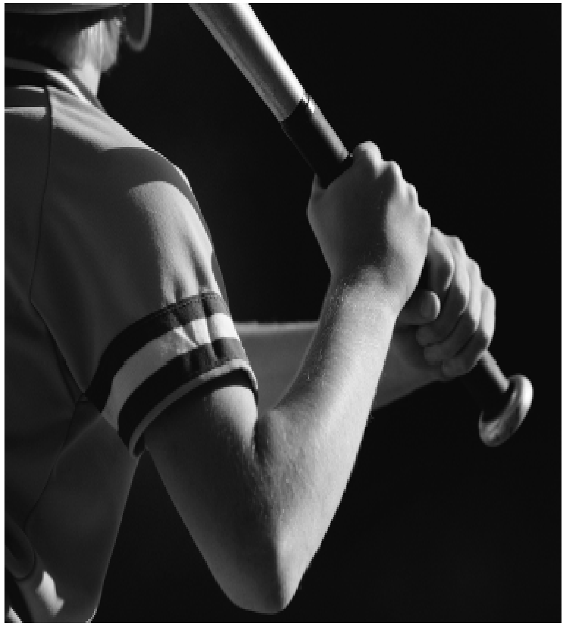
Introduction to

Materials Science and Engineering

Chap. 6. Mechanical Properties

Technological Significance

Aircraft, such as the one shown here, makes use of aluminum alloys and carbon-fiber-reinforced composites.



The materials used in sports equipment must be lightweight, stiff, tough, and impact resistant.

Various Tests for Plastic Deformation

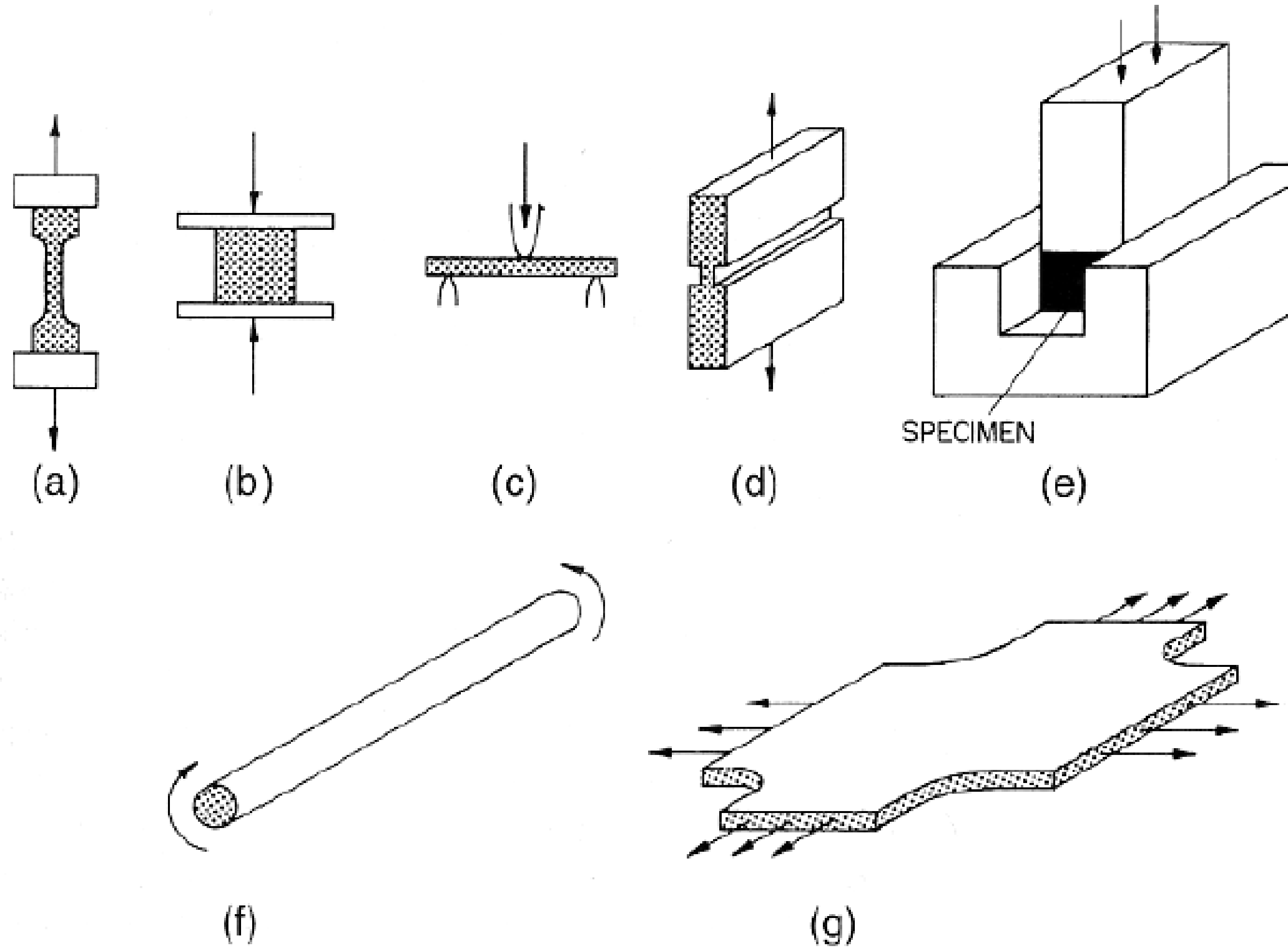
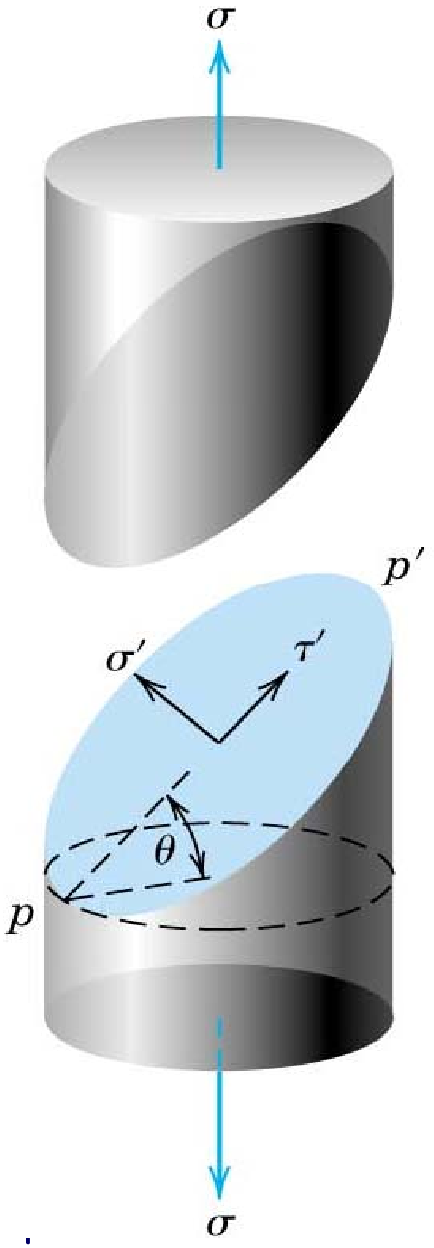
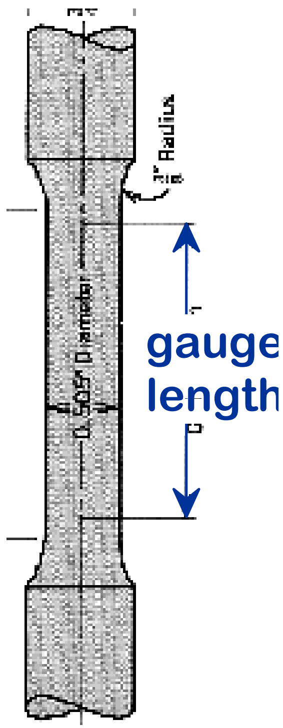


Figure 3.1 Common tests used to determine the monotonic strength of metals. (a) Uniaxial tensile test. (b) Upsetting test. (c) Three-point bending test. (d) Plane-strain tensile test. (e) Plane-strain compression (Ford) test. (f) Torsion test. (g) Biaxial test.

Schematics of Normal and Tensile Stresses



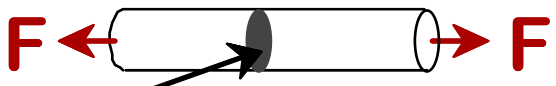


(Fig. 6-4)

Schematic representation showing normal (σ') and shear (τ') stresses that act on a plane oriented at an angle θ relative to the plane taken perpendicular to the direction along which a pure tensile stress (σ) is applied.

Common States of Stress

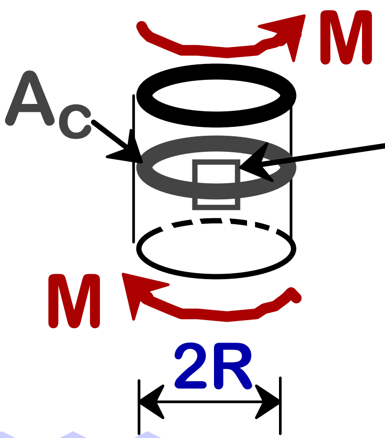
Simple tension: cable

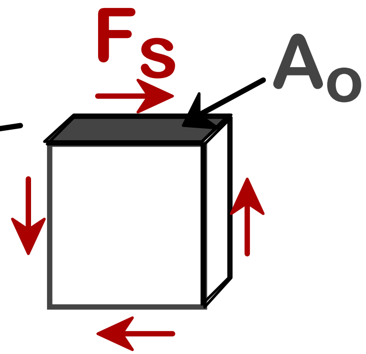


A_o = cross sectional Area (when unloaded)

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

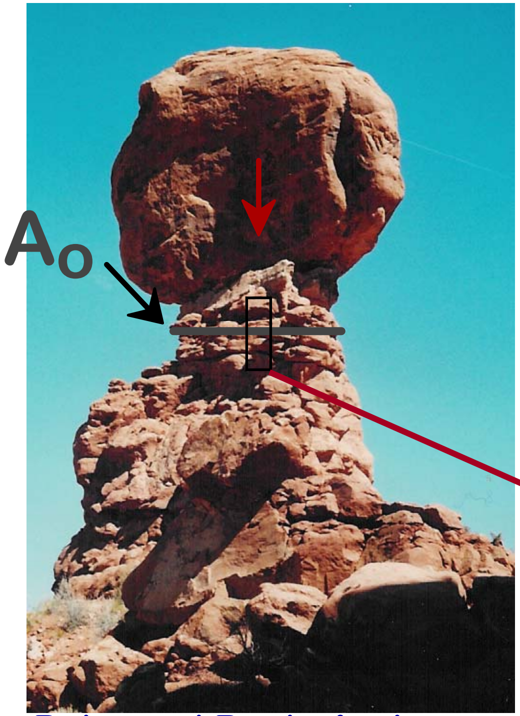
Simple shear: drive shaft



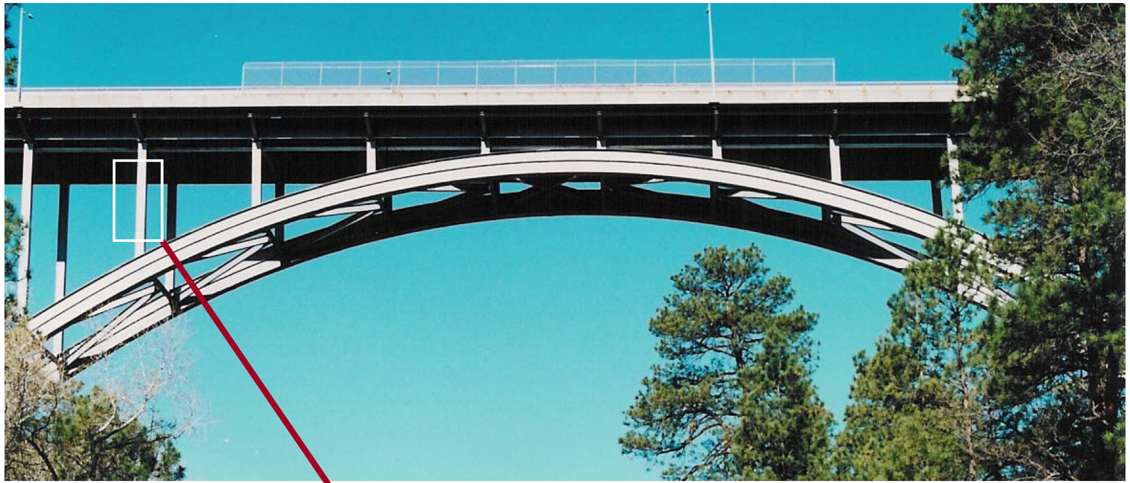


$$\tau = \frac{F_s}{A_o}$$

Simple compression

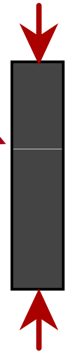


Balanced Rock, Arches National Park



Canyon Bridge, Los Alamos, NM

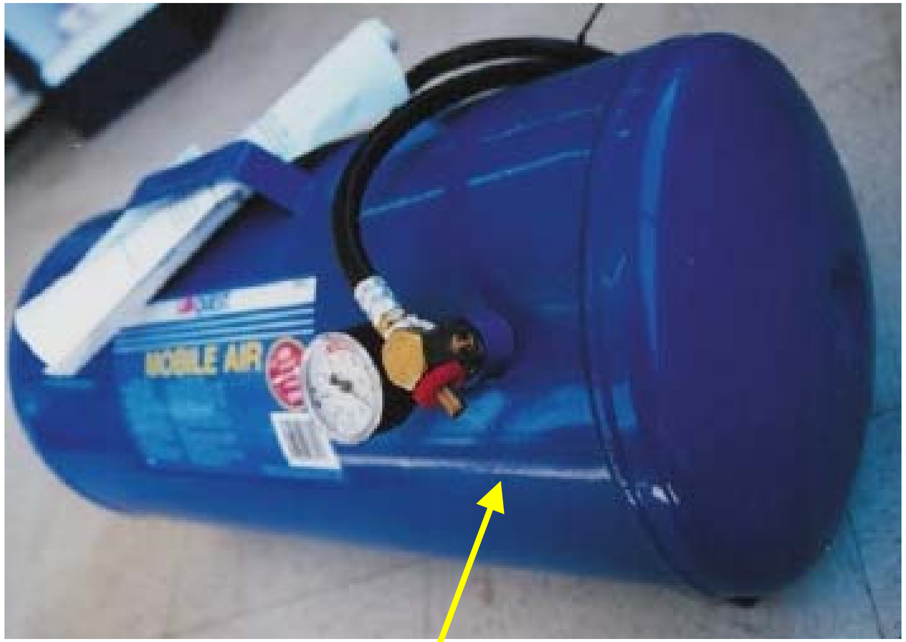
$$\sigma = \frac{F}{A_o}$$



Compressive structure member

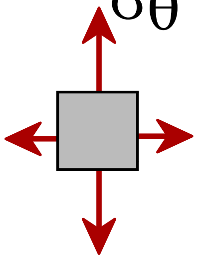
Common States of Stress

Hydrostatic Tension



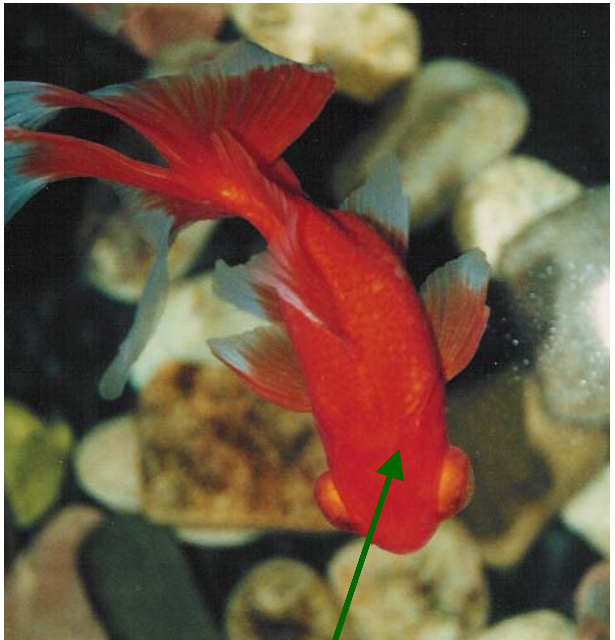
Pressurized tank

$\sigma_\theta > 0$

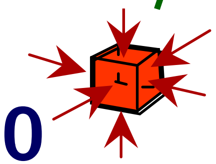


$\sigma_z > 0$

Hydrostatic Compression



Fish under water



$\sigma_h < 0$

- **Stress and strain:**

  What are they and why are they used, instead of load and deformation?

- **Elastic behavior:**

  When loads are small, how much deformation occurs? What materials deform least?

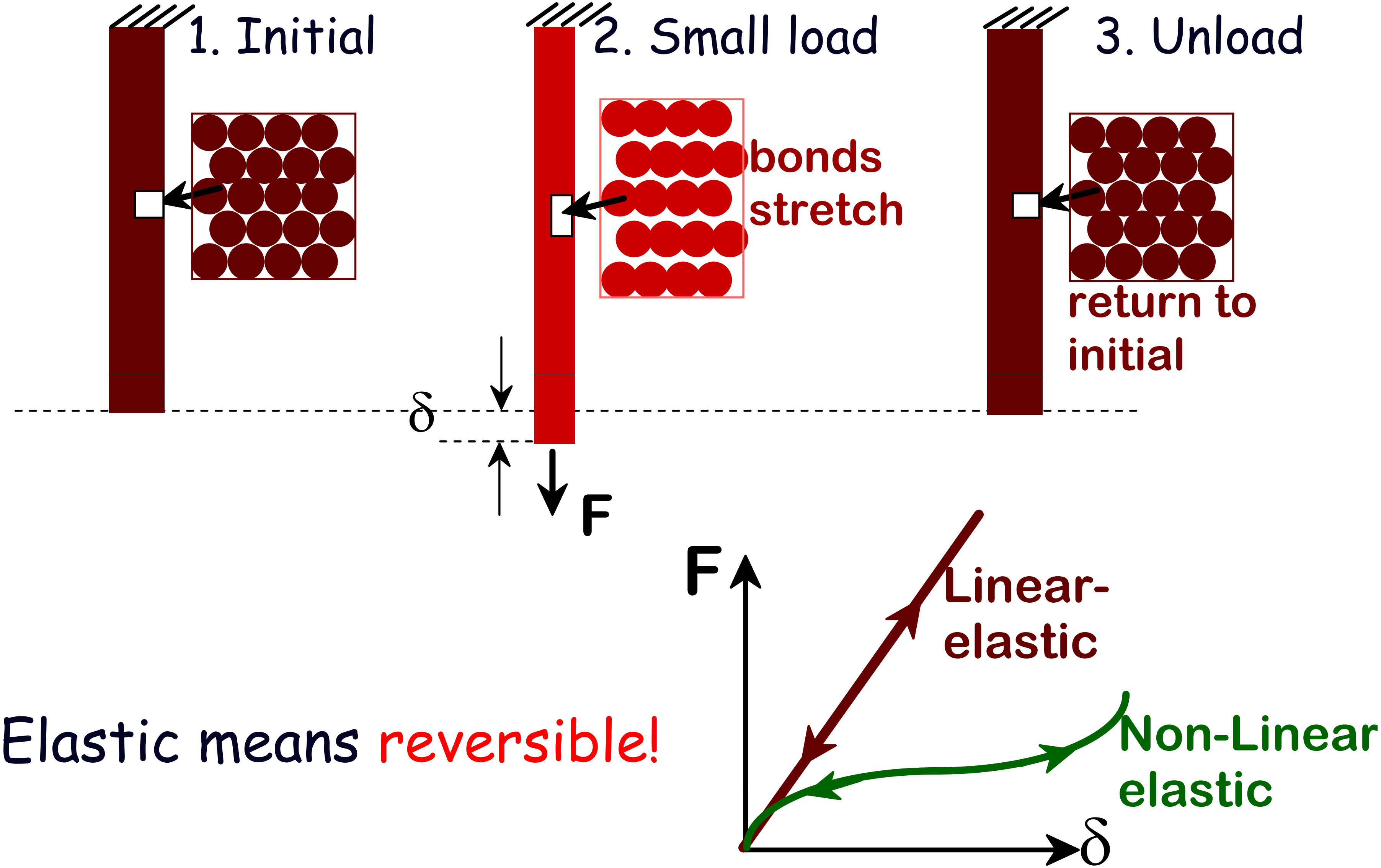
- **Plastic behavior:**

  At what point do dislocations cause permanent deformation? What materials are most resistant to permanent deformation?

Contents

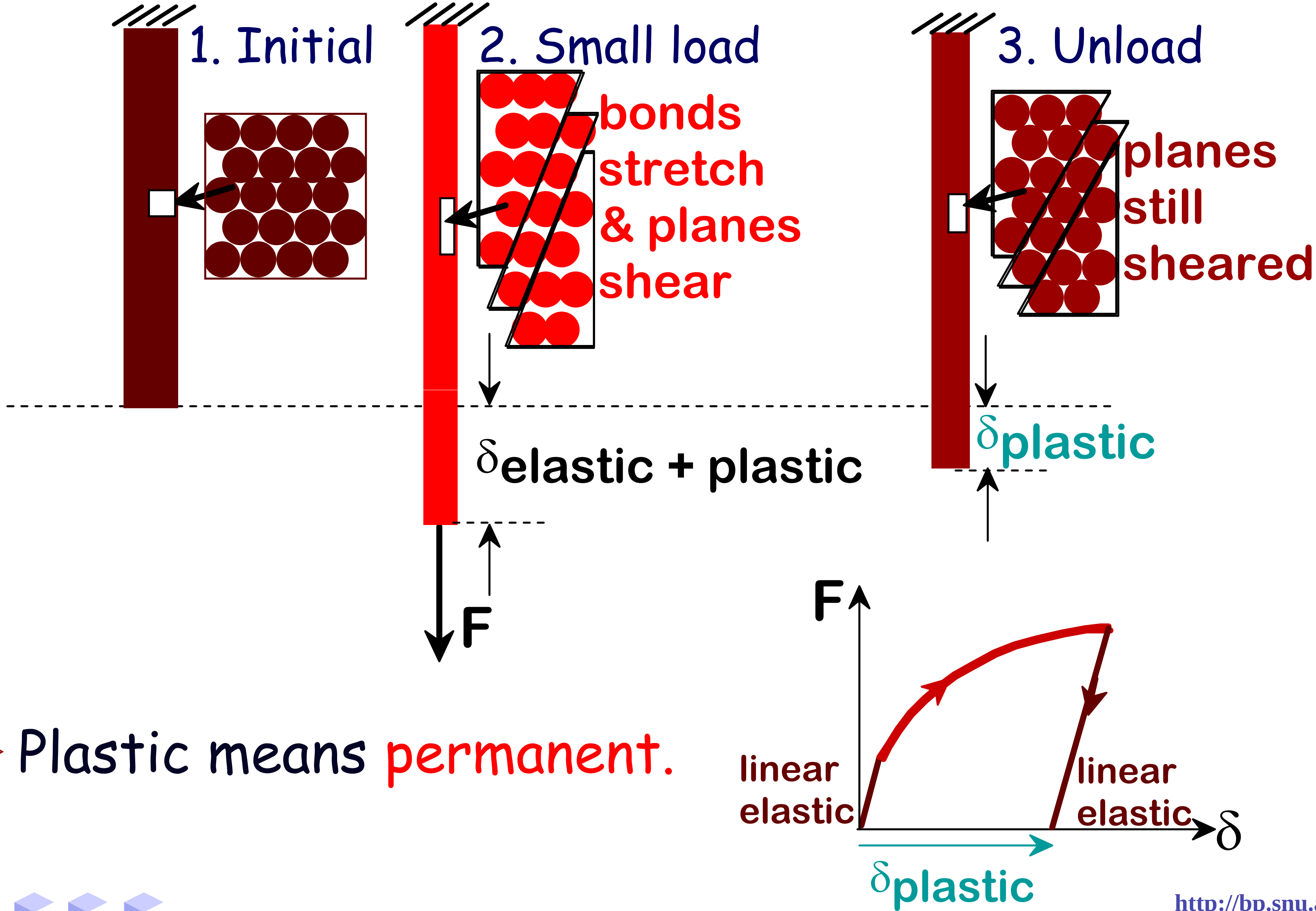
- Load - The force applied to a material during testing
- Stress - Force or load per unit area of cross-section overwhich the force or load is acting
- Strain - Elongation change in dimension per unit length
- Engineering stress - The applied load, or force, divided by the original cross-sectional area of the material
- Engineering strain - The amount that a material deforms per unit length in a tensile test
- True stress - The load divided by the actual cross-sectional area of the specimen at that load
- True strain - The strain calculated using actual and not original dimensions, given by $\varepsilon_t \ln(l/l_0)$
- Young's modulus (E) - The slope of the linear part of the stress-strain curve in the elastic region, same as modulus of elasticity
- Shear modulus (G) - The slope of the linear part of the shear stress-shear strain curve

Elastic Deformation



- Elastic means reversible!

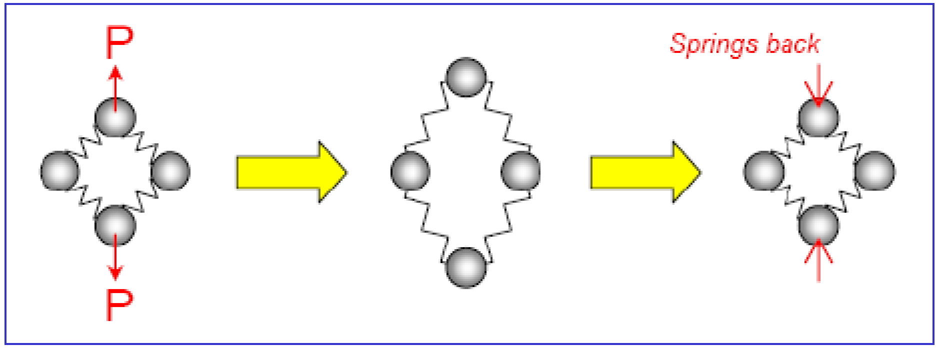
Plastic Deformation (Metals)



- Plastic means **permanent.**

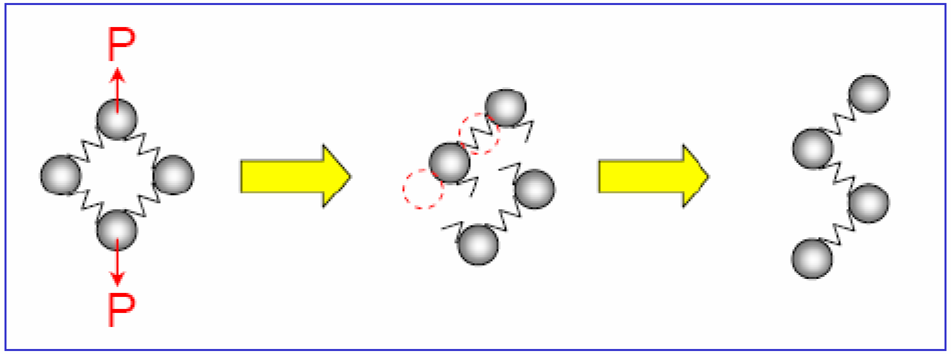
Elastic and Plastic Deformation

Elastic



- Initially we stretch atomic bonds.
- When we release the applied load, the atomic bonds return to their original state.

Plastic



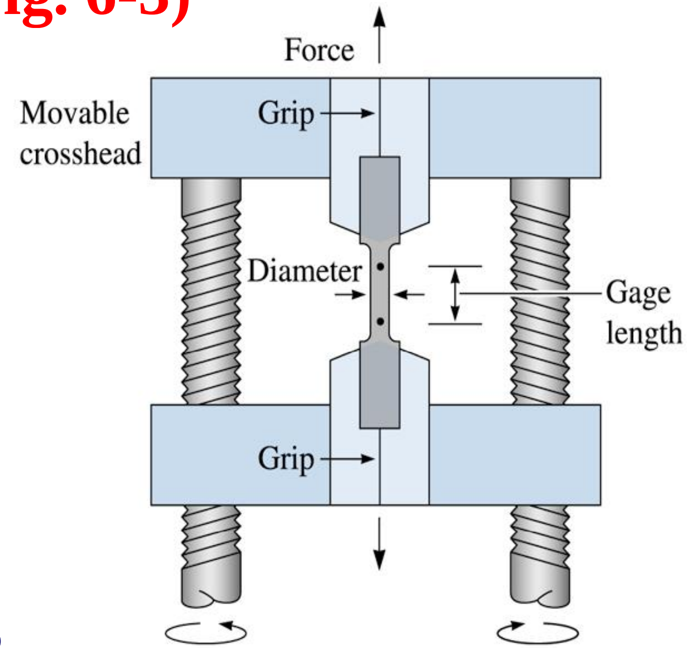
- When the applied load is large enough, some atomic bonds are broken.
- Atoms move from their original positions, and atomic bonds are re-formed.

Contents

Tensile Test

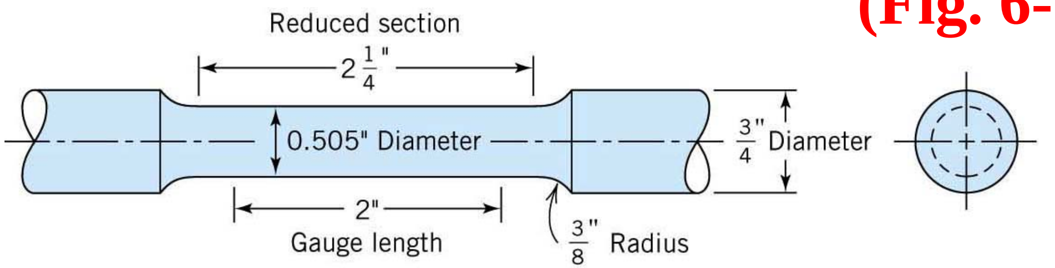
- Measures the resistance of a material to a static or slowly applied force.
- As the force is applied, the metal deforms (elongated).

(Fig. 6-3)



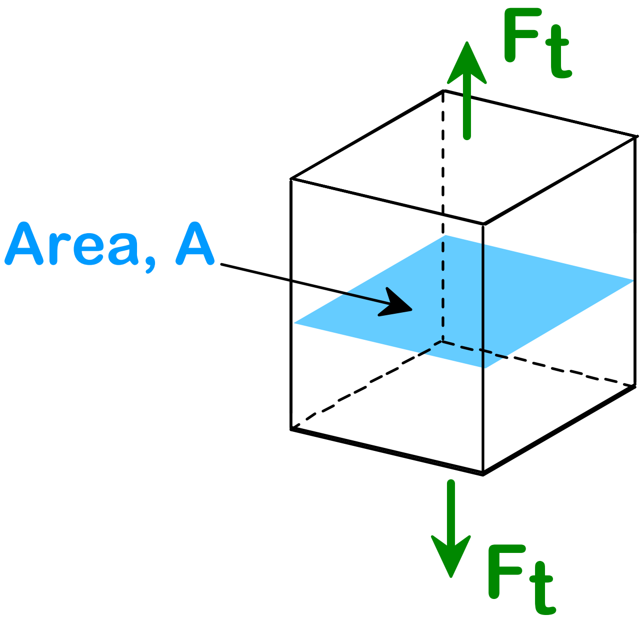
Typical tensile specimen

(Fig. 6-2)



Engineering Stress

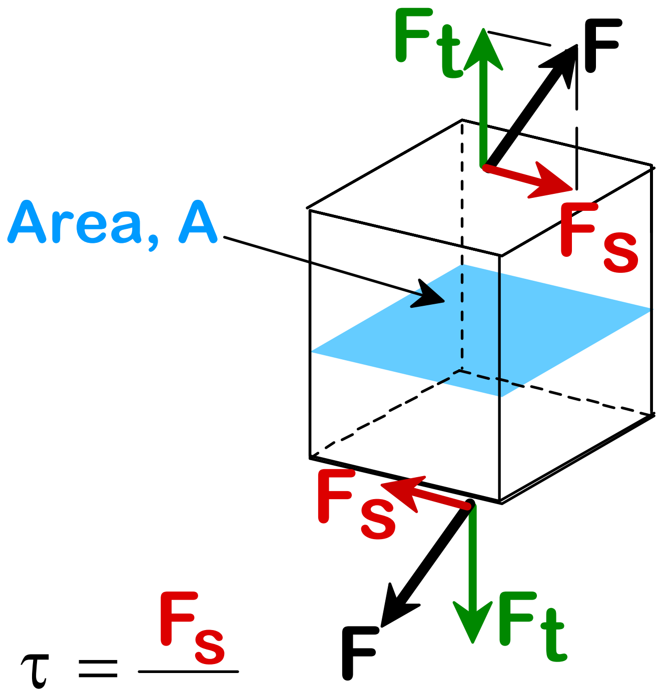
- Tensile stress, σ



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

original area before loading

- Shear stress, τ



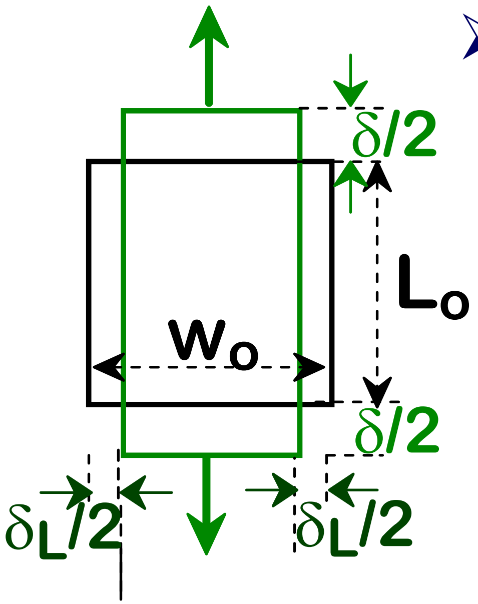
$$\tau = \frac{F_s}{A_o}$$

(Fig. 6-1)

Stress has units:
N/m^2 (= pascal or Pa)

- **Tensile strain:**

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



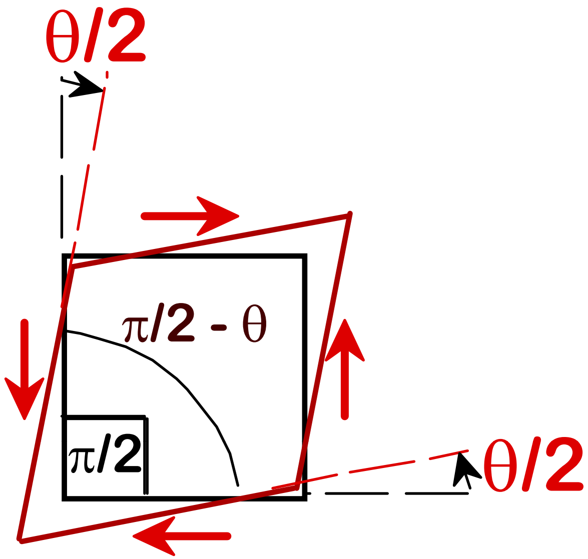
- **Lateral strain:**

$$\varepsilon_L = \frac{-\delta_L}{w_o}$$

(Eq. 6-2)

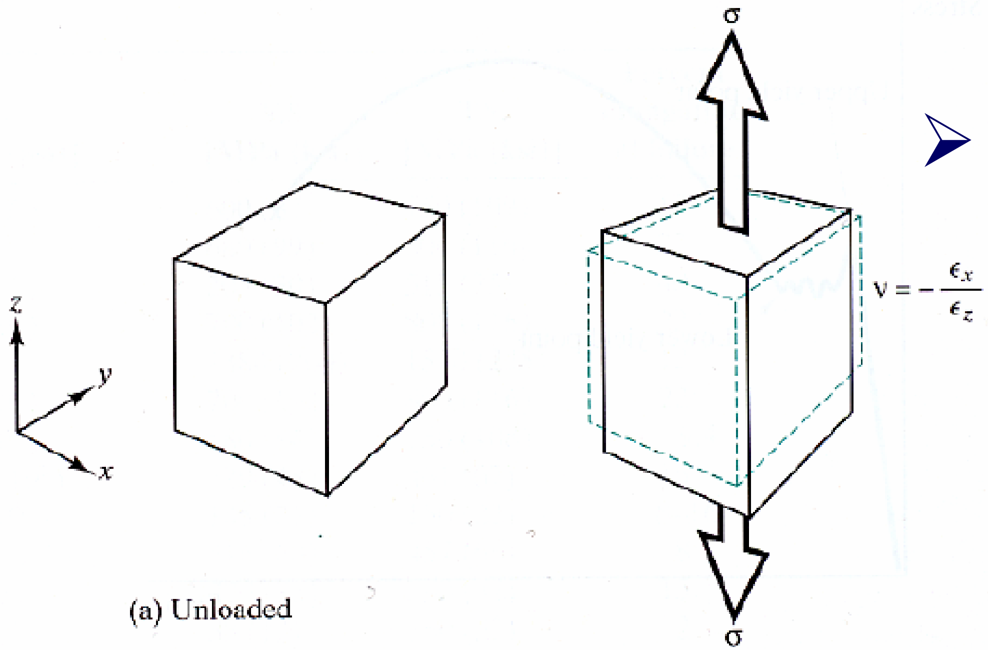
(Fig. 6-1)

- **Shear strain:**



Strain is always dimensionless, cm/cm or nm/cm.

Tensile Stress and Shear Stress

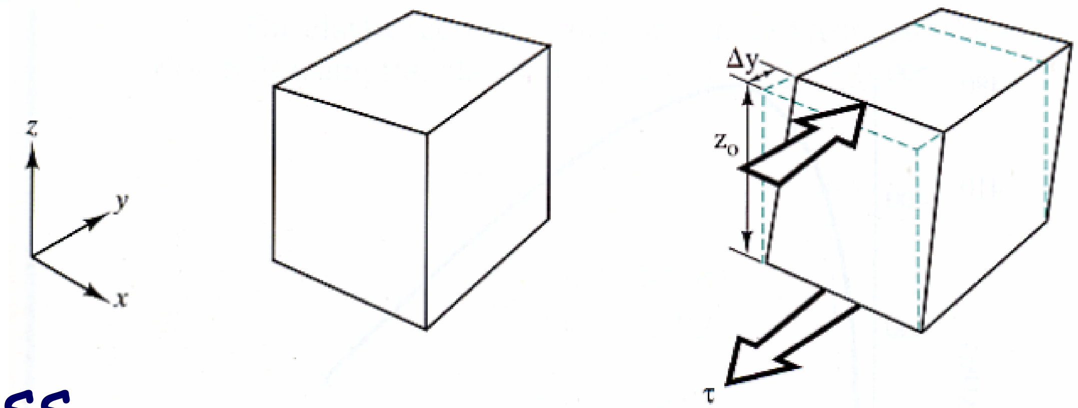


(a) Unloaded

(b) Loaded

- Tensile Stress

(Fig. 6-1)



- Shear Stress

(a) Unloaded

(b) Loaded

Schematics of Different Stress States

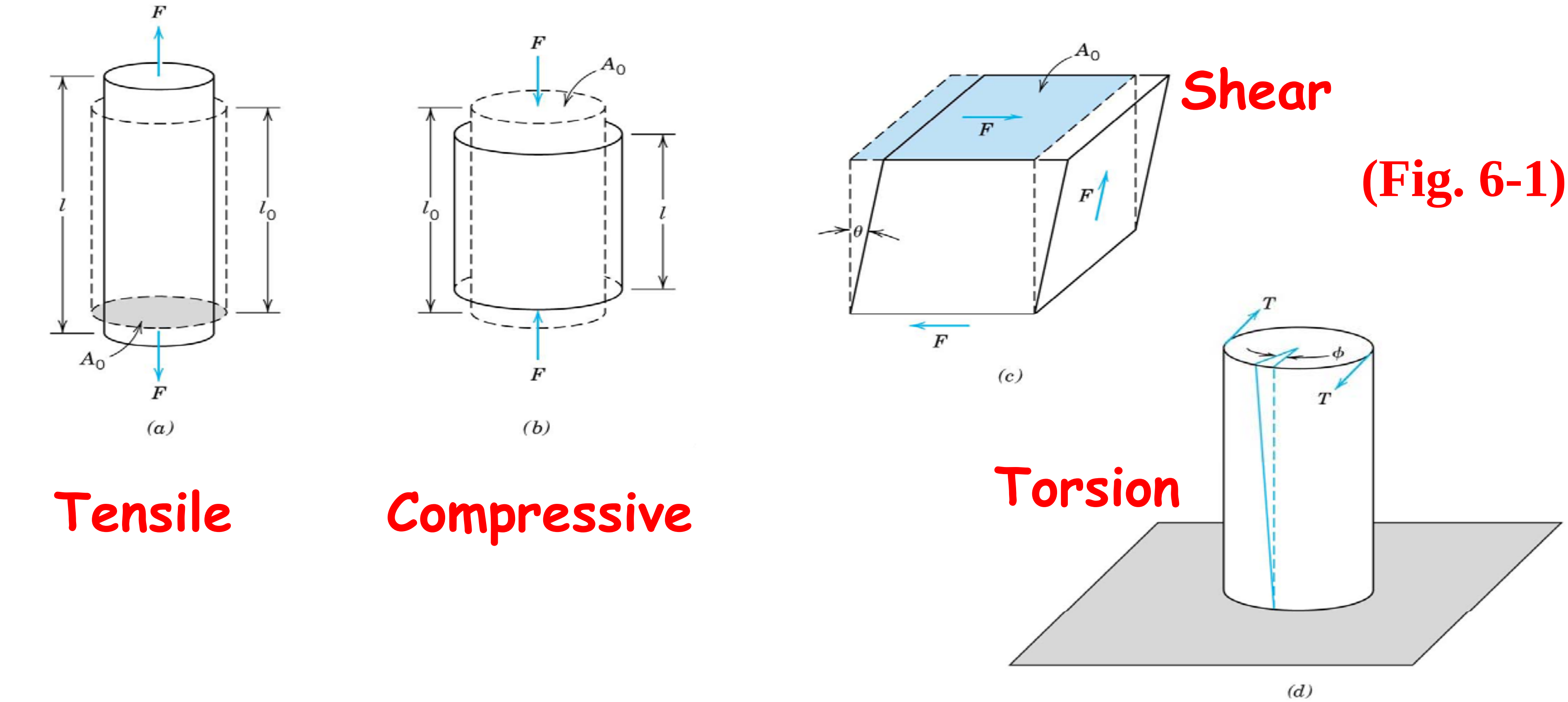


FIGURE 6.1 (a) Schematic illustration of how a tensile load produces an elongation and positive linear strain. Dashed lines represent the shape before deformation; solid lines, after deformation. (b) Schematic illustration of how a compressive load produces contraction and a negative linear strain. (c) Schematic representation of shear strain γ, where $\gamma = \tan\theta$. (d) Schematic representation of torsional deformation (i.e., angle of twist ϕ) produced by an applied torque T.

Contents

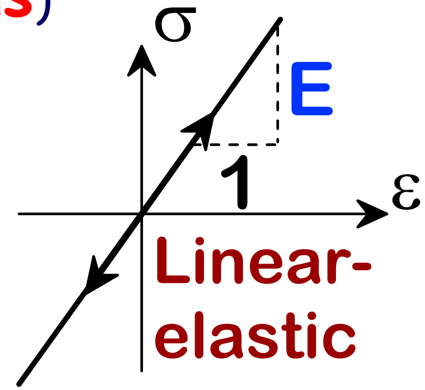
Linear Elastic Properties

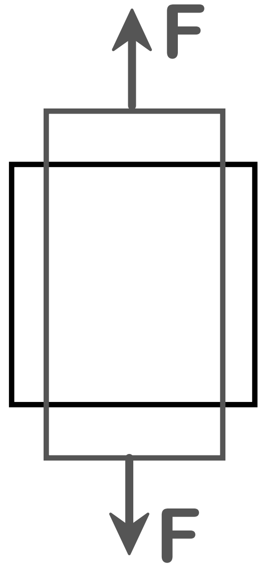
- **Modulus of Elasticity**, *E*: resistance to elastic deformation

(Eq. 6-5)

(also known as **Young's Modulus**)

- Hooke's Law: $\sigma = E\varepsilon$





simple tension test

(Fig. 6-9)

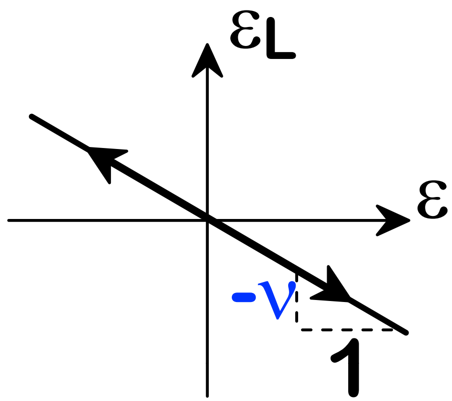
- **Poisson's Ratio**, **ν**:

$$\nu = -\frac{\varepsilon_L}{\varepsilon}$$

√ metals: ~ 0.33

√ ceramics: ~ 0.25

√ polymers: ~ 0.40



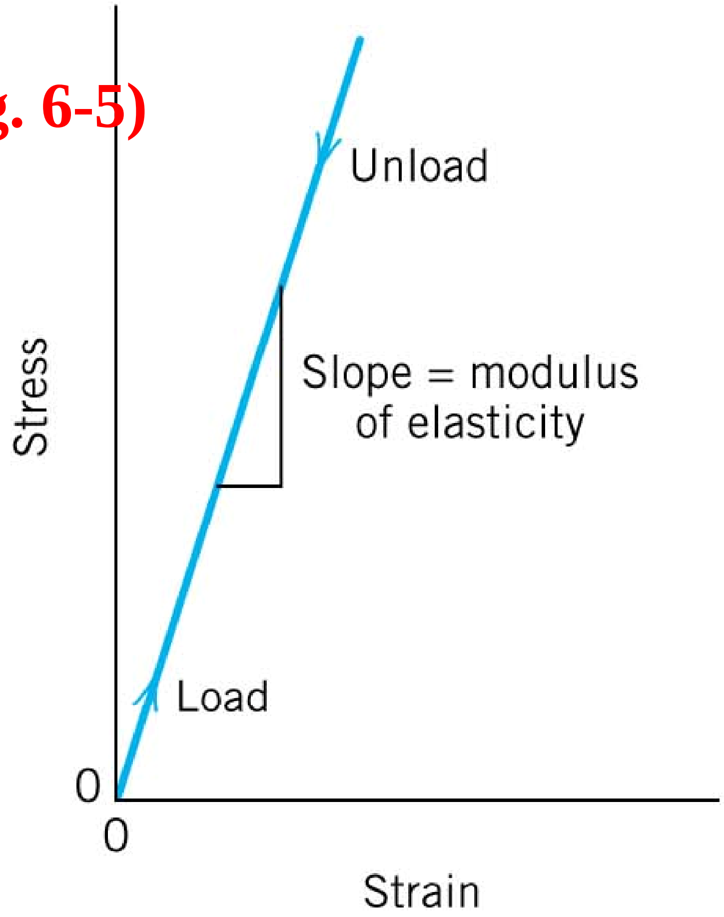
(Eq. 6-8)

- *E*: [GPa]

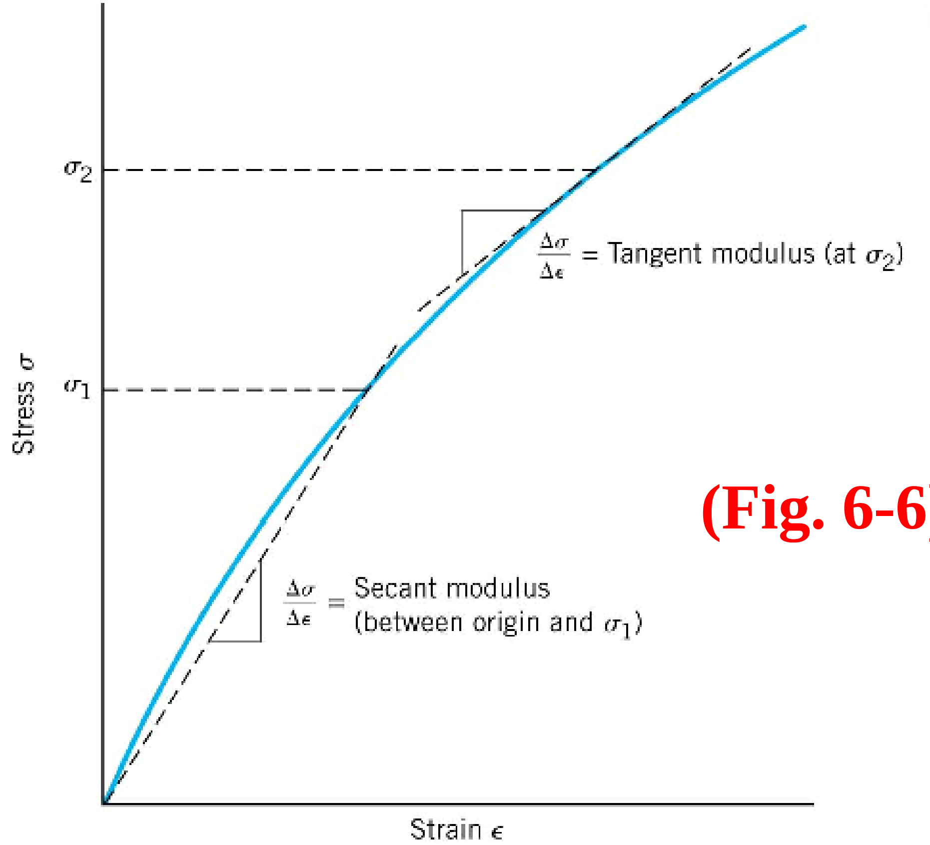
ν: dimensionless

Elastic Properties

(Fig. 6-5)



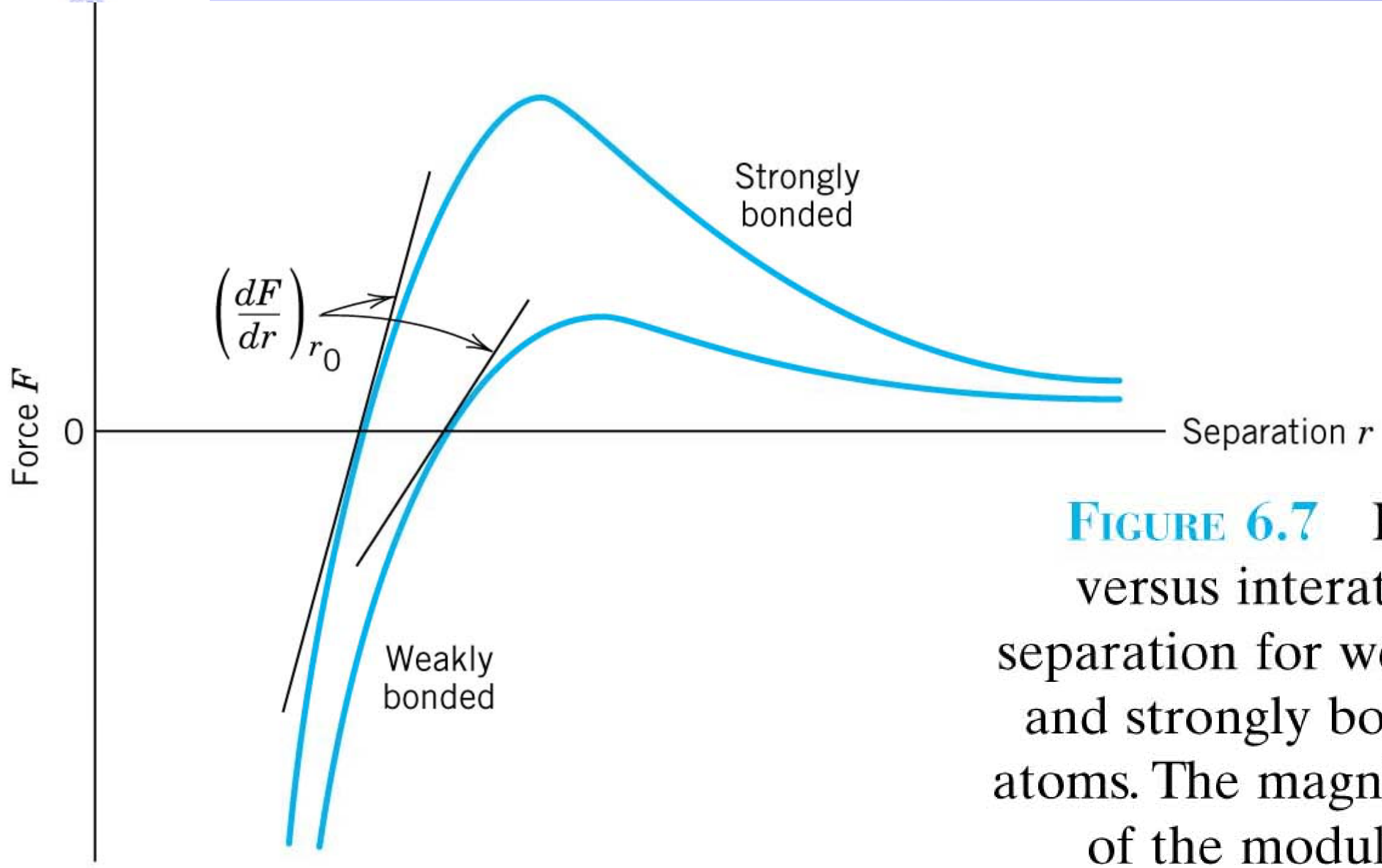
➢ Linear elastic deformation for loading and unloading cycles.



(Fig. 6-6)

➢ Nonlinear elastic deformation

Force versus Interatomic Separation



(Fig. 6-7)

FIGURE 6.7 Force versus interatomic separation for weakly and strongly bonded atoms. The magnitude of the modulus of elasticity is proportional to the slope of each curve at the equilibrium interatomic separation r_0.

Elastic Modulus

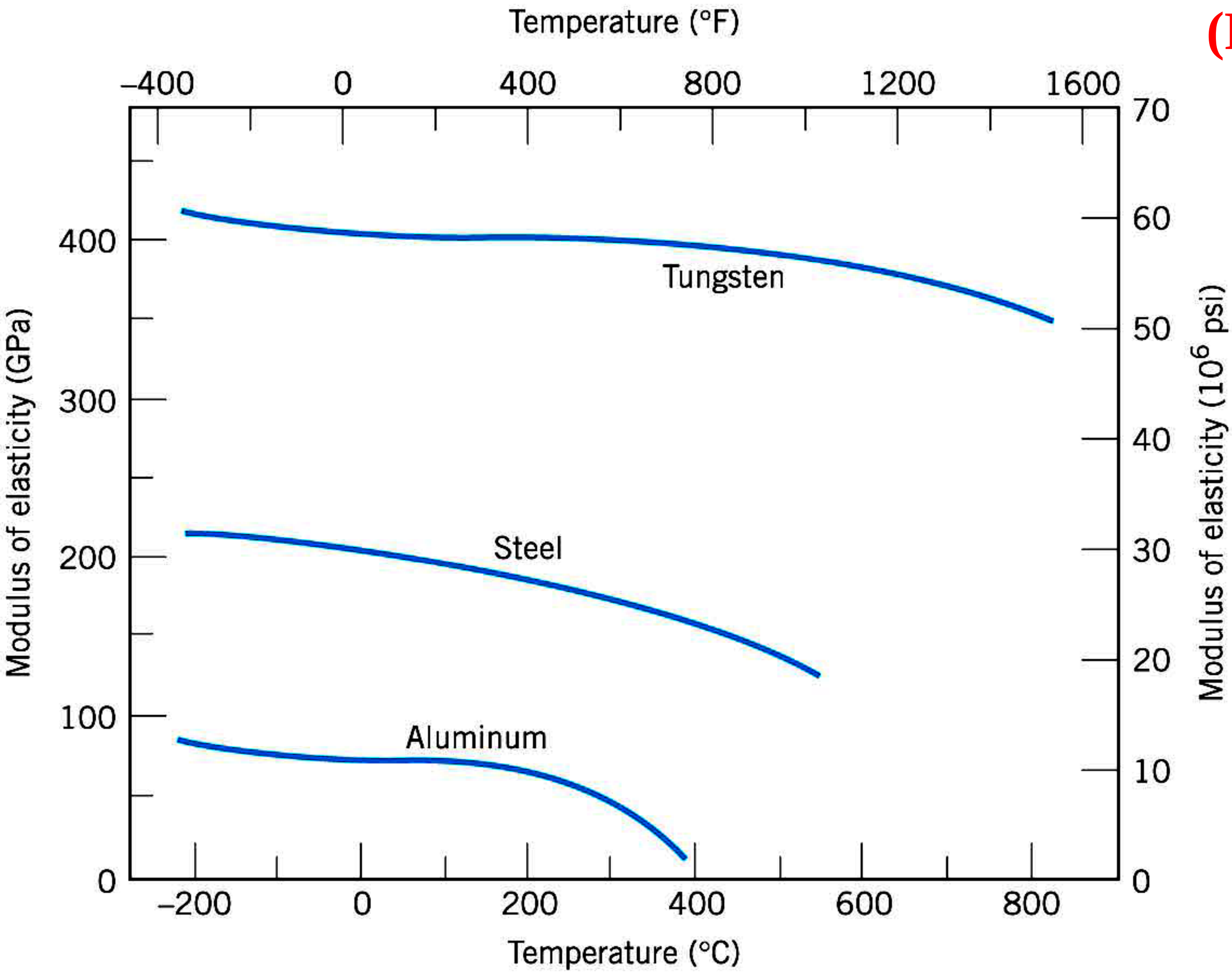
(Table 6-1)

Table 6.1 Room-Temperature Elastic and Shear Moduli, and Poisson's Ratio for Various Metal Alloys

Metal Alloy	*Modulus of Elasticity*		*Shear Modulus*		*Poisson's Ratio* (~1/3)
	GPa	*10^6 psi*	*GPa*	*10^6 psi*	
Aluminum	69	10	25	3.6	0.33
Brass	97	14	37	5.4	0.34
Copper	110	16	46	6.7	0.34
Magnesium	45	6.5	17	2.5	0.29
Nickel	207	30	76	11.0	0.31
Steel	207	30	83	12.0	0.30
Titanium	107	15.5	45	6.5	0.34
Tungsten	407	59	160	23.2	0.28

Elastic Modulus vs. Temperature

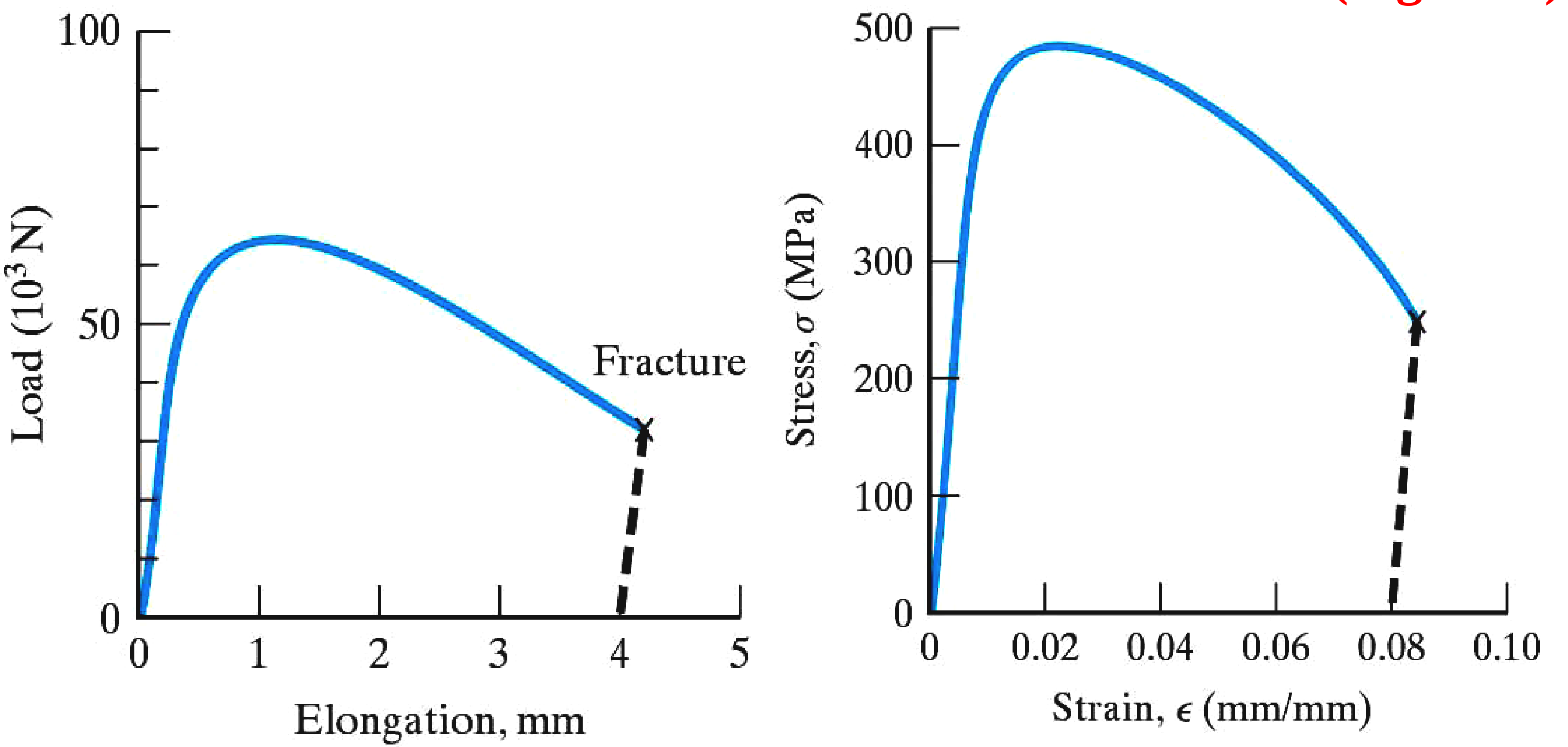
(Fig. 6-8)



Contents

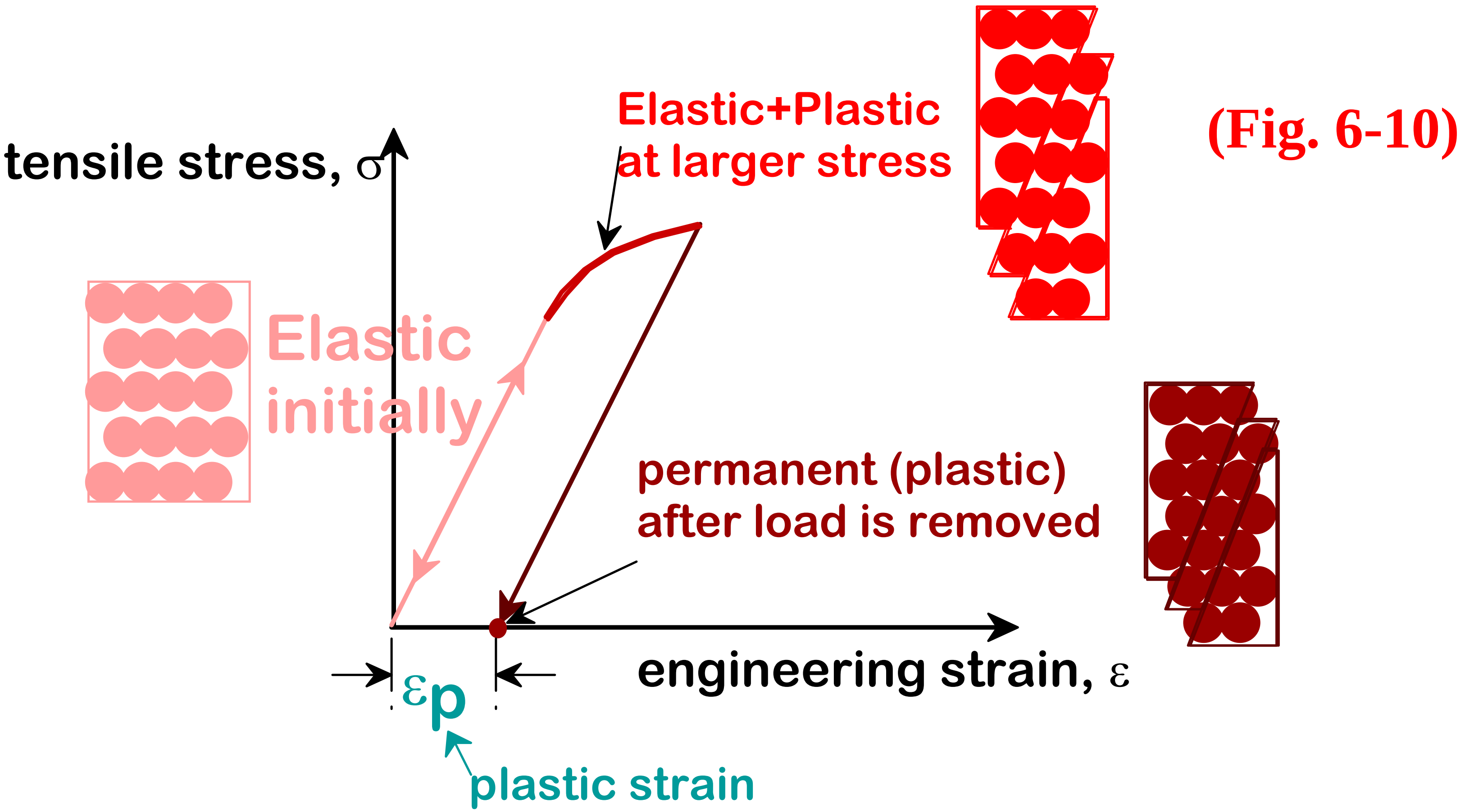
Stress-Strain Testing

(Fig. 6-11)



Plastic (Permanent) Deformation

- Simple tension test (at lower temperatures, $T < T_m/3$)

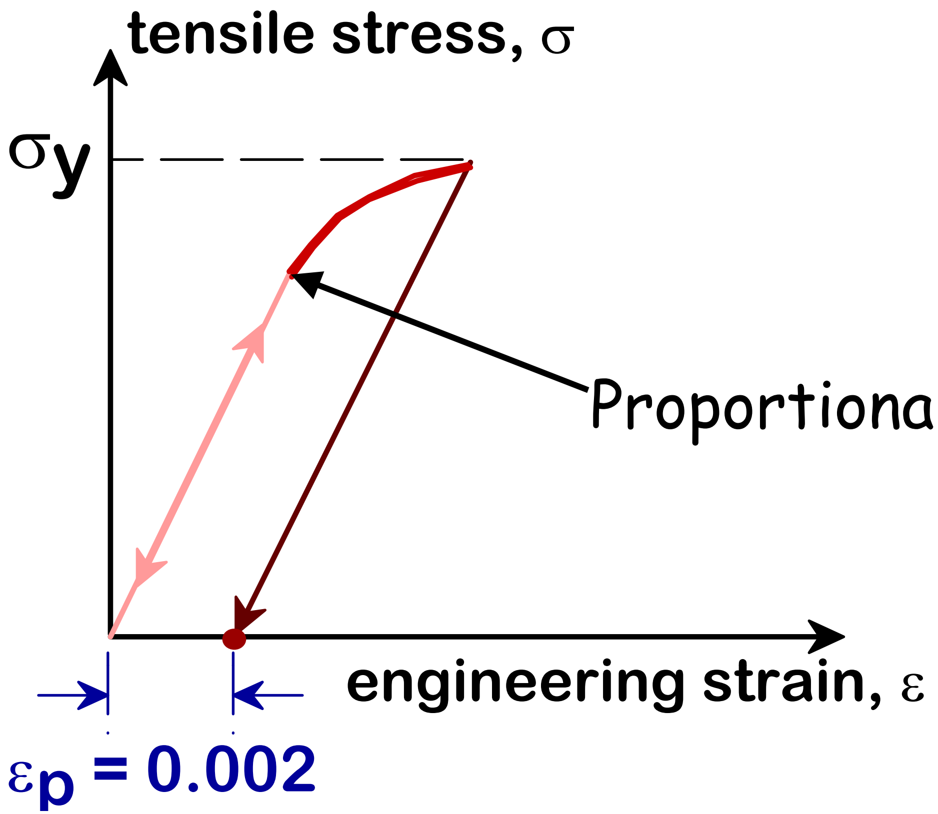


- Crystalline solids ← slip
- Noncrystalline solids & liquids ← viscous flow

Yield Strength, σ_y

- Measure of resistance to plastic deformation.
- Stress at which *noticeable* plastic deformation has occurred.

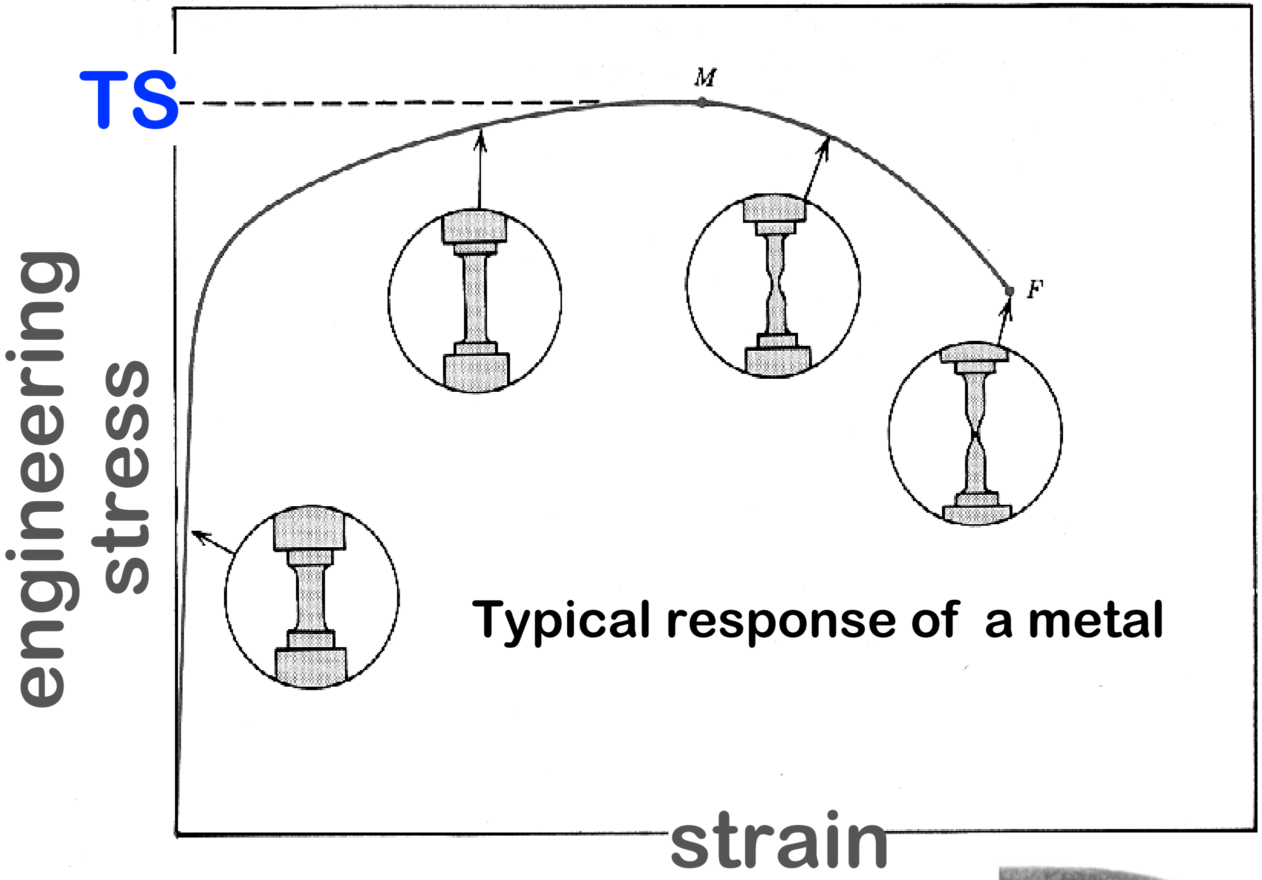
when $\varepsilon_p = 0.002$



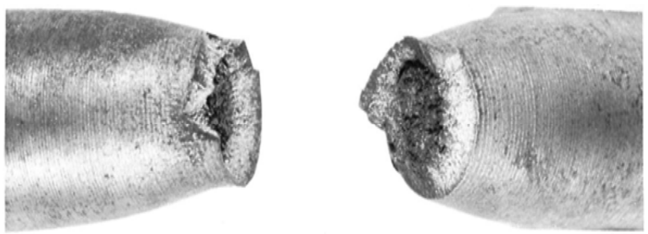
(Fig. 6-10)

Tensile Strength, TS

- Maximum possible engineering stress in tension



(Fig. 6-11)

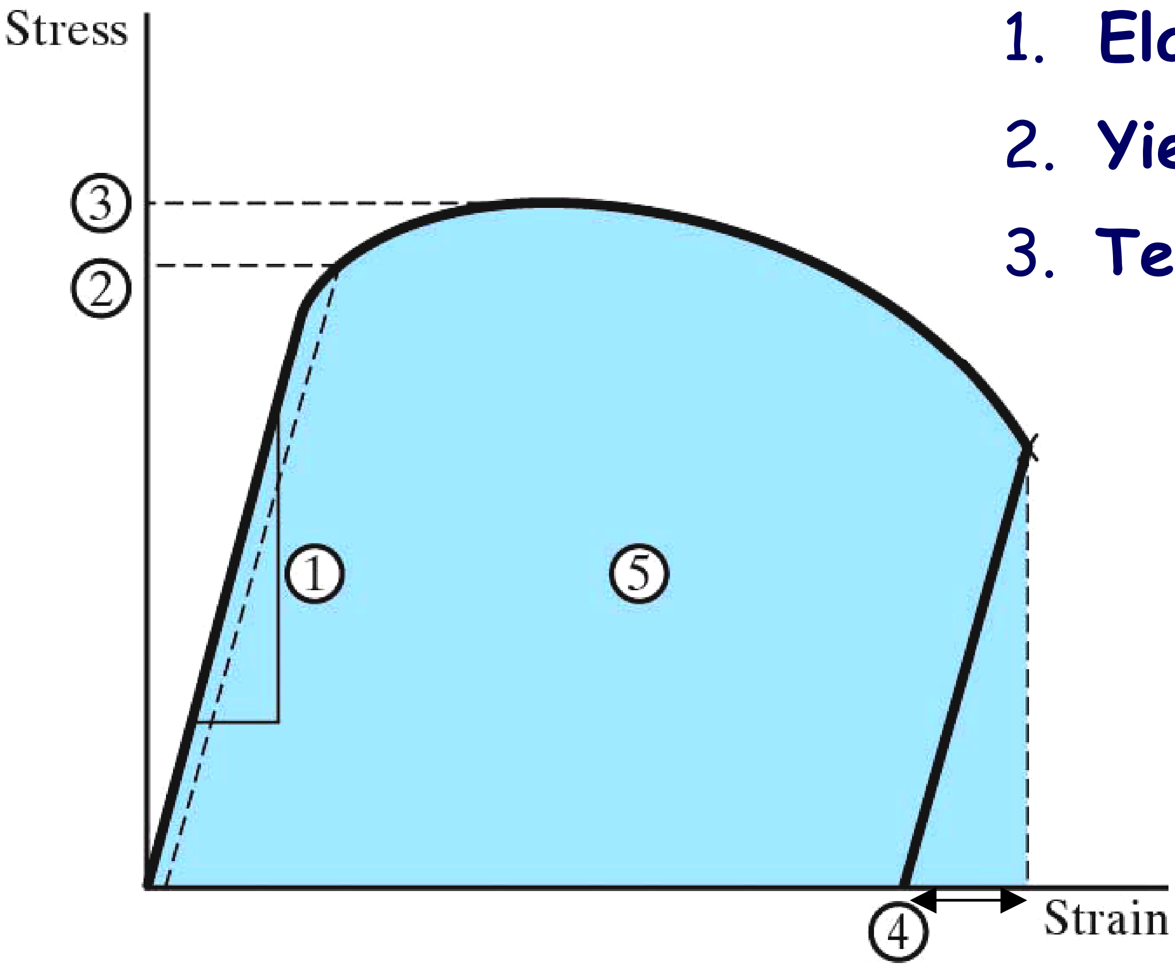


Mechanical Properties of Several Metals

Table 6.2 Typical Mechanical Properties of Several Metals and Alloys in an Annealed State

Metal Alloy	*Yield Strength MPa (ksi)*	*Tensile Strength MPa (ksi)*	*Ductility, %EL [in 50 mm (2 in.)]*
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

Tensile Test



1. **Elastic Modulus**, *E*
2. **Yield Strength**, Y.S.
3. **Tensile Strength**, T.S.

(Fig. 6-10)

(Fig. 6-11)

- Elastic Strain Recovery
- Strain Hardening (= Work Hardening)

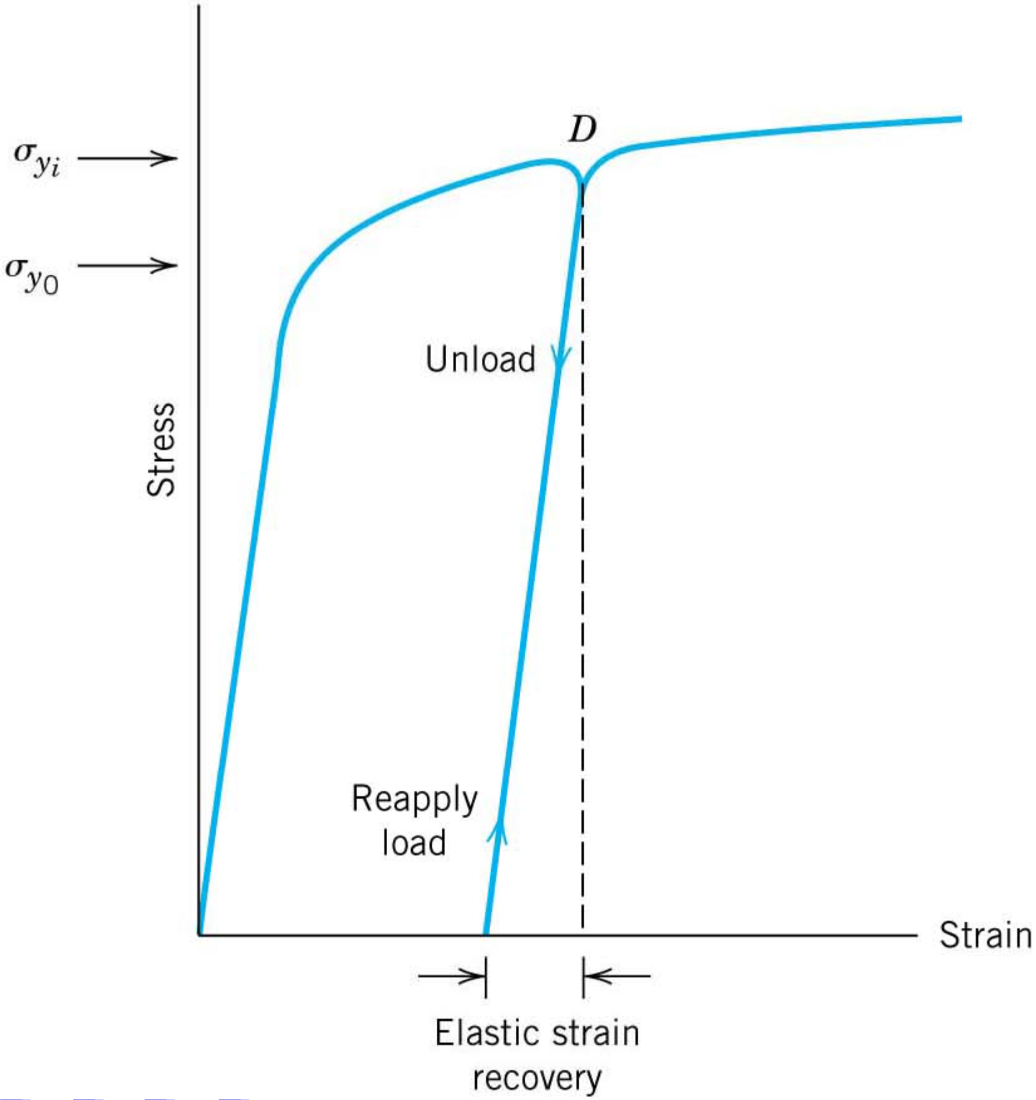
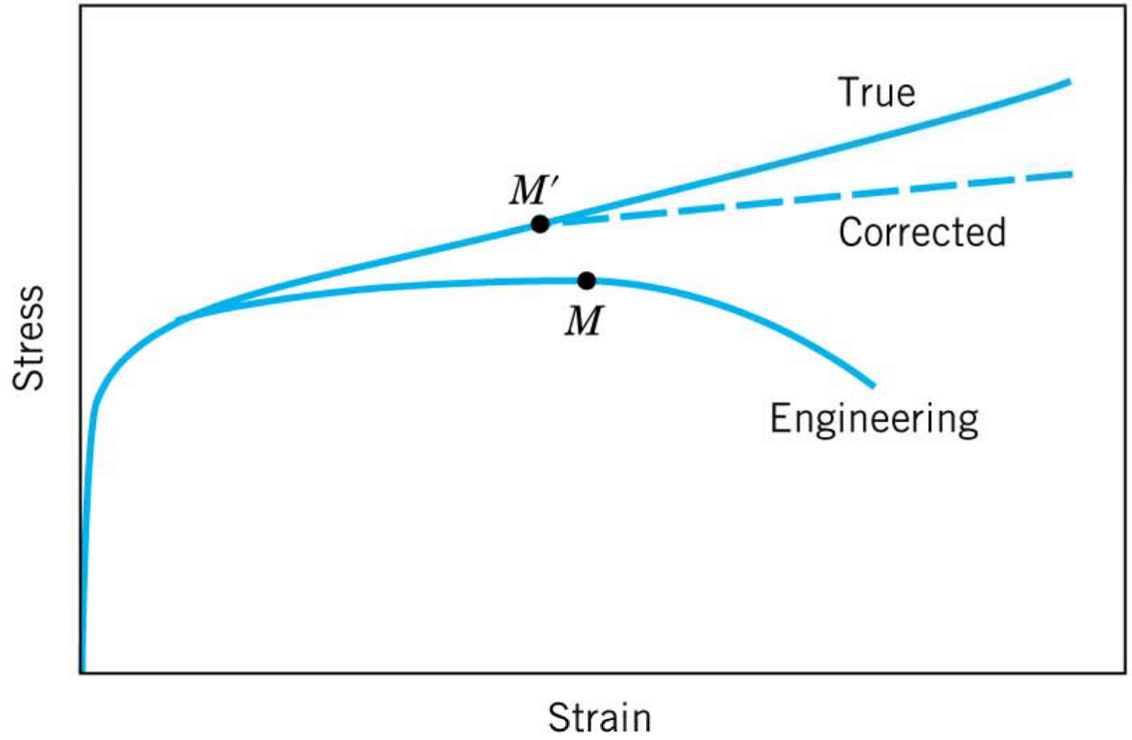


FIGURE 6.17 Schematic tensile stress–strain diagram showing the phenomena of elastic strain recovery and strain hardening. The initial yield strength is designated as σ_{y_0}; σ_{y_i} is the yield strength after releasing the load at point *D*, and then upon reloading.

(Fig. 6-17)

Engineering and True Stress-Strain Curves



(Fig. 6-16)

Figure 6.16 A comparison of typical tensile engineering stress–strain and true stress–strain behaviors. Necking begins at point M on the engineering curve, which corresponds to M' on the true curve. The "corrected" true stress–strain curve takes into account the complex stress state within the neck region.

true stress σ_t

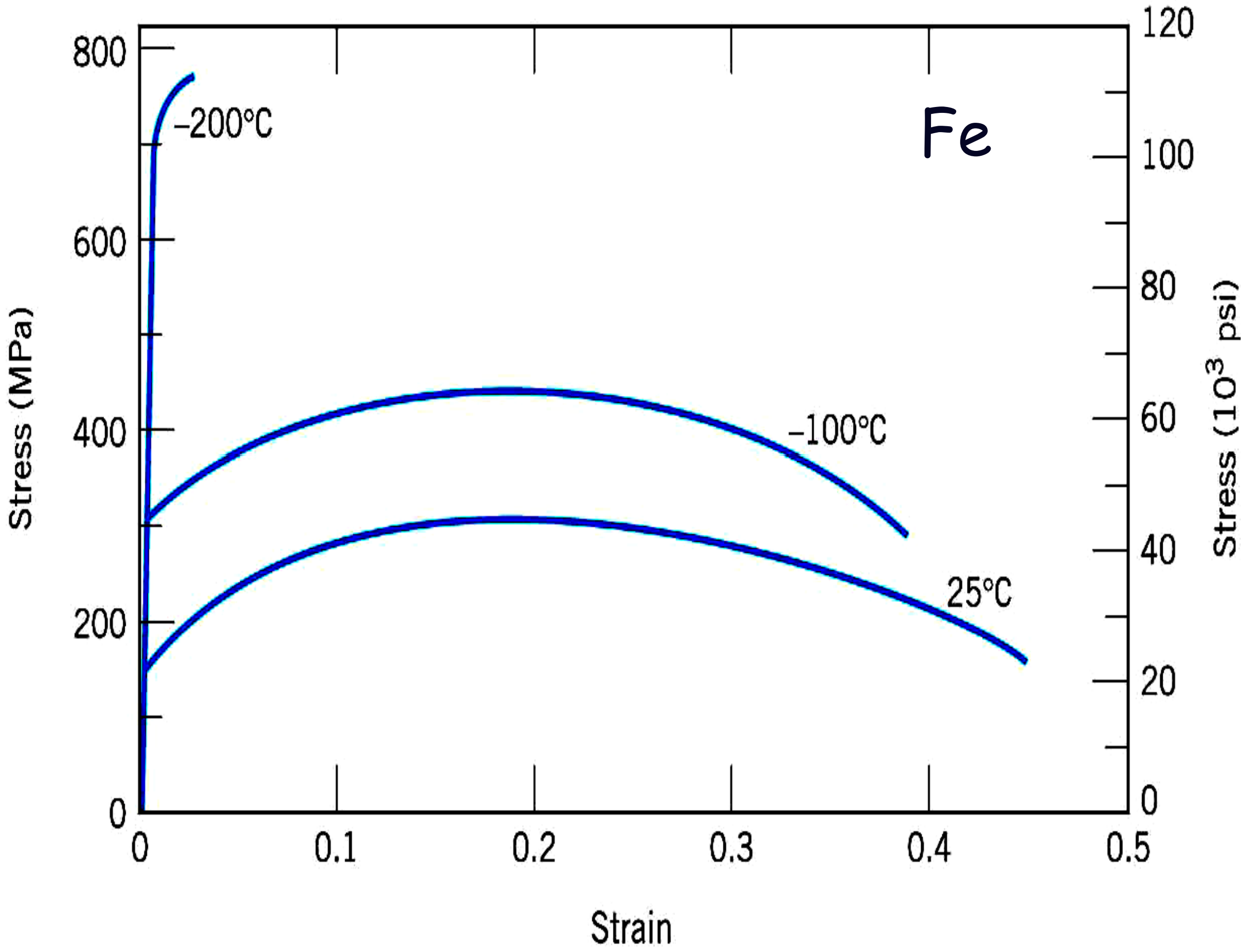
$$\sigma_t = \frac{F}{A_i}$$

true strain ε_t

$$\varepsilon_t = \int_{l_o}^{l} \frac{dl}{l} = \ln\left(\frac{l}{l_o}\right)$$

(Eq. 6-15)
(Eq. 6-16)
(Eq. 6-17)
(Eq. 6-18)

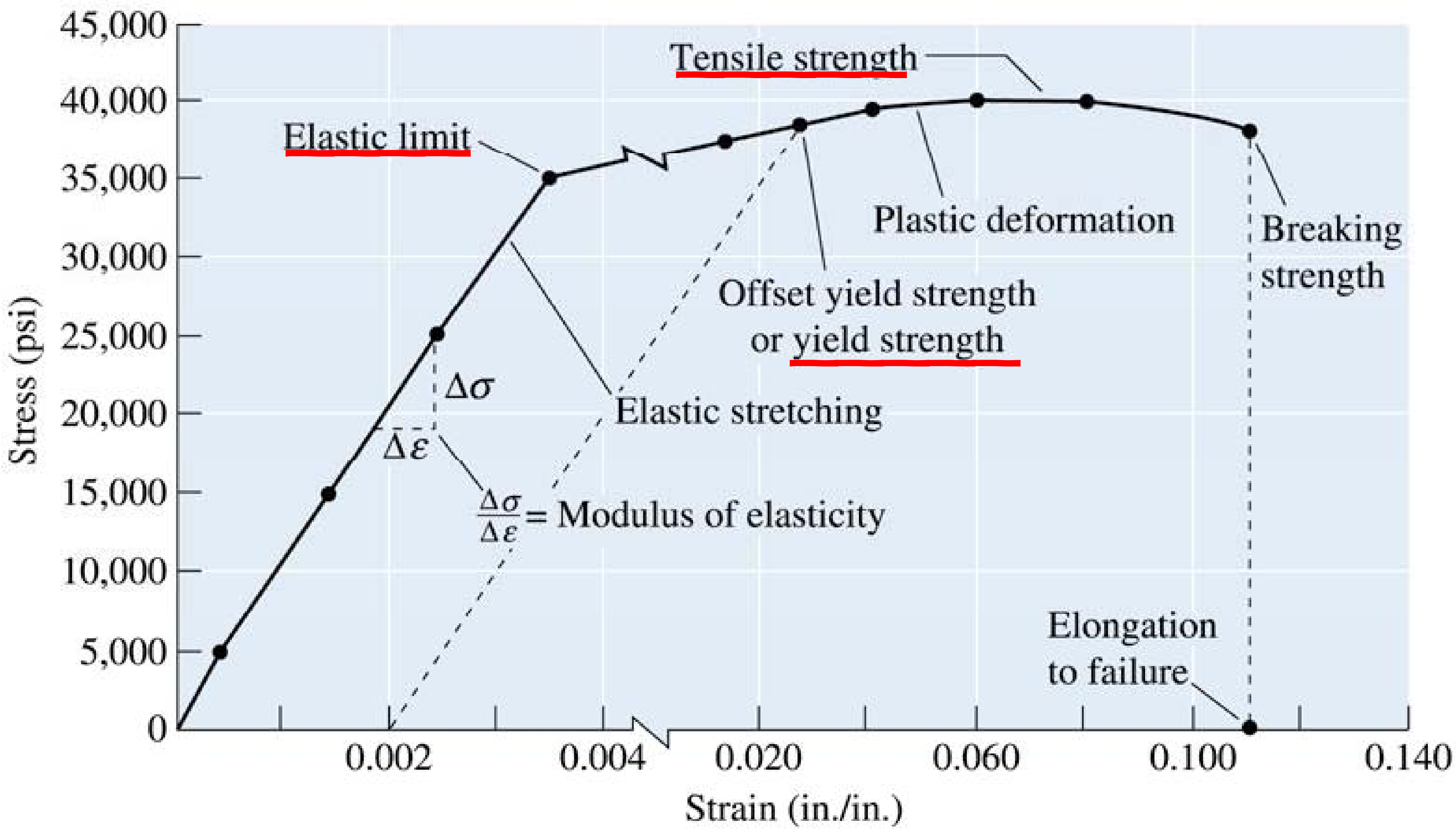
Temperature Effect



(Fig. 6-14)

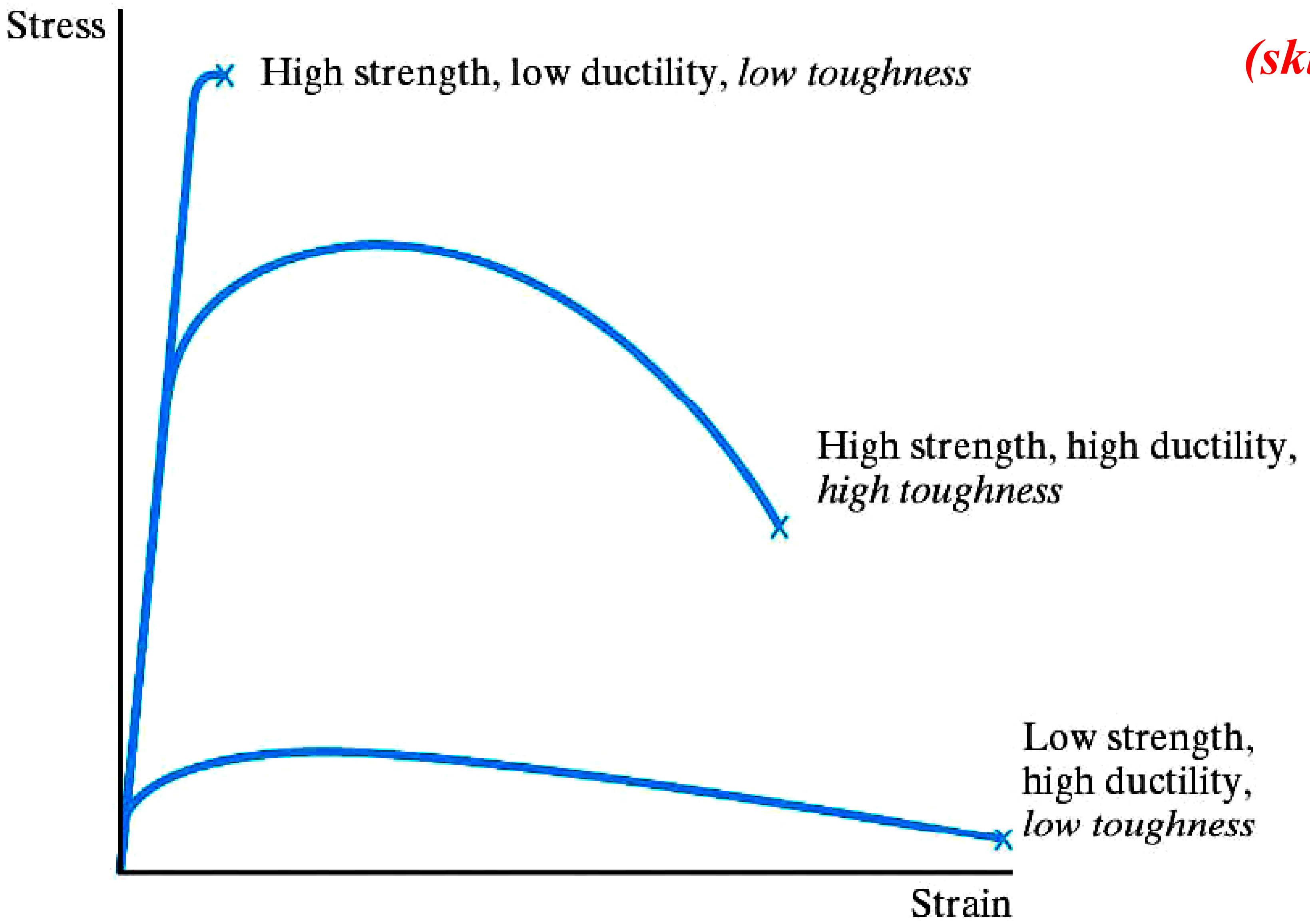
Contents

The stress-strain curve for an aluminum alloy



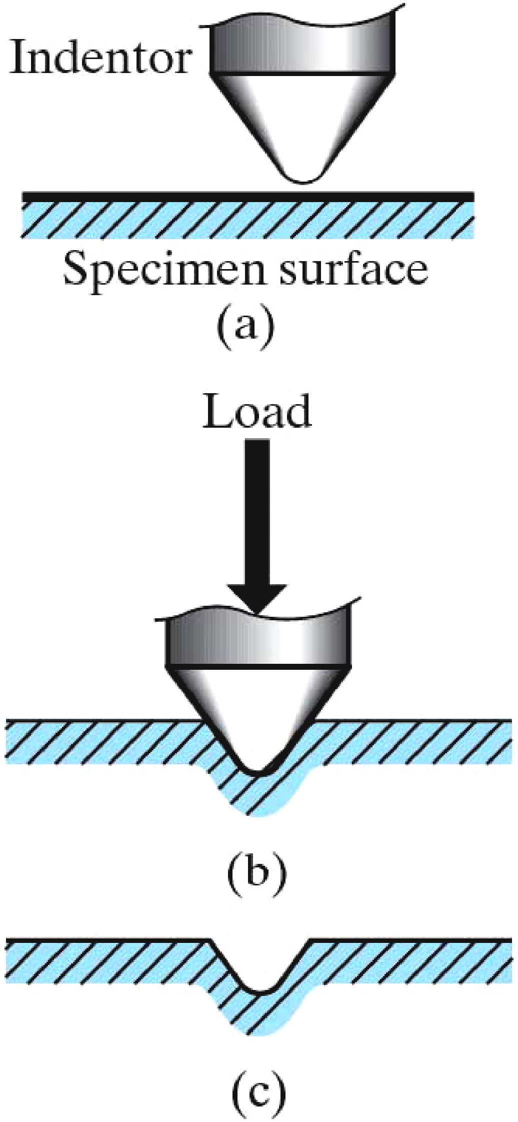
Tensile Test

(skip)



Hardness

(skip)



- Resistance to Permanently Indenting the Surface
- A Measure of a Material's Resistance to Localized Plastic Deformation

- Test
  - ✓ A hard indenter is pressed into the specimen. Standard load is applied.
  - ✓ Magnitude of indentation is measured: Area of Indentation, or Depth of Indentation.

Summary

- Stress and strain:

  Size-independent measures of load and displacement, respectively.

- Elastic behavior: Reversible behavior.
- Plastic behavior: Permanent deformation (at the yield strength).
- Ductility: The plastic strain at failure.

- Problems from Chap. 6 http://bp.snu.ac.kr

  Prob. 6-3 Prob. 6-5 Prob. 6-9 Prob. 6-16

  Prob. 6-24 Prob. 6-34 Prob. 6-44