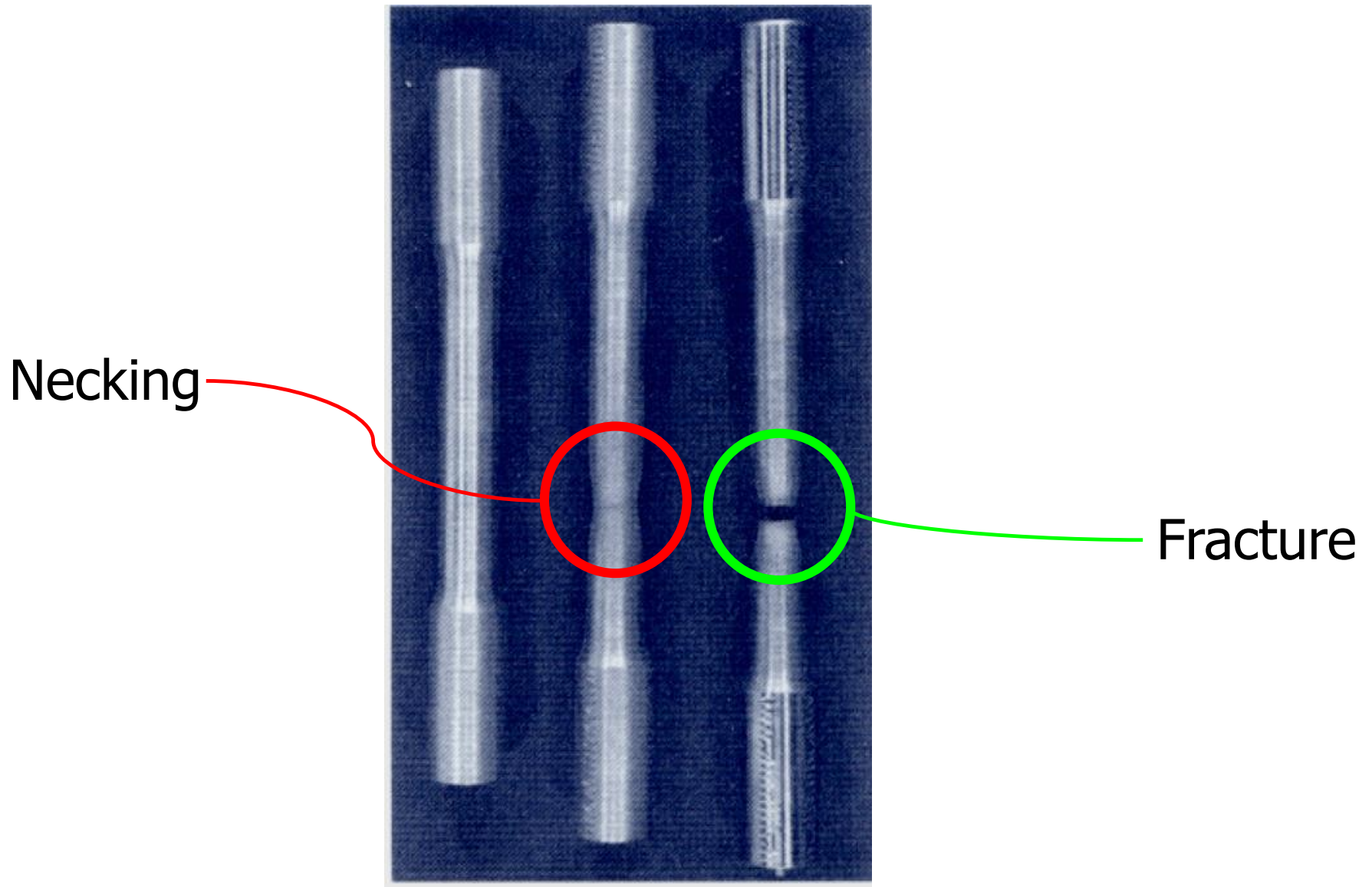


Necking

- At F the stress begins to drop as the specimen begins to “neck down.”
- $\sigma_G \rightarrow$ fracture stress σ_f



Necking (cont'd)



Engineering Stress & Strain

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

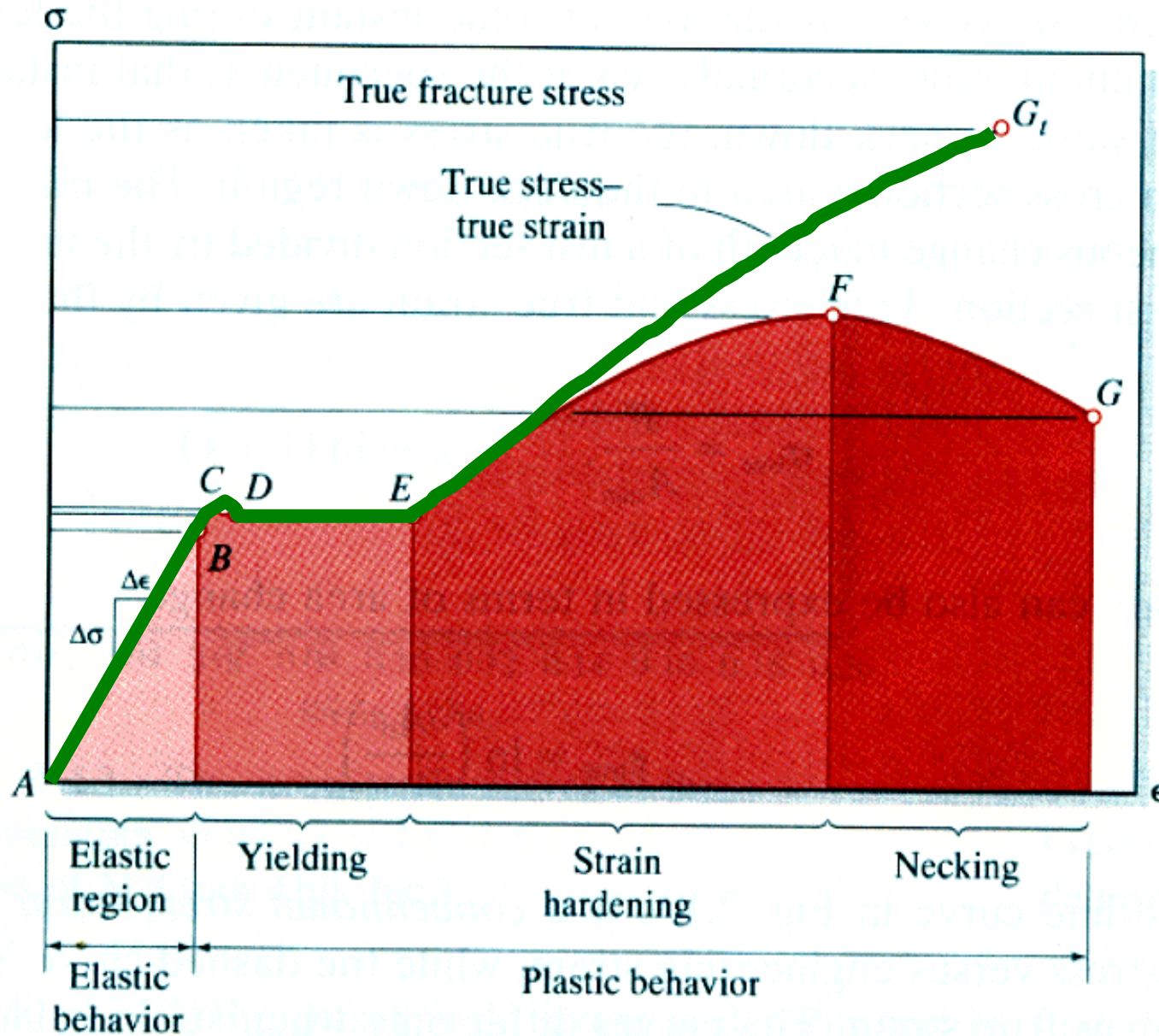
True Stress & Strain

- 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

$$\sigma_t = \frac{P}{A}$$

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

Steel True σ - True ϵ Curve



Ductile & Brittle Materials

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

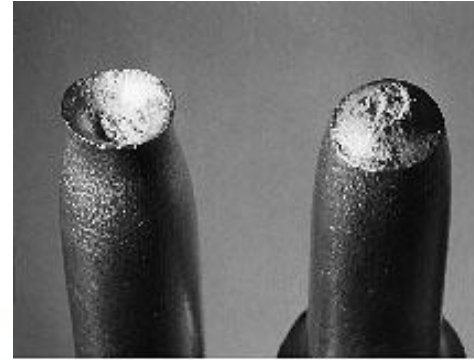
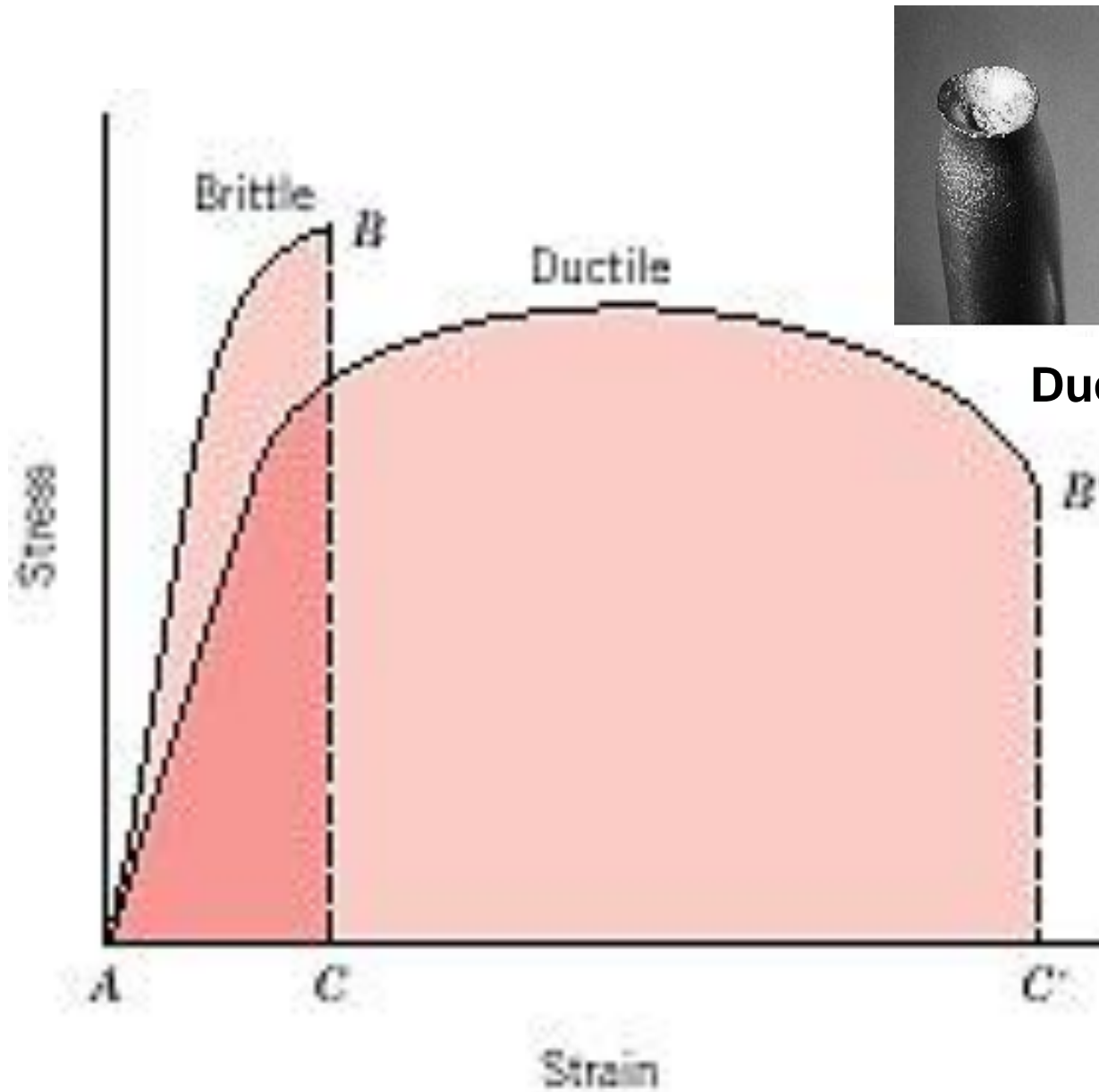
- Ductility measured as:
 - % elongation
 - % reduction of area

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

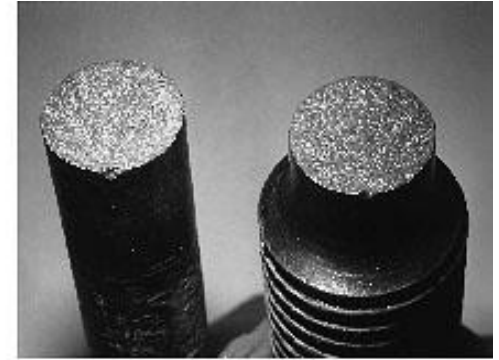
Brittle Materials

- Materials that exhibit **little or no yielding** before failure

Ductile vs. Brittle Materials



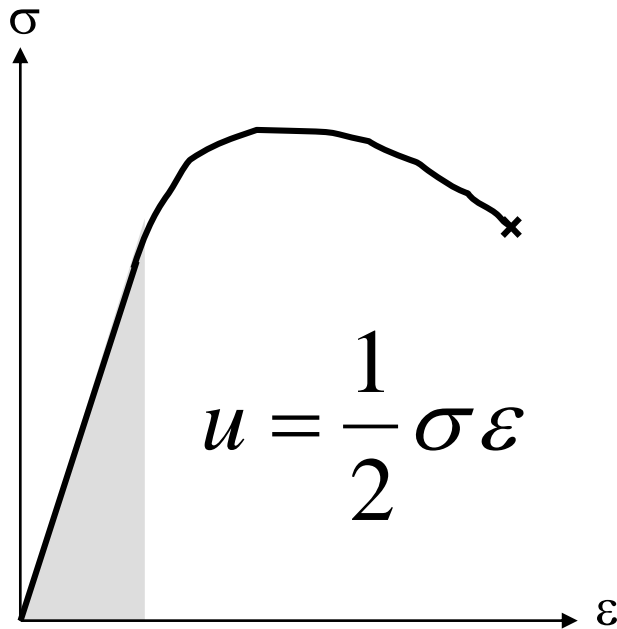
Ductile



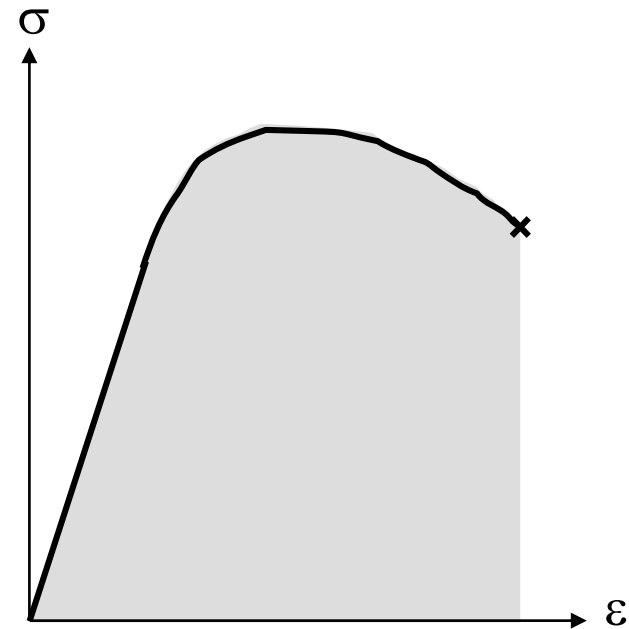
Brittle

Resilience - Toughness

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



Modulus of resilience

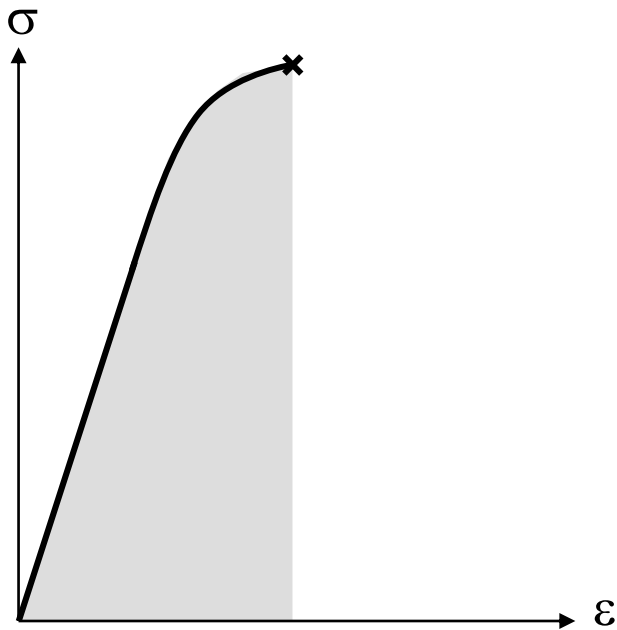


Modulus of toughness

Strength vs. Toughness

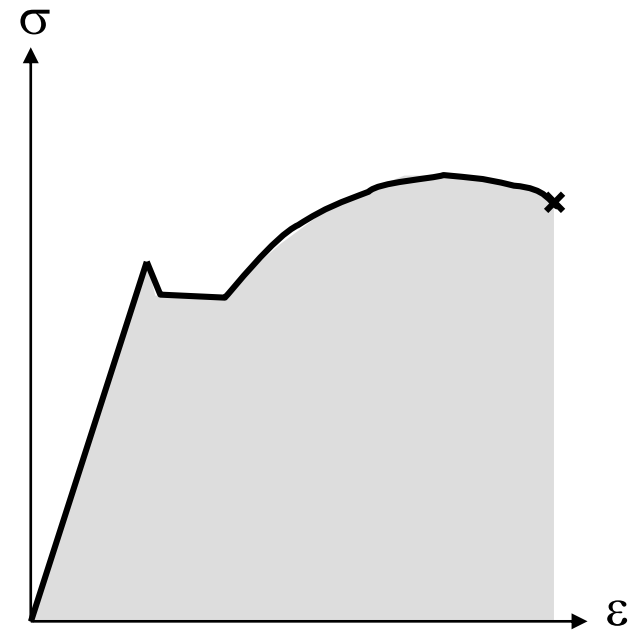
Example: Steel

- Often increase in material strength is achieved at the cost of reduced ductility



High-carbon steel

high strength, low toughness, brittle

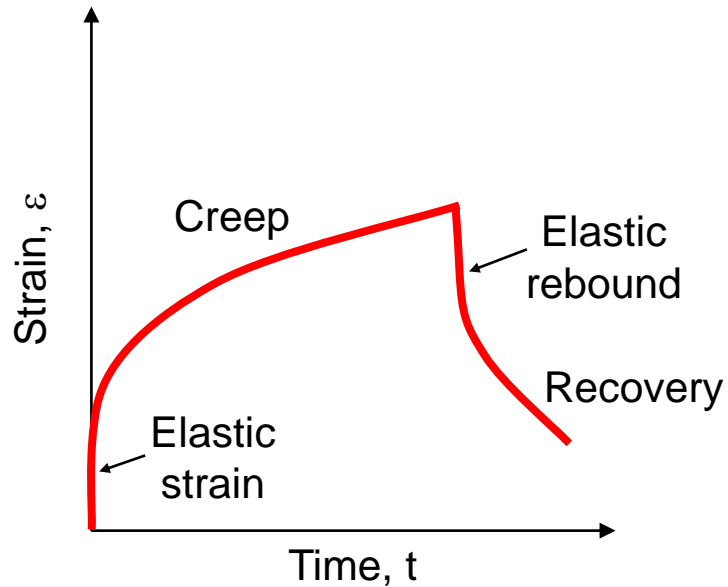
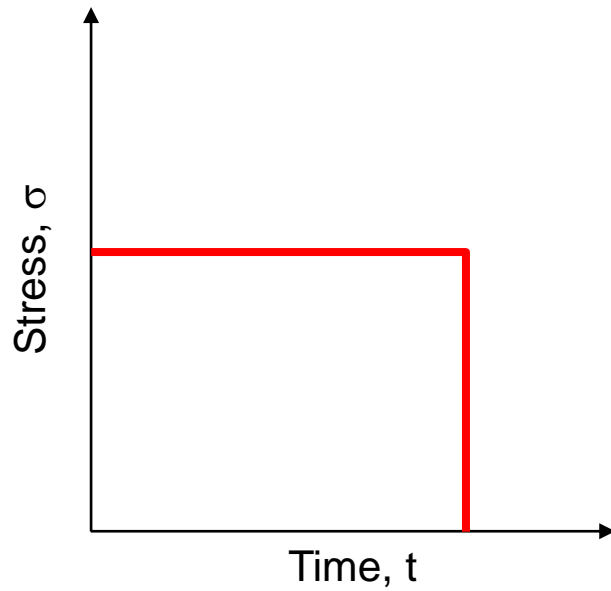


Low-carbon steel

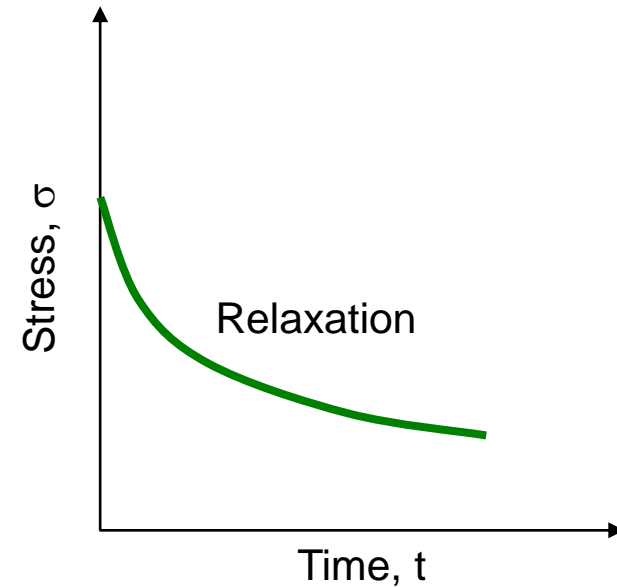
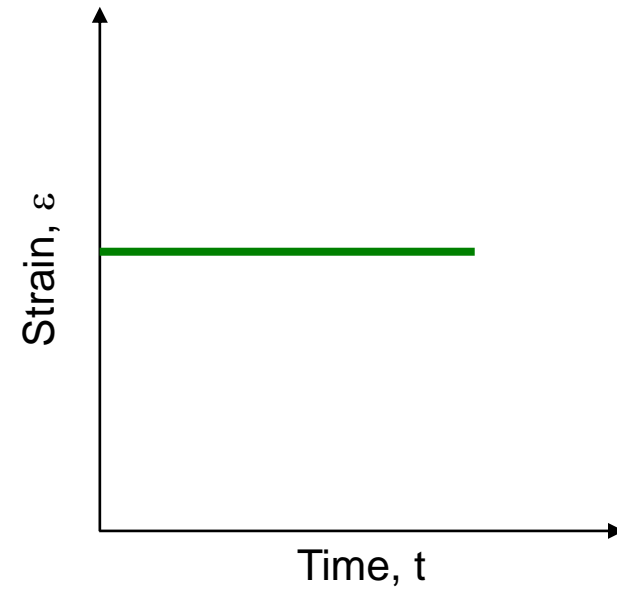
lower strength, higher toughness, ductile

Time-Dependent Response

Creep



Relaxation

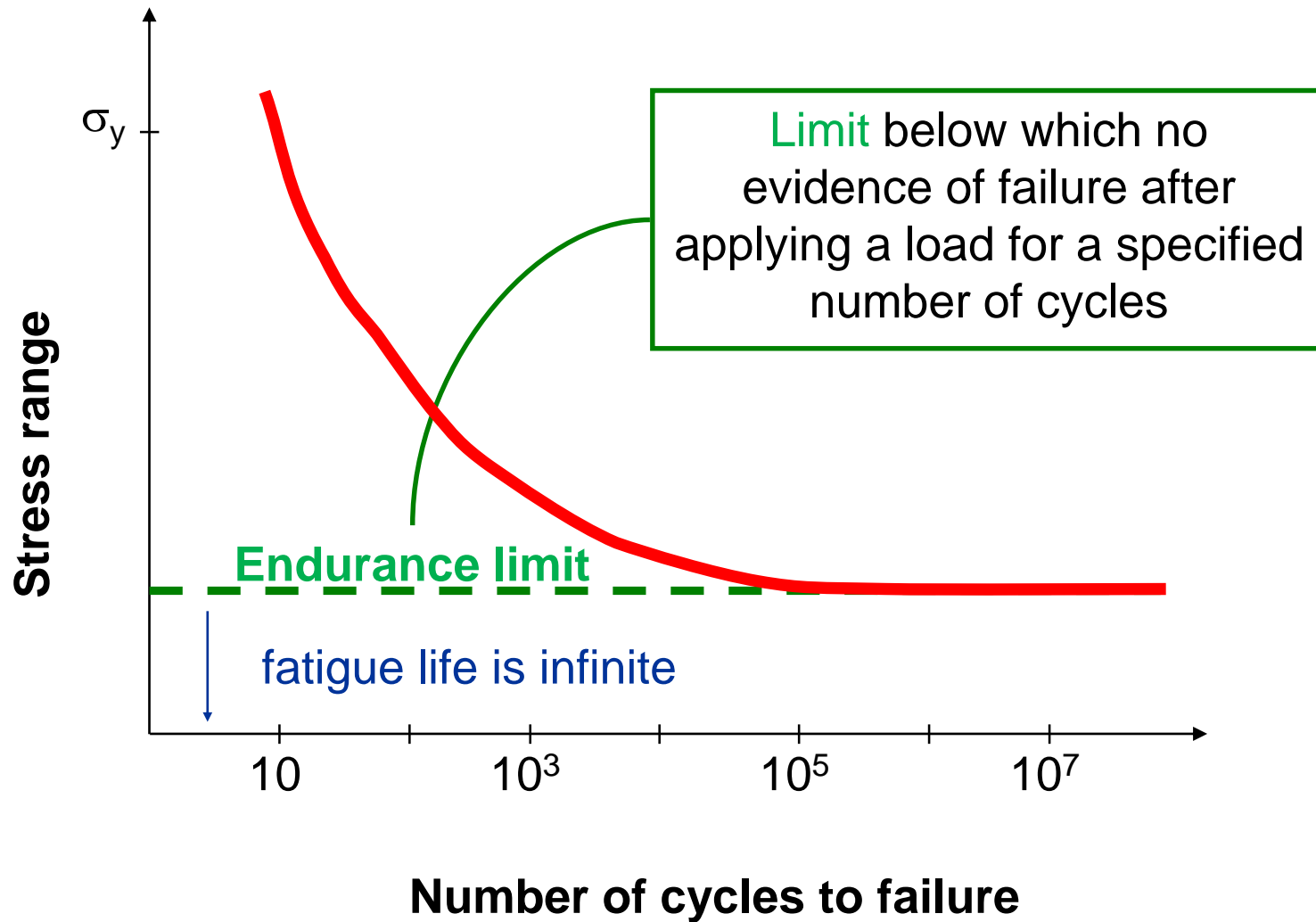


Fatigue

- 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, ...



Fatigue



Laboratory measuring devices

Direct

- Ruler, dial gauge, calipers
- Physical & material properties are usually measured (time, deformation, force, etc.)

Indirect

- LVDT, strain gauge, load cell
- measuring changes in electric voltage and relating to deformation, stress, or strain
- must be calibrated



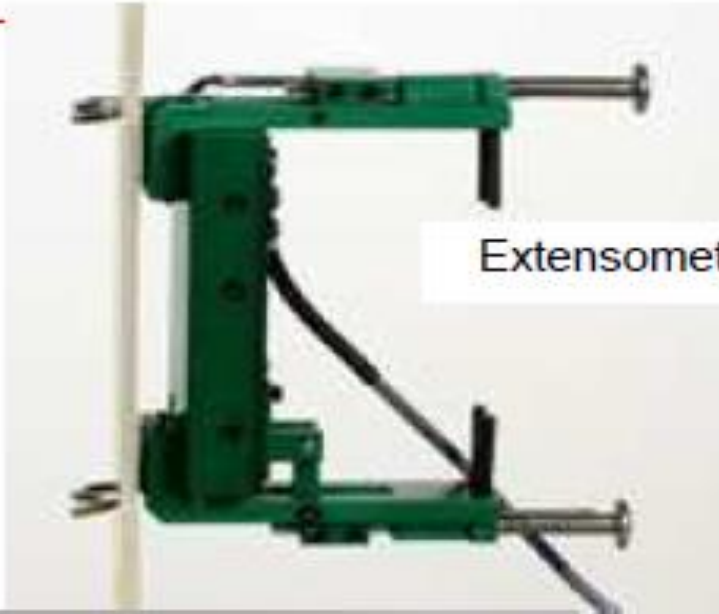
Dial Gauge



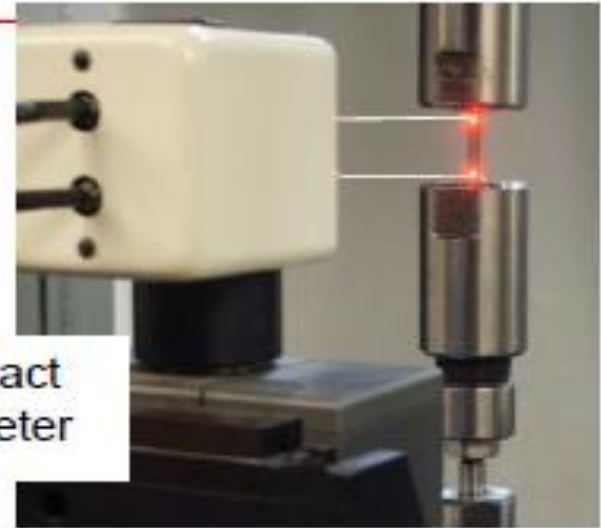
LVDT

Strain Gauge





Extensometer



Non-Contact
Extensometer



Load
Cell

