

Chapter Outline

Mechanical Properties of Metals

How do metals respond to external loads?

- **Stress and Strain**

- Tension
- Compression
- Shear
- Torsion

- **Elastic deformation**

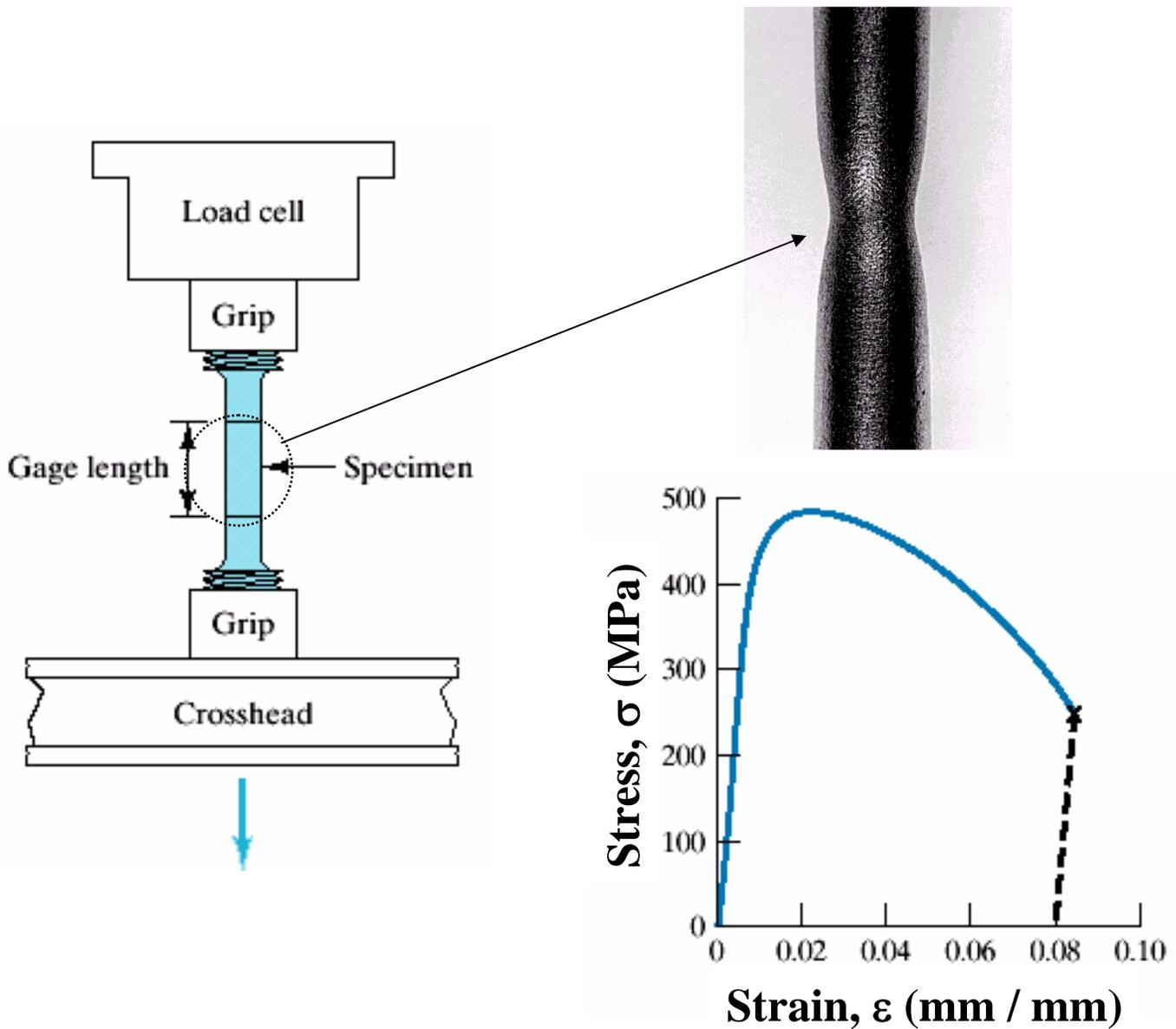
- **Plastic Deformation**

- Yield Strength
- Tensile Strength
- Ductility
- Toughness
- Hardness

Optional reading (not tested): *details of the different types of hardness tests, variability of material properties* (starting from the middle of page 174)

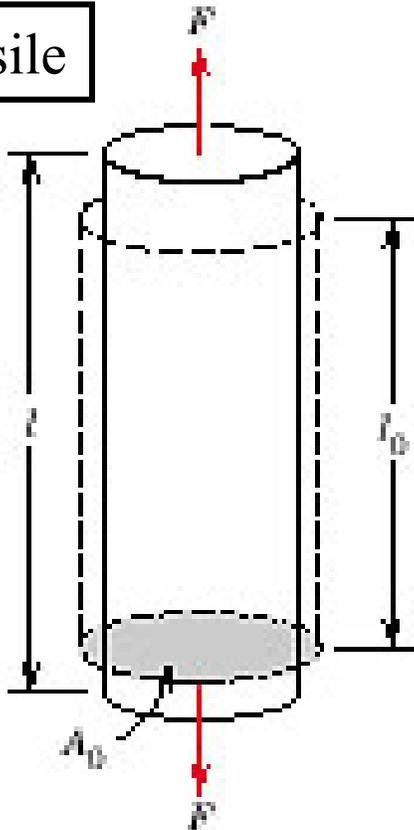
Introduction

To understand and describe how materials deform (elongate, compress, twist) or break as a function of applied load, time, temperature, and other conditions we need first to discuss standard test methods and standard language for mechanical properties of materials.

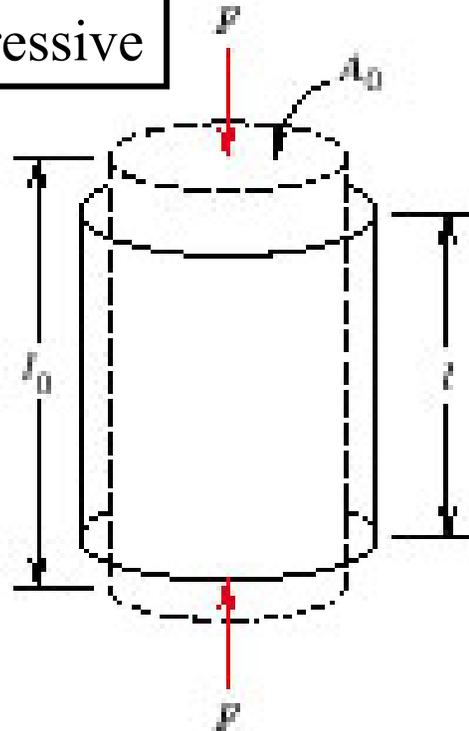


Types of Loading

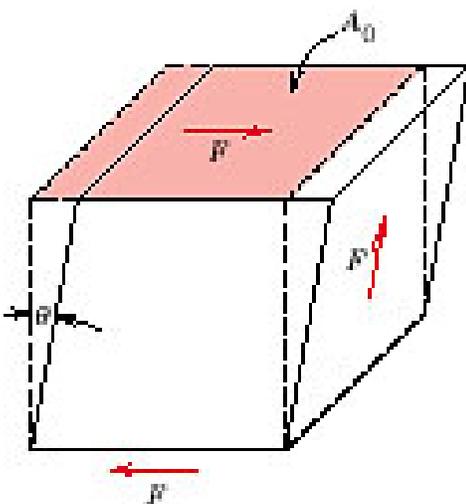
Tensile



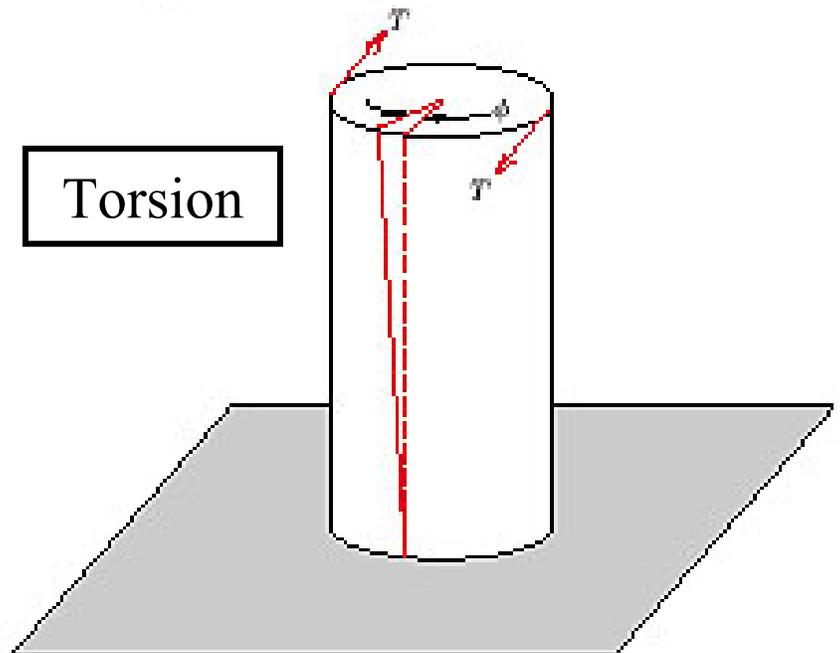
Compressive



Shear



Torsion



Concepts of Stress and Strain (tension and compression)

To compare specimens of different sizes, the load is calculated per unit area.

Engineering stress: $\sigma = F / A_0$

F is load applied perpendicular to specimen cross-section; A_0 is cross-sectional area (perpendicular to the force) **before** application of the load.

Engineering strain: $\epsilon = \Delta l / l_0 \quad (\times 100 \%)$

Δl is change in length, l_0 is the original length.

These definitions of stress and strain allow one to compare test results for specimens of different cross-sectional area A_0 and of different length l_0 .

Stress and strain are positive for tensile loads, negative for compressive loads

Concepts of Stress and Strain (shear and torsion)

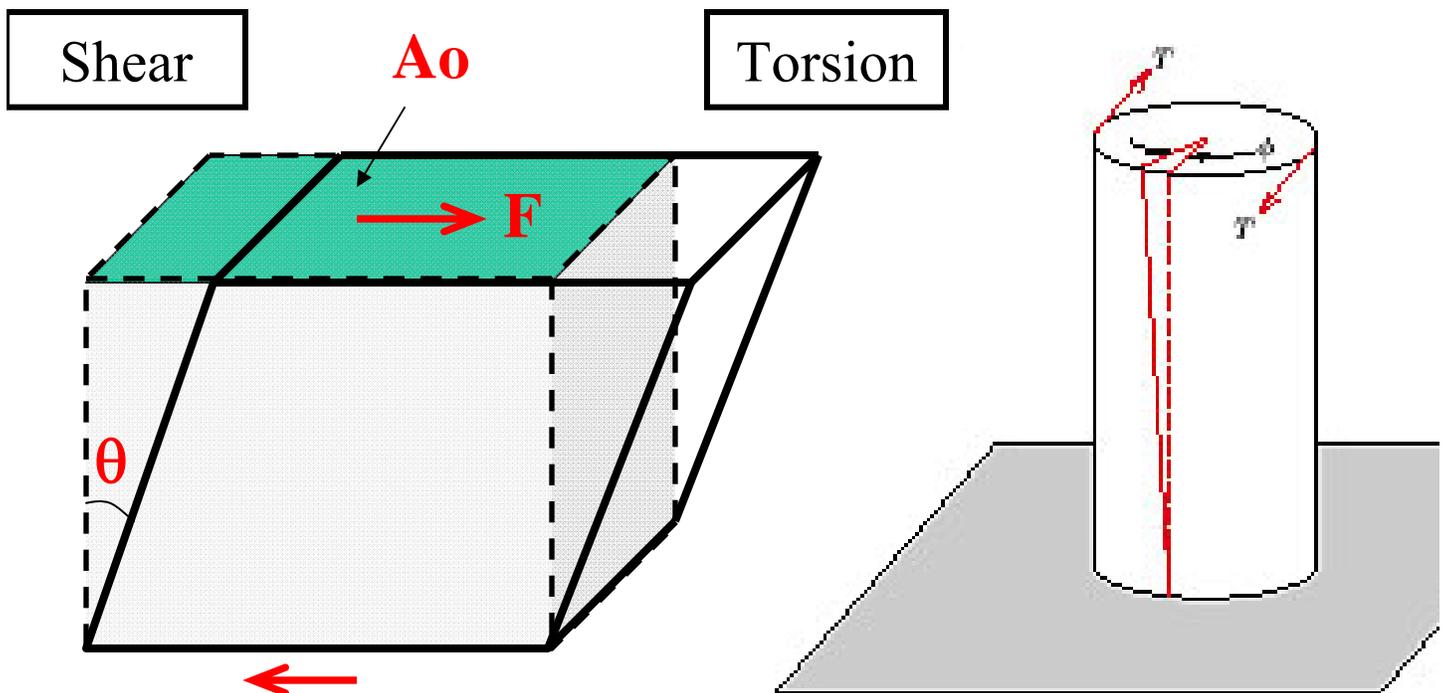
Shear stress: $\tau = F / A_0$

F is load applied parallel to the upper and lower faces each of which has an area A_0 .

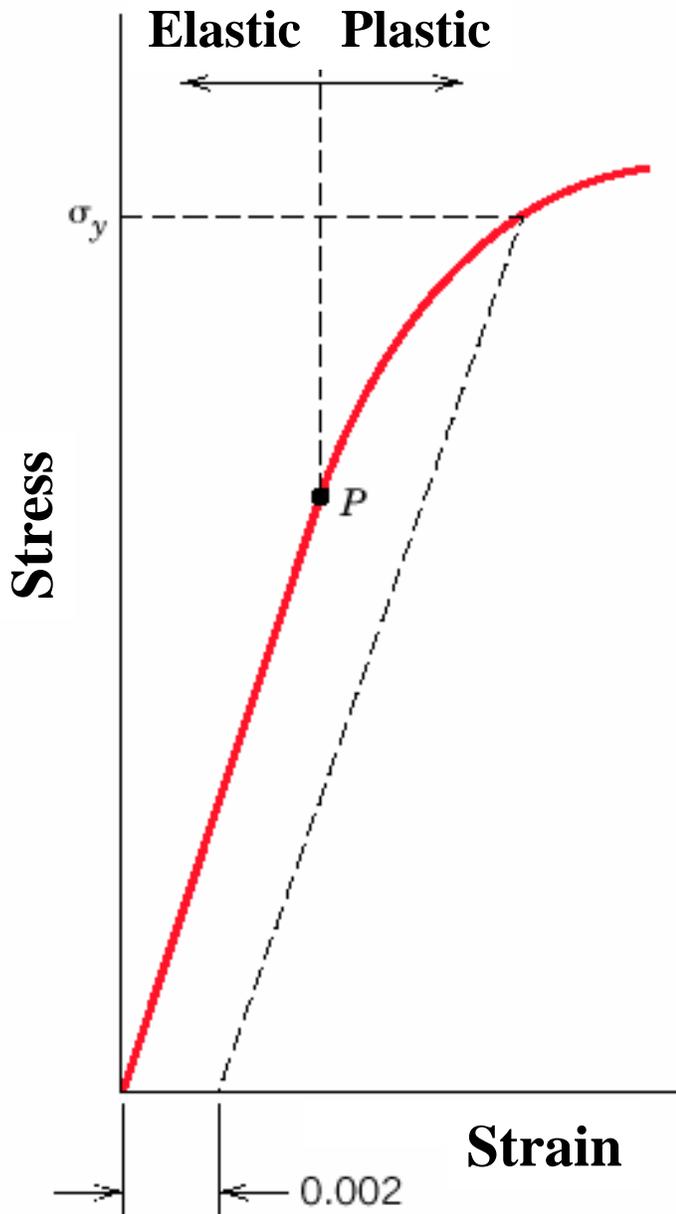
Shear strain: $\gamma = \text{tg}\theta$ ($\times 100\%$)

θ is strain angle

Torsion is variation of pure shear. The shear stress in this case is a function of applied torque T, shear strain is related to the angle of twist, ϕ .



Stress-Strain Behavior



Elastic deformation

Reversible: when the stress is removed, the material returns to the dimensions it had before the loading.

Usually strains are small (except for the case of some plastics, e.g. rubber).

Plastic deformation

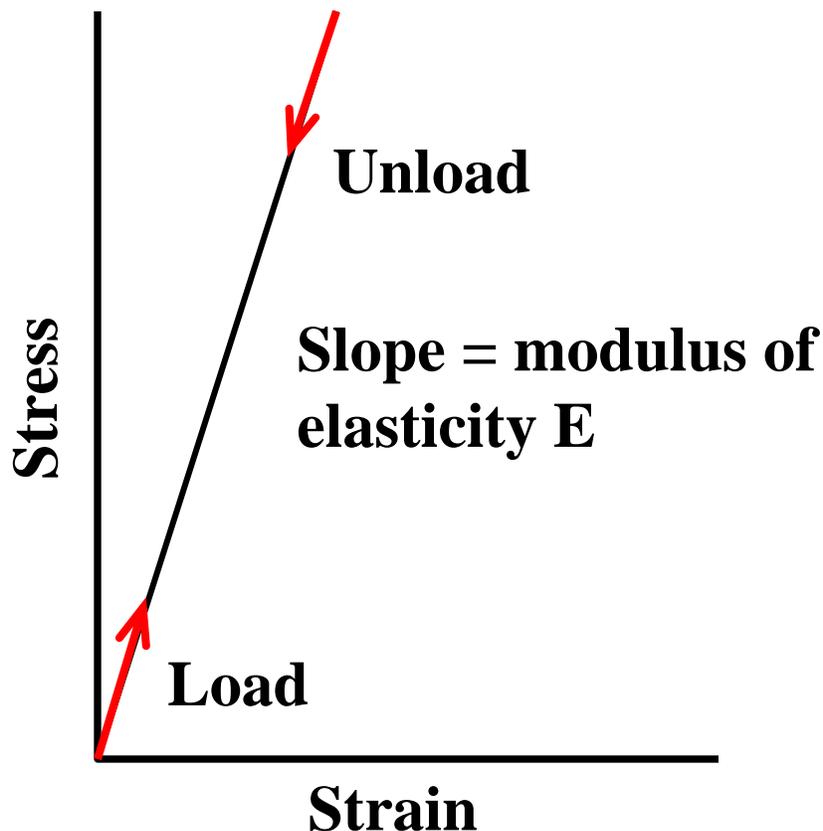
Irreversible: when the stress is removed, the material does not return to its original dimensions.

Stress-Strain Behavior: Elastic Deformation

In tensile tests, if the deformation is elastic, the stress-strain relationship is called **Hooke's law**:

$$\sigma = E \varepsilon$$

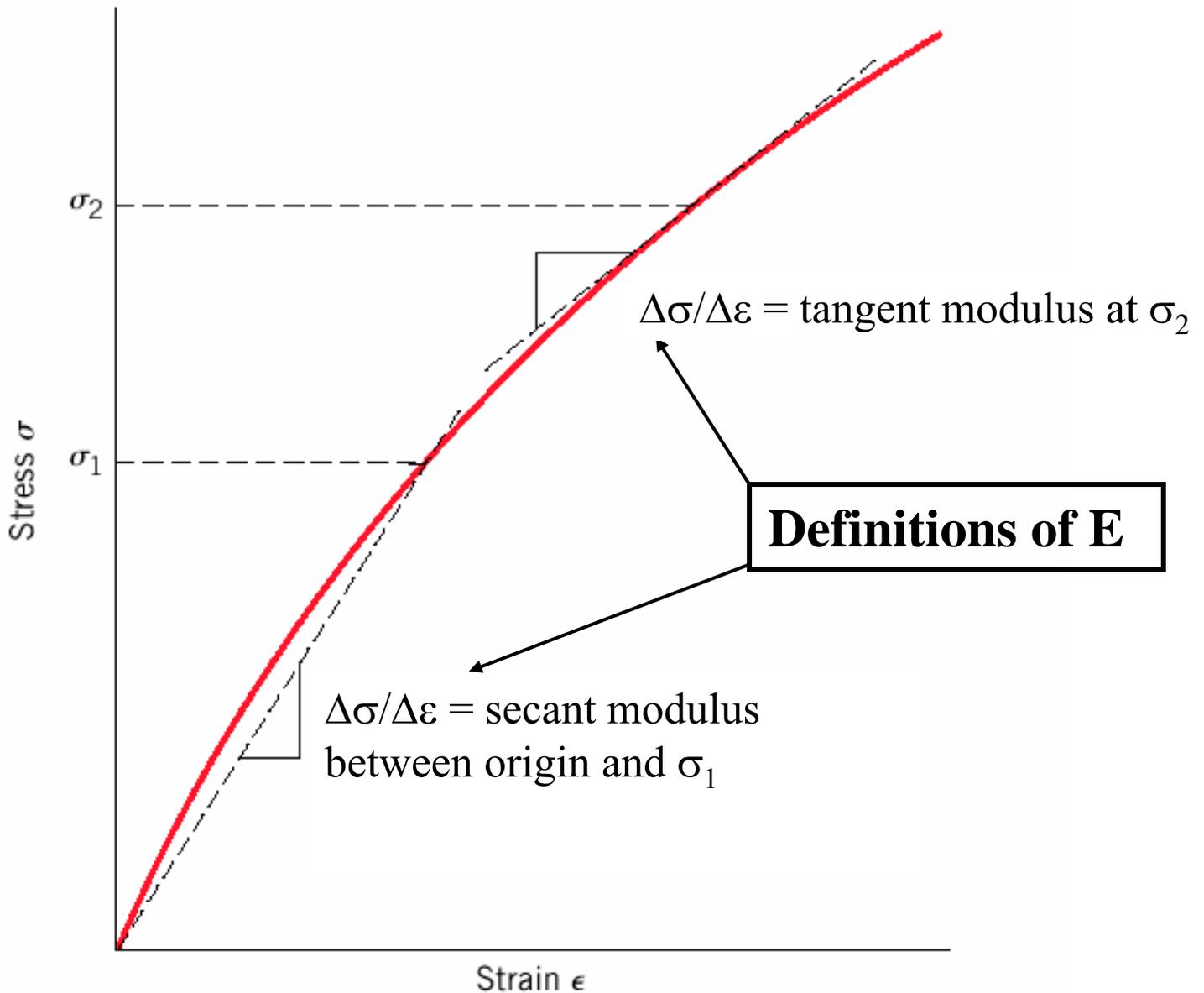
E is **Young's modulus** or **modulus of elasticity**, has the same units as σ , N/m^2 or Pa



Higher E → higher “stiffness”

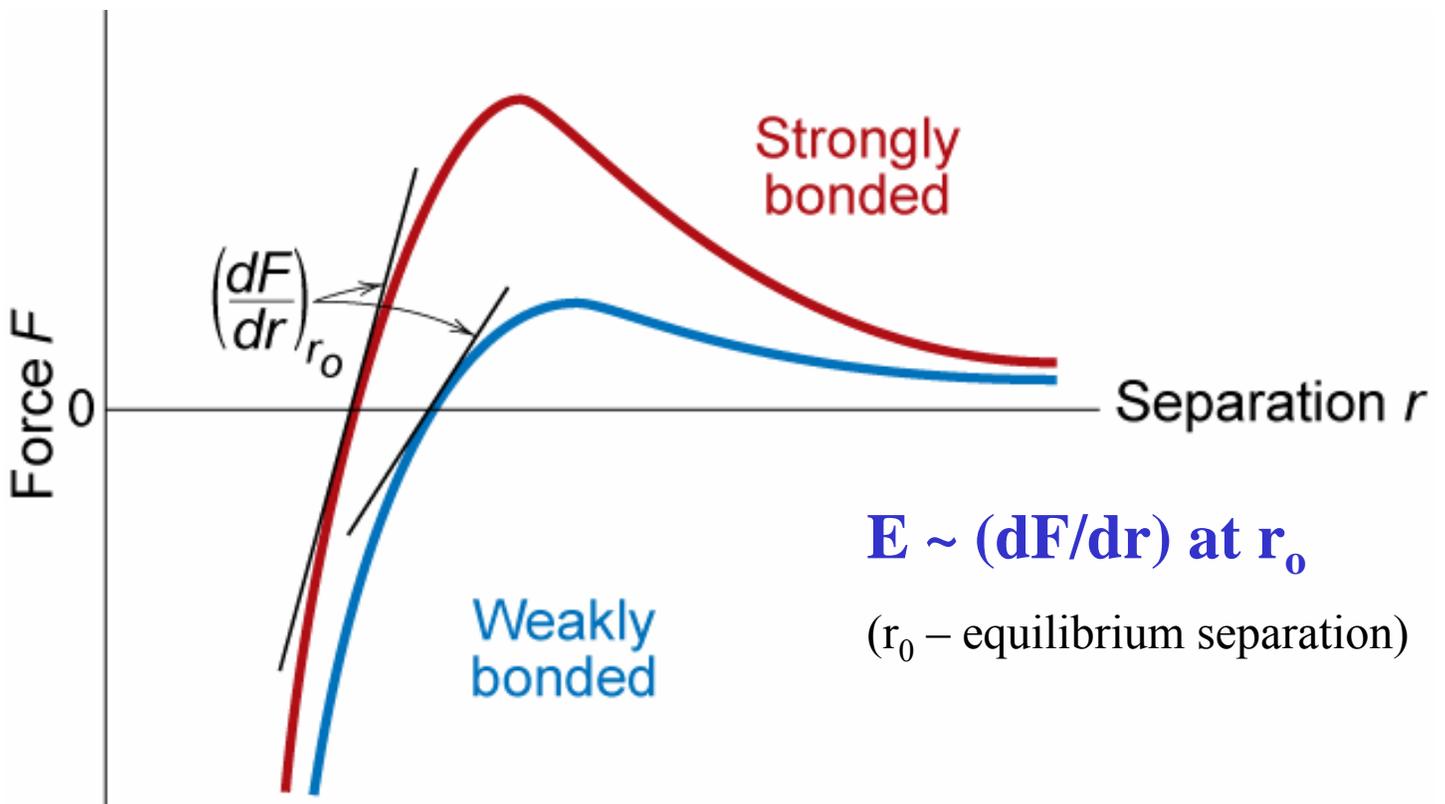
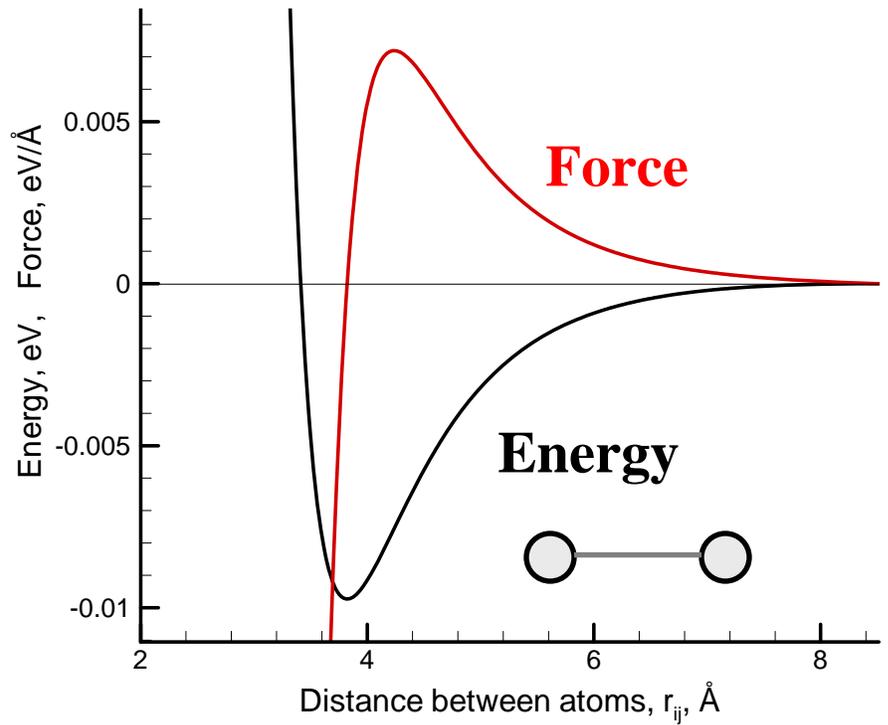
Elastic Deformation: Nonlinear Elastic Behavior

In some materials (many polymers, concrete...), elastic deformation is not linear, but it is still reversible.



Elastic Deformation: Atomic scale picture

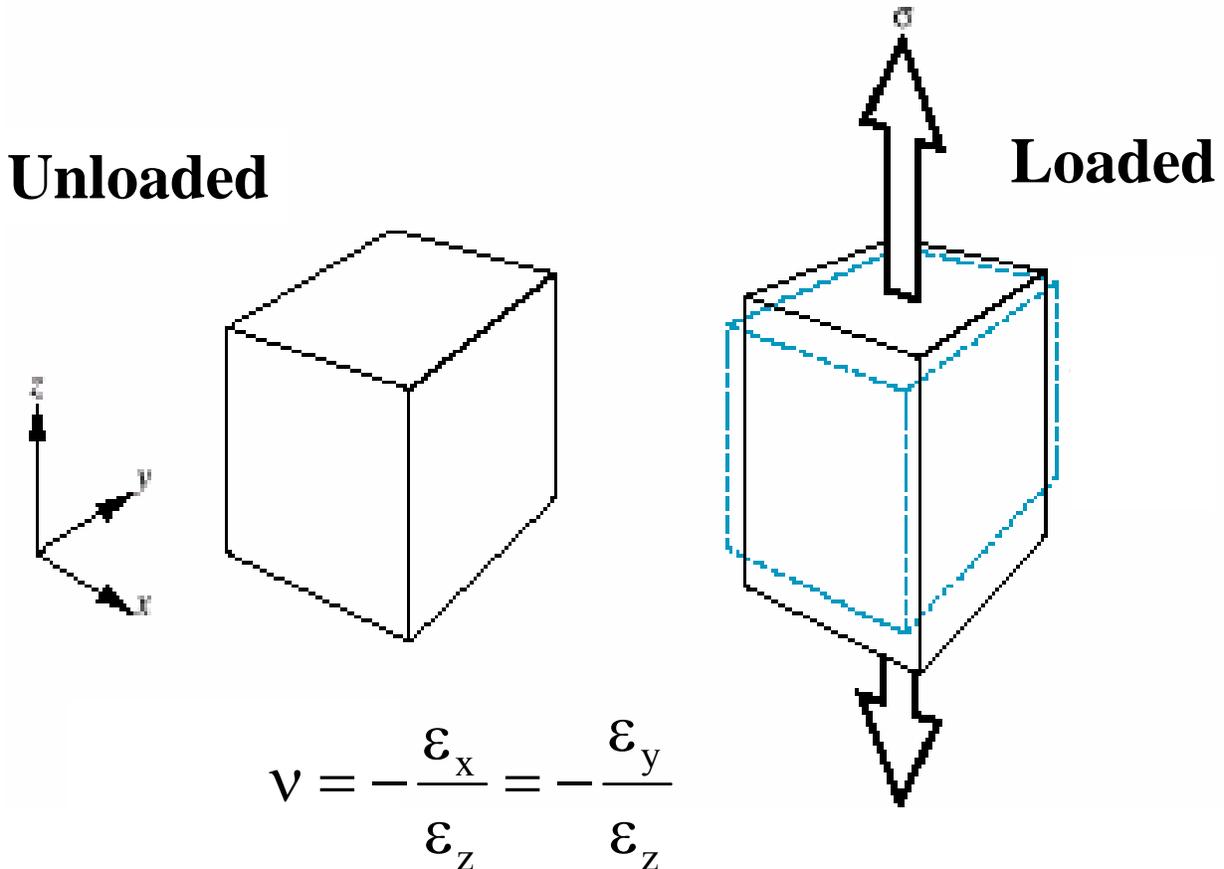
Chapter 2:
force-separation
curve for
interacting atoms



Elastic Deformation: Anelasticity (time dependence of elastic deformation)

- So far we have assumed that elastic deformation is time independent (i.e. applied stress produces instantaneous elastic strain)
- However, in reality elastic deformation takes time (finite rate of atomic/molecular deformation processes) - continues after initial loading, and after load release. This time dependent elastic behavior is known as **anelasticity**.
- The effect is normally small for metals but can be significant for polymers (“**visco-elastic behavior**”).

Elastic Deformation: Poisson's ratio



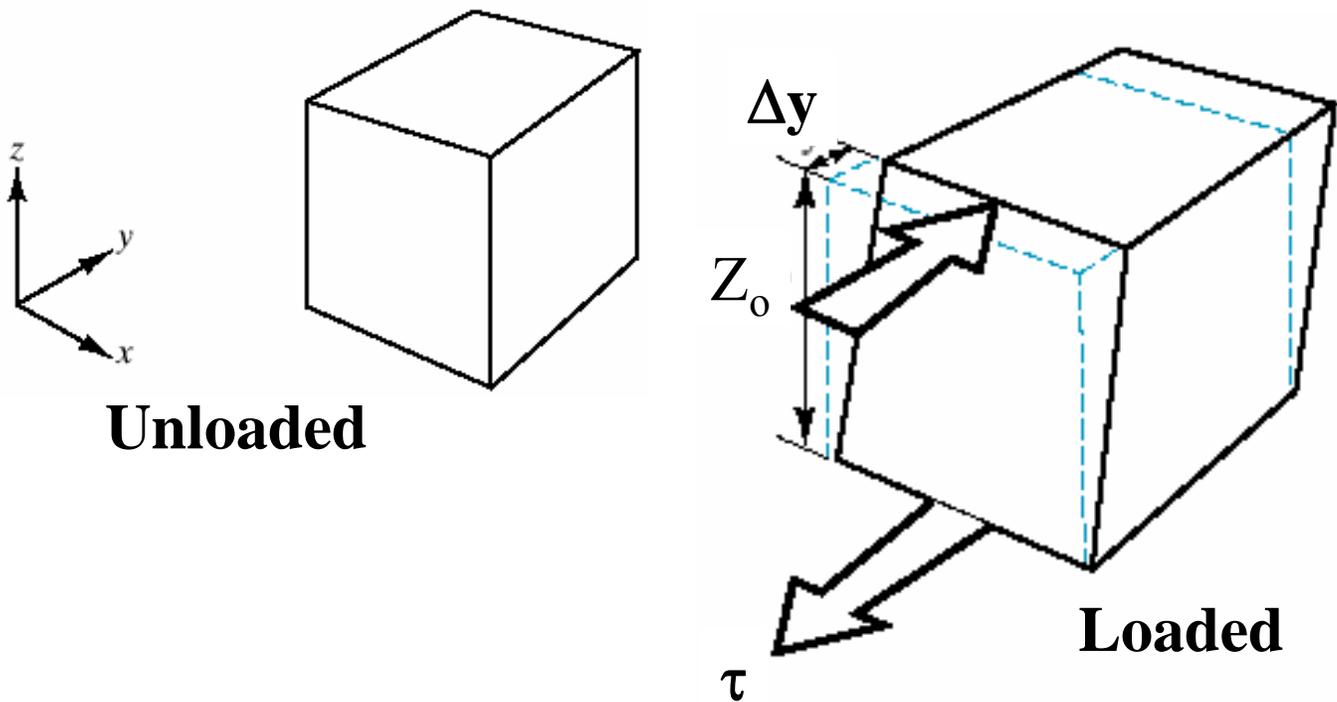
Materials subject to tension shrink laterally. Those subject to compression, bulge. The ratio of lateral and axial strains is called the **Poisson's ratio** ν . Sign in the above equations shows that lateral strain is in opposite sense to longitudinal strain

ν is dimensionless

Theoretical value for isotropic material: 0.25

Maximum value: 0.50, Typical value: 0.24 - 0.30

Elastic Deformation: Shear Modulus



Relationship of shear stress to shear strain:

$$\tau = G \gamma, \text{ where: } \gamma = \text{tg}\theta = \Delta y / z_0$$

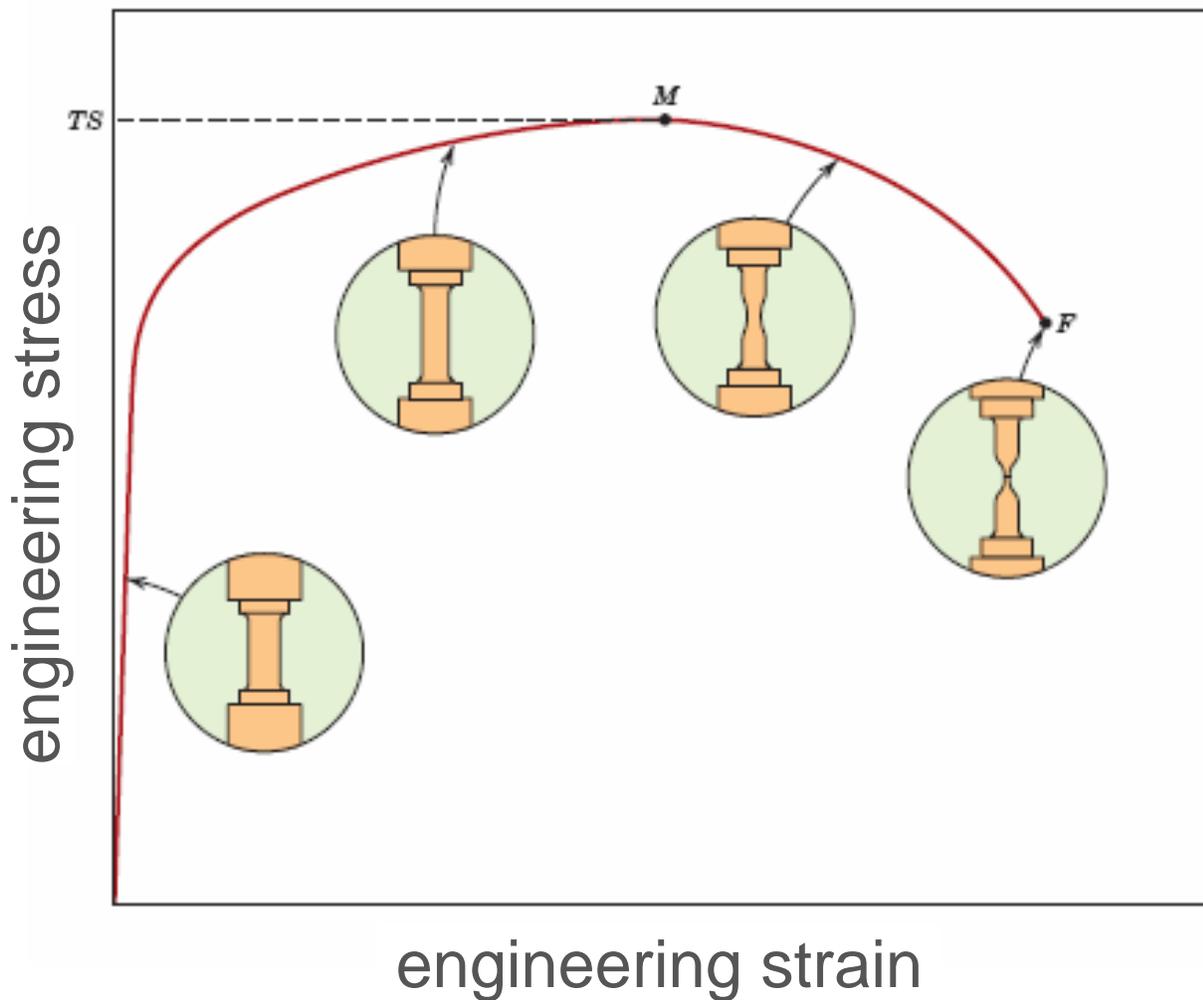
G is Shear Modulus (Units: N/m^2 or Pa)

For isotropic material:

$$\mathbf{E} = 2\mathbf{G}(1+\nu) \rightarrow G \sim 0.4E$$

(Note: single crystals are usually elastically anisotropic: the elastic behavior varies with crystallographic direction, see Chapter 3)

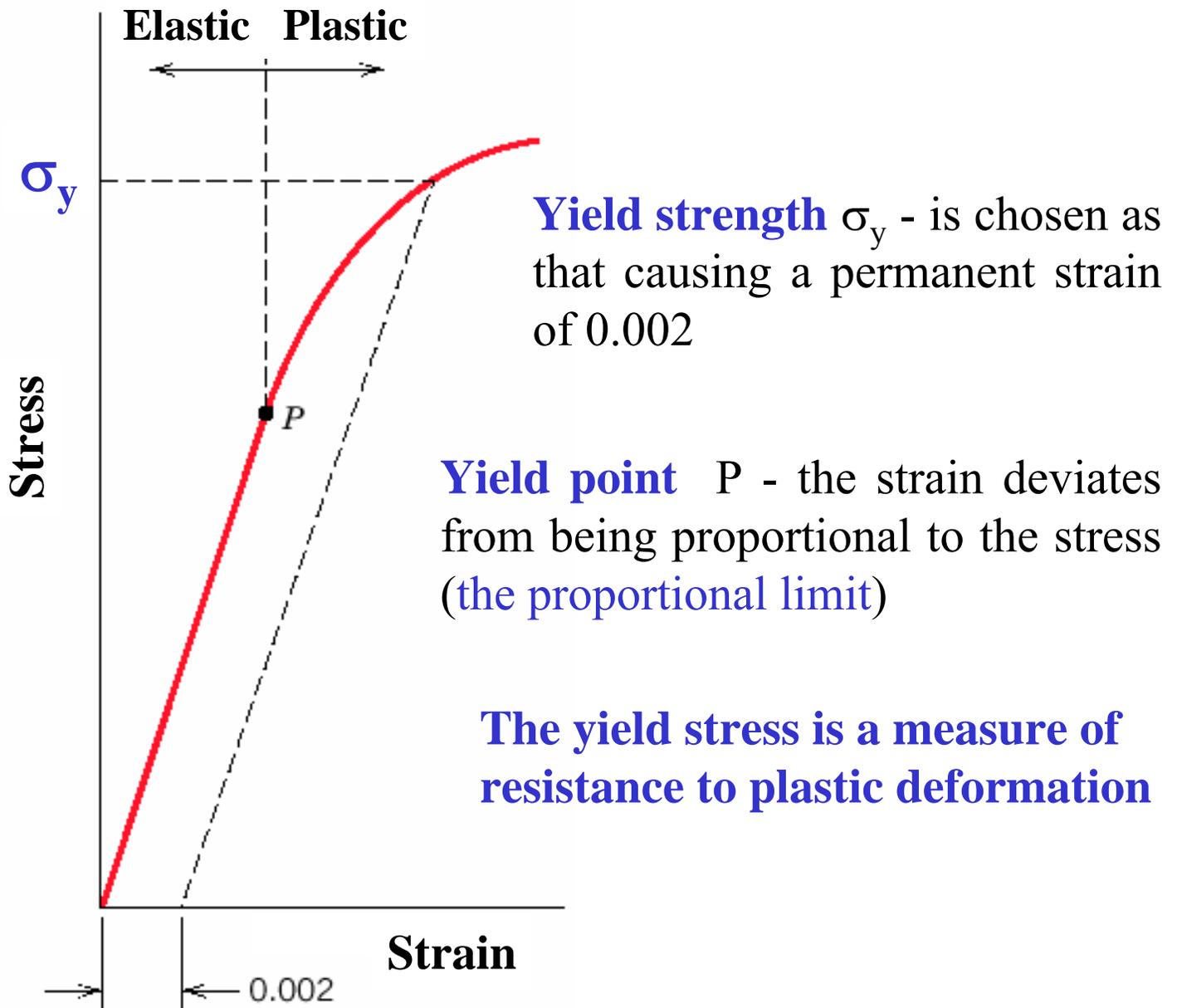
Stress-Strain Behavior: Plastic deformation



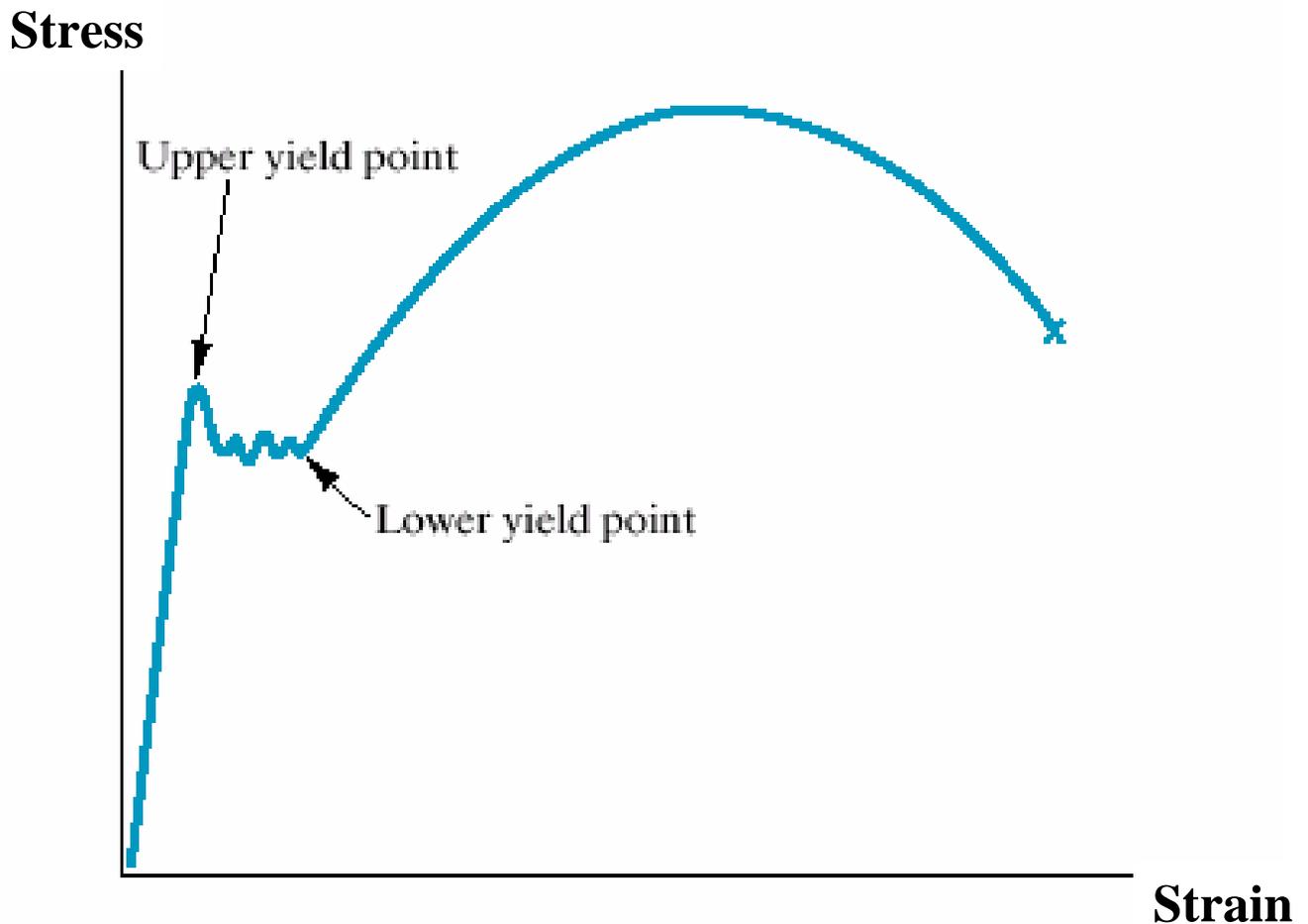
Plastic deformation:

- stress and strain are not proportional to each other
- the deformation is not reversible
- deformation occurs by breaking and re-arrangement of atomic bonds (in crystalline materials primarily by motion of dislocations, Chapter 7)

Tensile Properties: Yielding



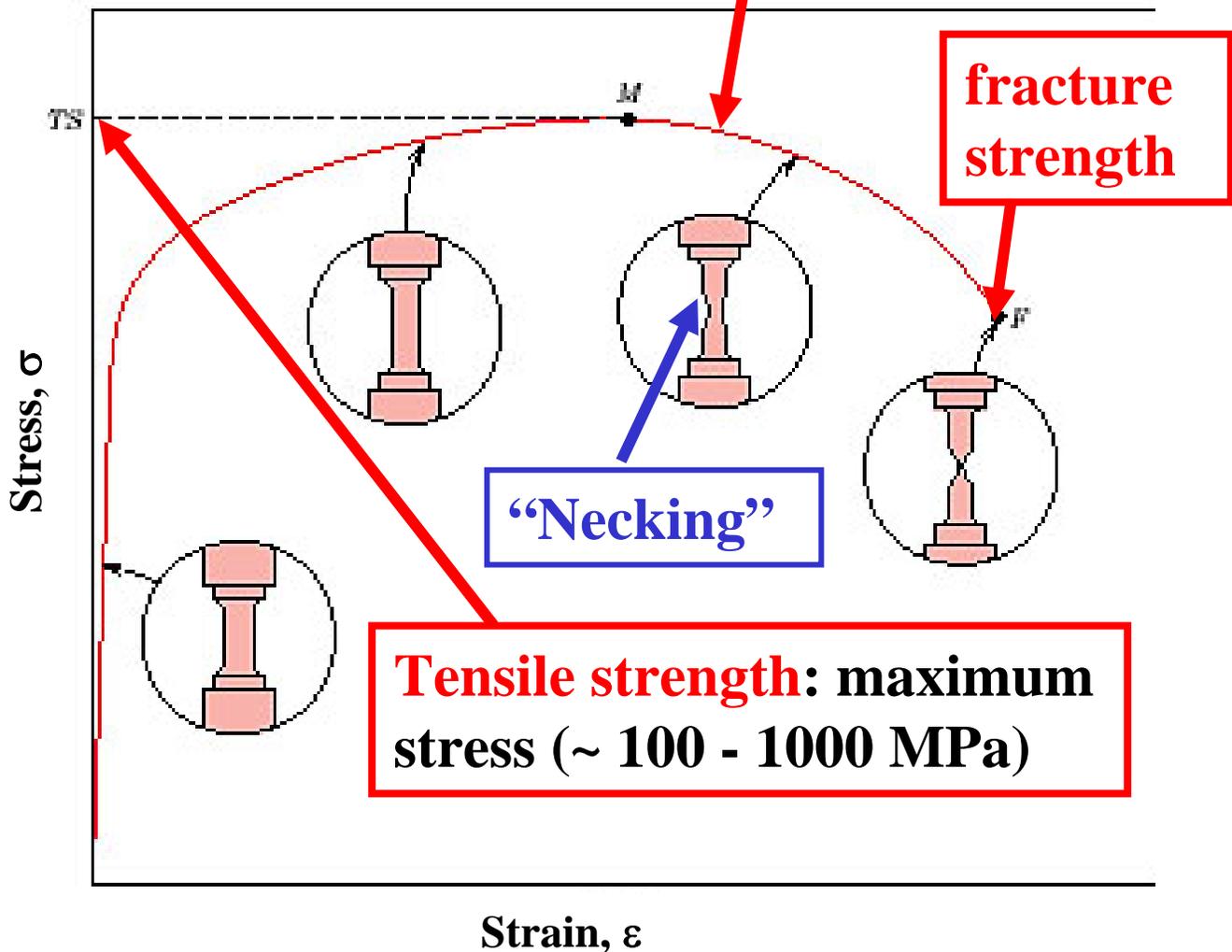
Tensile Properties: Yielding



In some materials (e.g. low-carbon steel), the stress vs. strain curve includes two yield points (upper and lower). The yield strength is defined in this case as the average stress at the lower yield point.

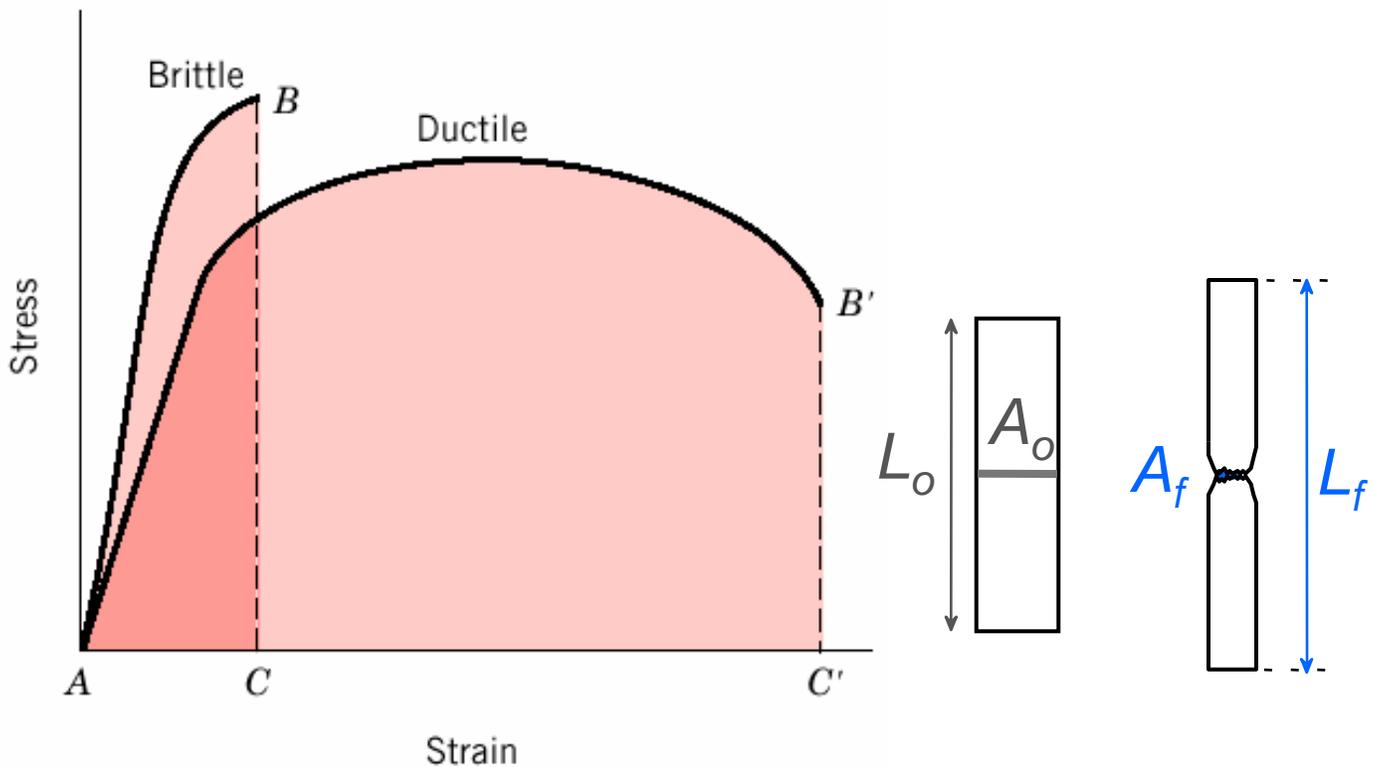
Tensile Strength

If stress = **tensile strength** is maintained then specimen will eventually break



For structural applications, the yield stress is usually a more important property than the tensile strength, since once the yield stress has passed, the structure has deformed beyond acceptable limits.

Tensile properties: Ductility



Ductility is a measure of the deformation at fracture

Defined by **percent elongation** (plastic tensile strain at failure)

$$\%EL = \left(\frac{l_f - l_0}{l_0} \right) \times 100$$

or **percent reduction in area**

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

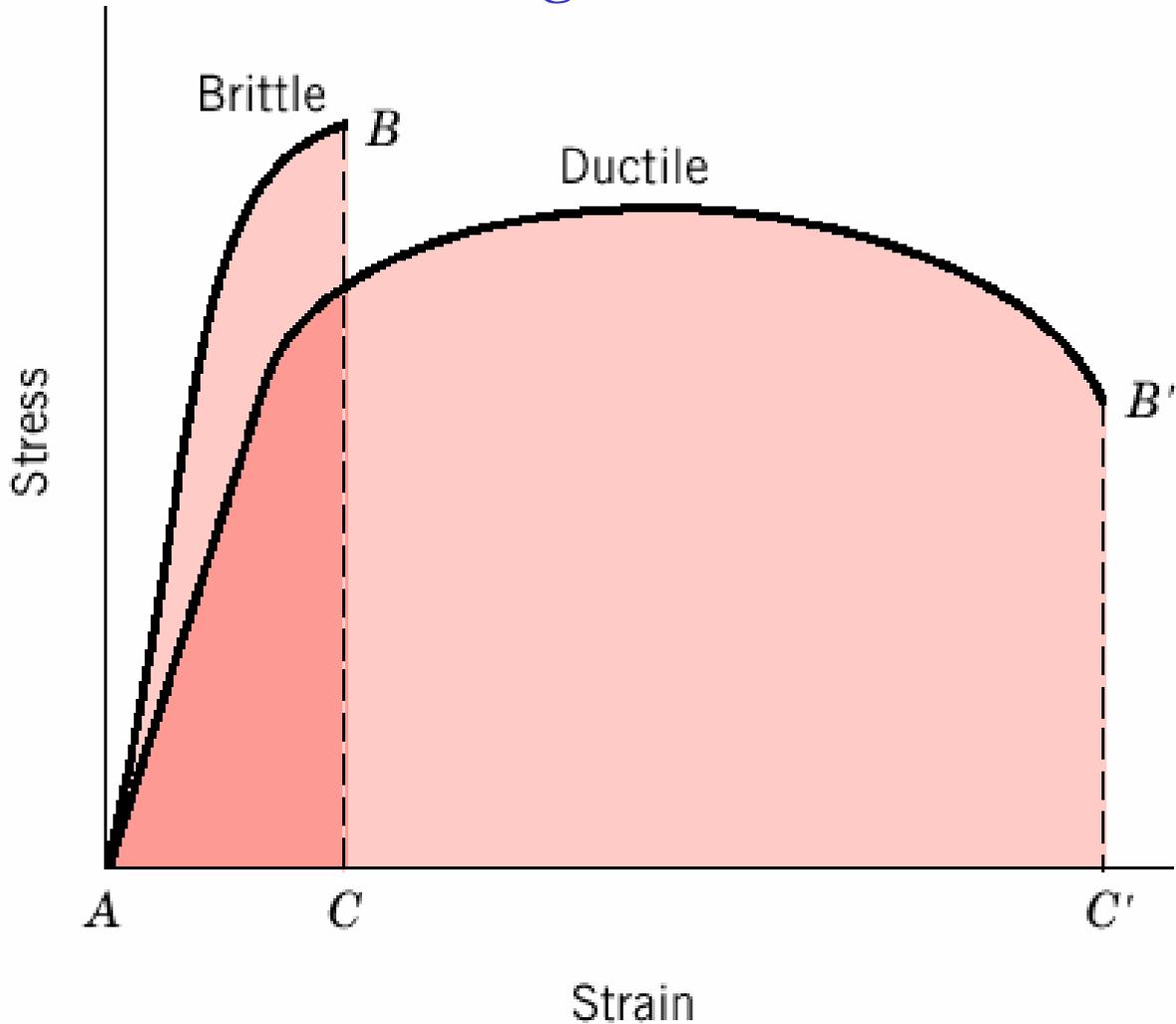
Typical mechanical properties of metals

| <i>Metal Alloy</i> | <i>Yield Strength MPa (ksi)</i> | <i>Tensile Strength MPa (ksi)</i> | <i>Ductility, %EL [in 50 mm (2 in.)]</i> |
|--------------------|-------------------------------------|---------------------------------------|--|
| Aluminum | 35 (5) | 90 (13) | 40 |
| Copper | 69 (10) | 200 (29) | 45 |
| Brass (70Cu–30Zn) | 75 (11) | 300 (44) | 68 |
| Iron | 130 (19) | 262 (38) | 45 |
| Nickel | 138 (20) | 480 (70) | 40 |
| Steel (1020) | 180 (26) | 380 (55) | 25 |
| Titanium | 450 (65) | 520 (75) | 25 |
| Molybdenum | 565 (82) | 655 (95) | 35 |

The yield strength and tensile strength vary with prior thermal and mechanical treatment, impurity levels, etc. This variability is related to the behavior of dislocations in the material, Chapter 7. But elastic moduli are relatively insensitive to these effects.

The yield and tensile strengths and modulus of elasticity decrease with increasing temperature, ductility increases with temperature.

Toughness



Toughness = the ability to absorb energy up to fracture = the total area under the strain-stress curve up to fracture

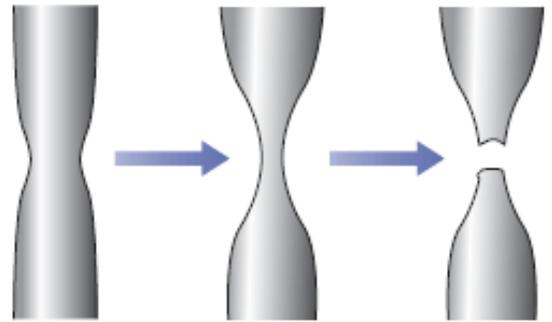
$$\int_0^{\epsilon_f} \sigma d\epsilon$$

Units: the energy per unit volume, e.g. J/m³

Can be measured by an impact test (Chapter 8).

True Stress and Strain

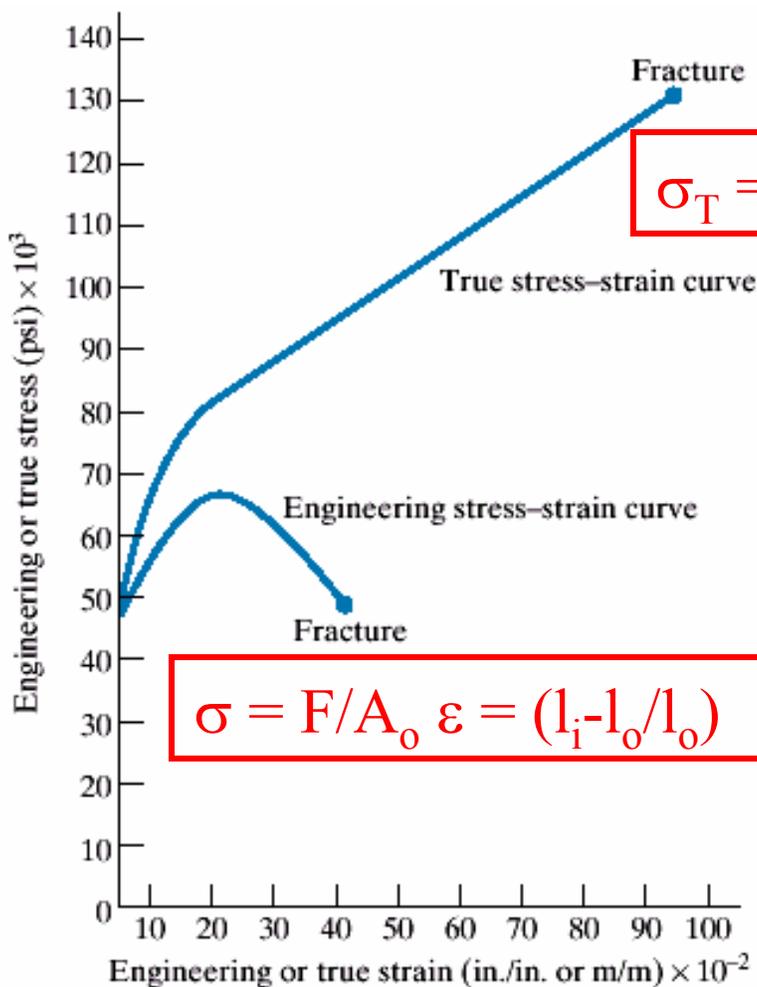
True stress = load divided by **actual area** in the necked-down region (A_i): $\sigma_T = F/A_i$



Sometimes it is convenient to use **true strain** defined as

$$\epsilon_T = \ln(l_i/l_o)$$

True stress continues to rise to the point of fracture, in contrast to the engineering stress.



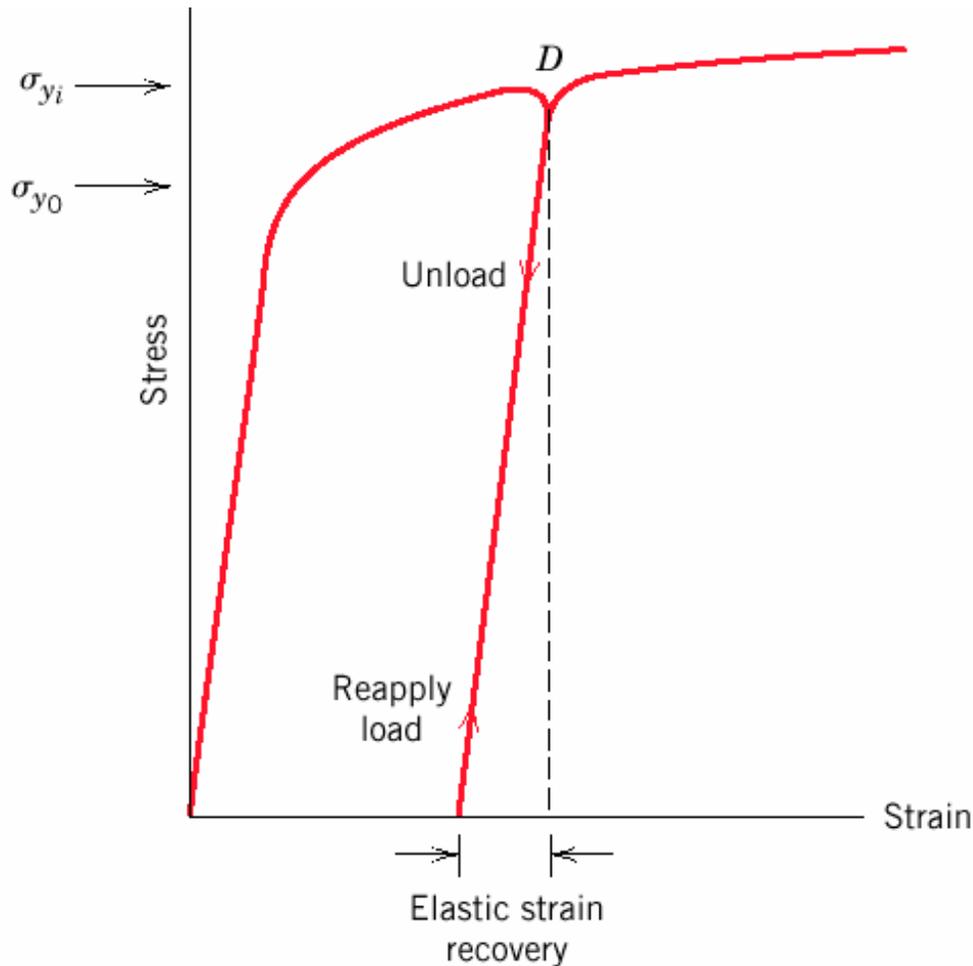
$$\sigma_T = F/A_i \quad \epsilon_T = \ln(l_i/l_o)$$

If no volume change occurs during deformation, $A_i l_i = A_0 l_0$ and the true and engineering stress and strain are related as

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

$$\epsilon_T = \ln(1 + \epsilon)$$

Elastic Recovery During Plastic Deformation



If a material is deformed plastically and the stress is then released, the material ends up with a permanent strain.

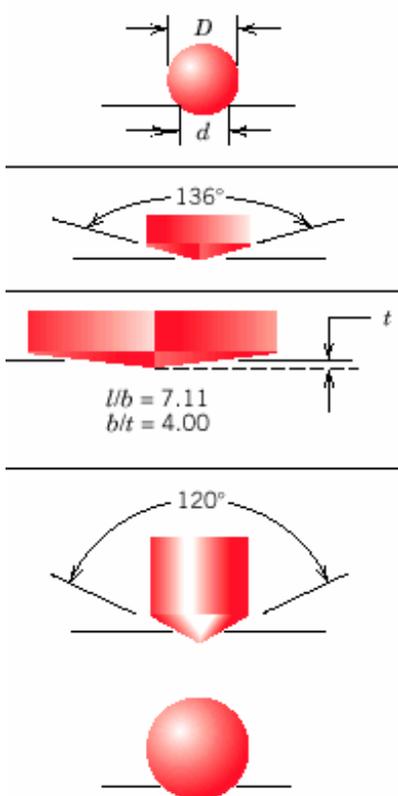
If the stress is reapplied, the material again responds elastically at the beginning up to a new yield point that is **higher than the original yield point**.

The amount of elastic strain that it will take before reaching the yield point is called **elastic strain recovery**.

Hardness (I)

Hardness is a measure of the material's resistance to localized plastic deformation (e.g. dent or scratch)

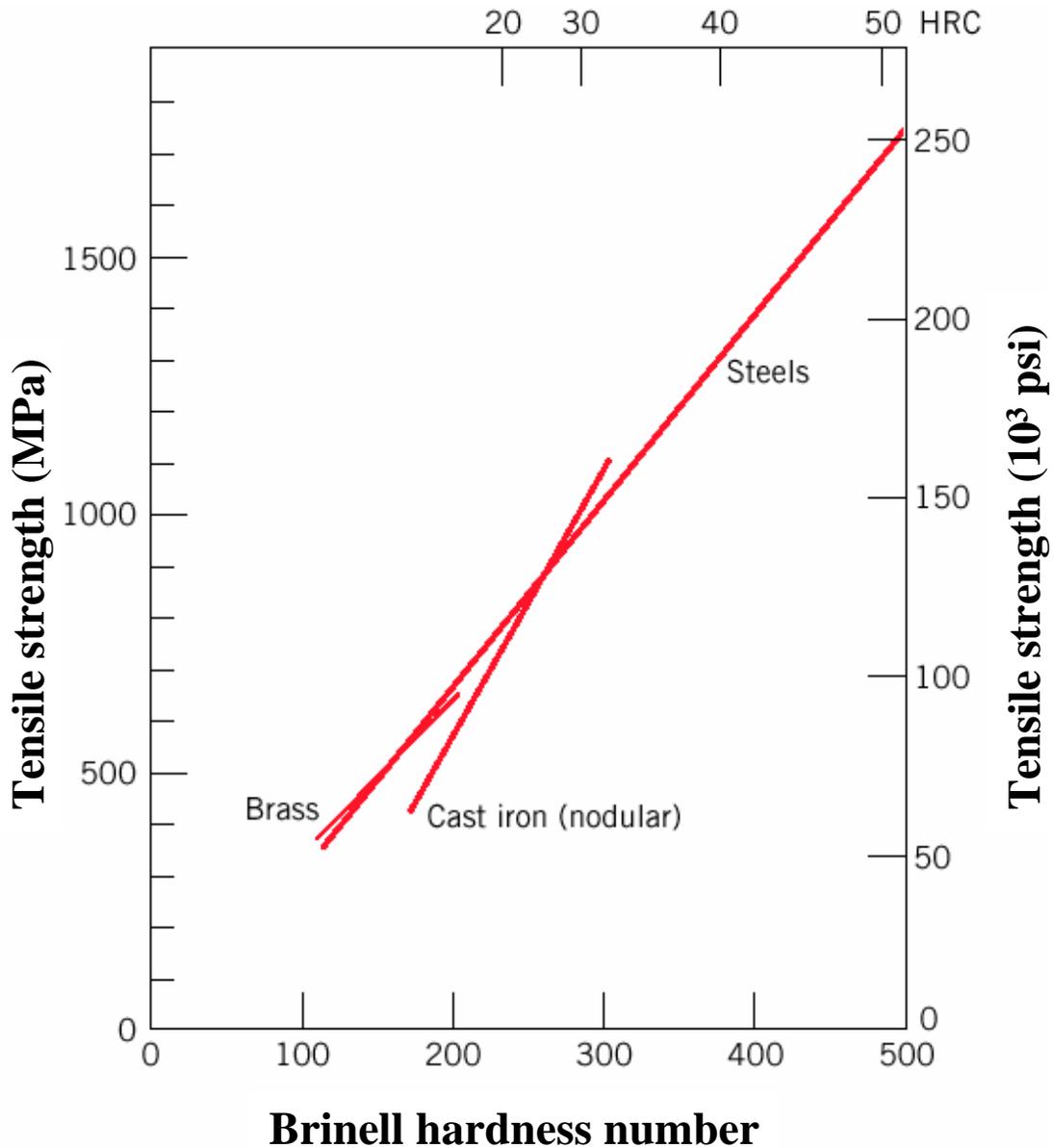
A qualitative Moh's scale, determined by the ability of a material to scratch another material: from 1 (softest = talc) to 10 (hardest = diamond).



Different types of quantitative hardness test has been designed (Rockwell, Brinell, Vickers, etc.). Usually a small indenter (sphere, cone, or pyramid) is forced into the surface of a material under conditions of controlled magnitude and rate of loading. The depth or size of indentation is measured.

The tests somewhat approximate, but popular because they are easy and non-destructive (except for the small dent).

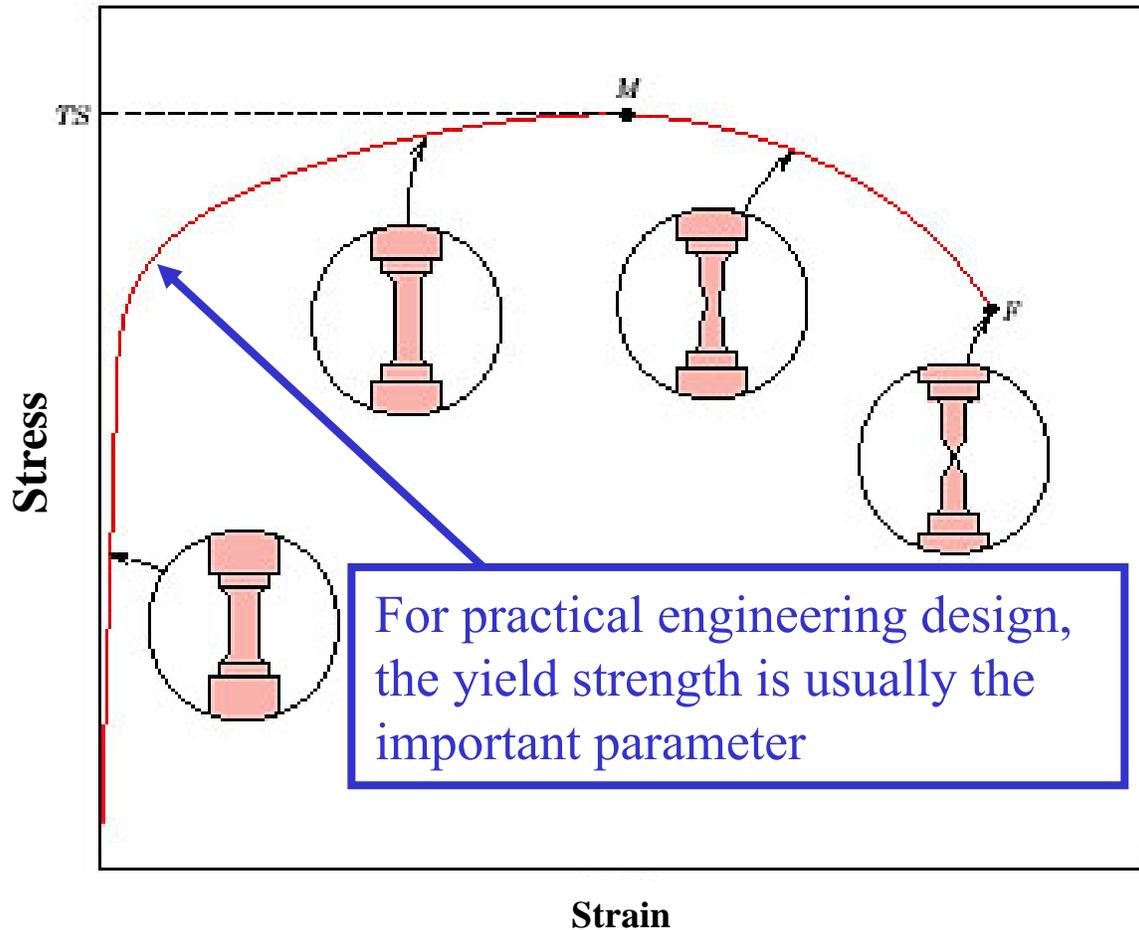
Hardness (II)



Both tensile strength and hardness may be regarded as degree of resistance to plastic deformation.

Hardness is proportional to the tensile strength - but note that the proportionality constant is different for different materials.

What are the limits of “safe” deformation?



Design stress: $\sigma_d = N'\sigma_c$ where σ_c = maximum anticipated stress, N' is the “design factor” > 1 . Want to make sure that $\sigma_d < \sigma_y$

Safe or working stress: $\sigma_w = \sigma_y/N$ where N is “factor of safety” > 1 .

Summary

- **Stress** and **strain**: Size-independent measures of load and displacement, respectively.
- **Elastic** behavior: Reversible mechanical deformation, often shows a linear relation between stress and strain.
- Elastic deformation is characterized by **elastic moduli** (E or G). To minimize deformation, select a material with a large elastic moduli (E or G).
- **Plastic** behavior: Permanent deformation, occurs when the tensile (or compressive) uniaxial stress reaches the **yield strength** σ_y .
- **Tensile strength**: maximum stress supported by the material.
- **Toughness**: The energy needed to break a unit volume of material.
- **Ductility**: The plastic strain at failure.

Summary

Make sure you understand language and concepts:

- Anelasticity
- Ductility
- Elastic deformation
- Elastic recovery
- Engineering strain and stress
- Engineering stress
- Hardness
- Modulus of elasticity
- Plastic deformation
- Poisson's ratio
- Shear
- Tensile strength
- True strain and stress
- Toughness
- Yielding
- Yield strength

Reading for next class:

Chapter 7: Dislocations and Strengthening Mechanisms

➤ Dislocations and Plastic Deformation

- ✓ Motion of dislocations in response to stress
- ✓ Slip Systems
- ✓ Plastic deformation in
 - single crystals
 - polycrystalline materials

➤ Strengthening mechanisms

- ✓ Grain Size Reduction
- ✓ Solid Solution Strengthening
- ✓ Strain Hardening

➤ Recovery, Recrystallization, and Grain Growth

Optional reading (Part that is not covered / not tested):

7.7 Deformation by twinning

In our discussion of slip systems, §7.4, we will not get into direction and plane nomenclature