MECHANICAL PROPERTIES OF MATERIALS

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MECHANICAL PROPERTIES

ISSUES TO ADDRESS...

- 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?
- Toughness and ductility: What are they and how do we measure them?
- Ceramic Materials: What special provisions/tests are made for ceramic materials?

- **Why Study the Mechanical Properties of Metals ?**
- It is important for engineers to understand
  - How the various mechanical properties are measured, and
  - What these properties represent

The role of structural engineers is to determine stresses and stress distributions within members that are subjected to well-defined loads

- **By experimental testing**
- **Theoretical and mathematical stress analysis.**

- Design structures/components using predetermined materials such that unacceptable levels of deformation and/or failure will not occur.

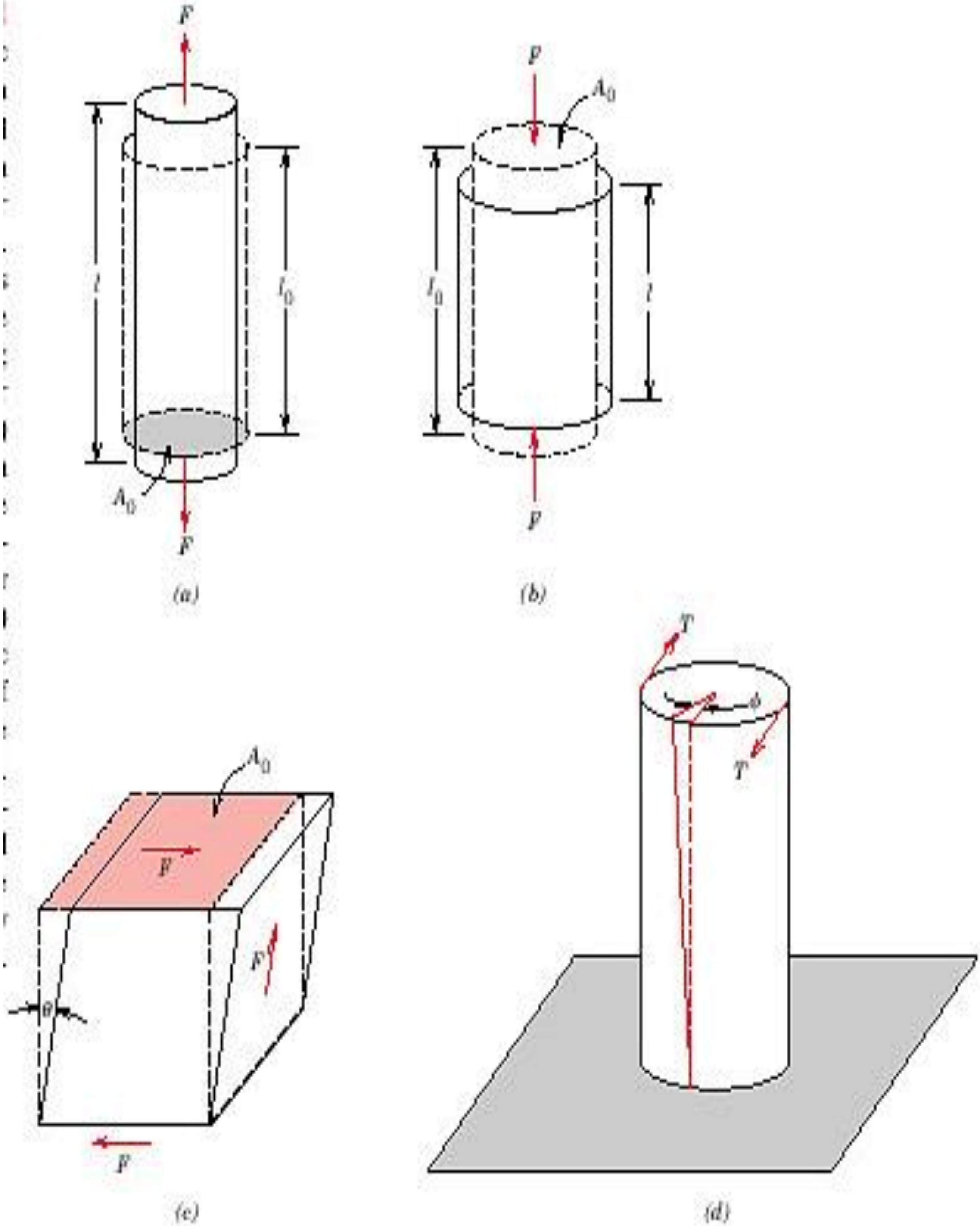
Stress and Strain

- **Stress:** **Intensity of the internal force, measured by force per unit area**
- **Strain:** **Elongation per unit length**
- **Nominal Stress:** **Force divided by the original cross sectional area**
- **True Stress:** **Force divided by the actual cross sectional area**

Concepts of Stress and Strain

- **Static load** ➔ changes relatively slowly with time

- **Applied uniformly** over a cross-section or surface of a member.
- **Tension**
- **Compression**
- **Shear**
- **Torsion**

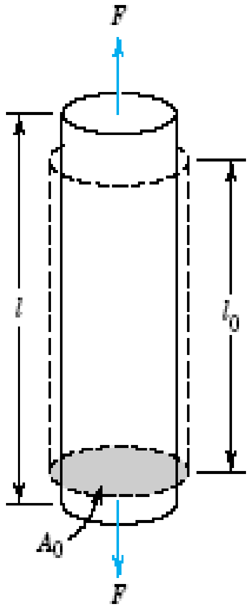


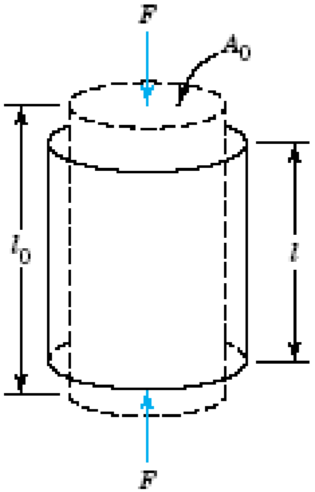
Concepts of Stress and Strain

- **Engineering Stress** (σ) = Instantaneous applied load (**F**) / Original Area (**Ao**)
- Unit: MPa, GPa, psi
- **Engineering strain** (ε)
- l_i = instantaneous length
- l_o = original length
- **COMPRESSION TESTS**
- Similar to tensile test, compressive load
- Sign convention, compressive force is taken negative ➔ stress negative
- Since $l_o > l_i$, negative strain

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

$$\varepsilon = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0}$$





Formulas for Stress and Strain

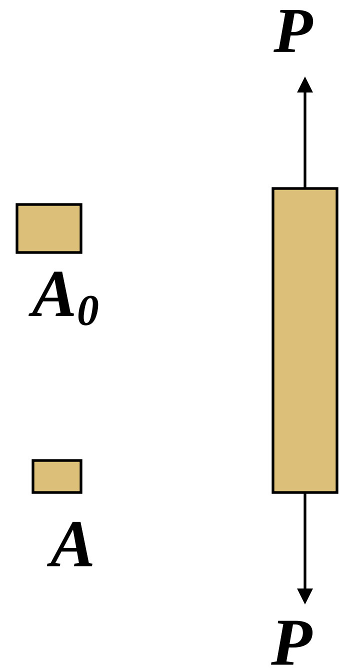
For an axially loaded member:

Nominal (or Engineering) Stress

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

True Stress

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

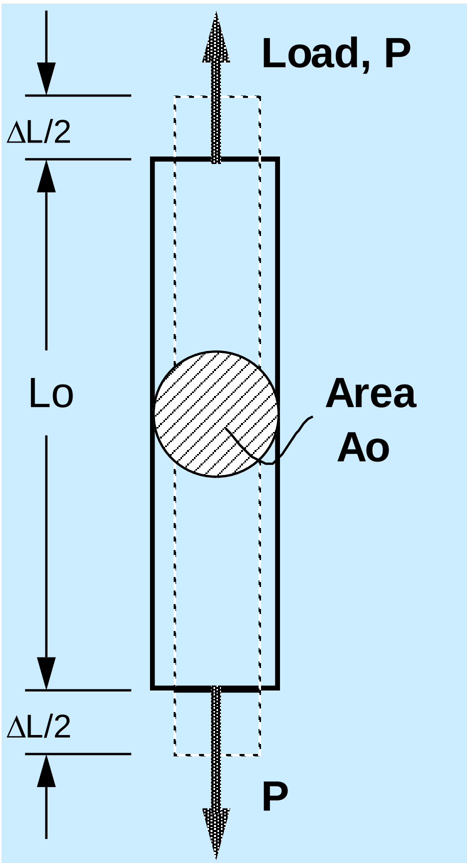


Where σ = stress, psi or pascal

P = magnitude of the applied force, lb or N

A_o = original cross sectional area, in^2 or m^2

A = cross sectional area at the moment the stress is calculated, in^2 or m^2

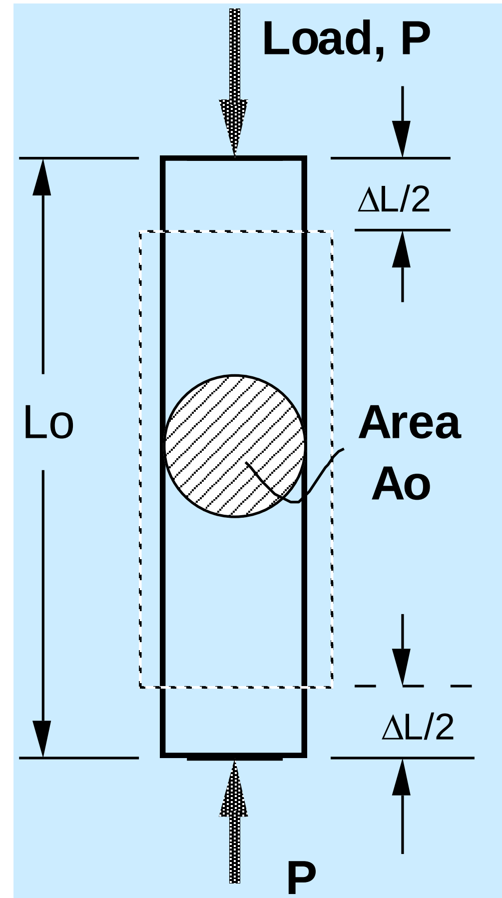


Engineering Stress

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

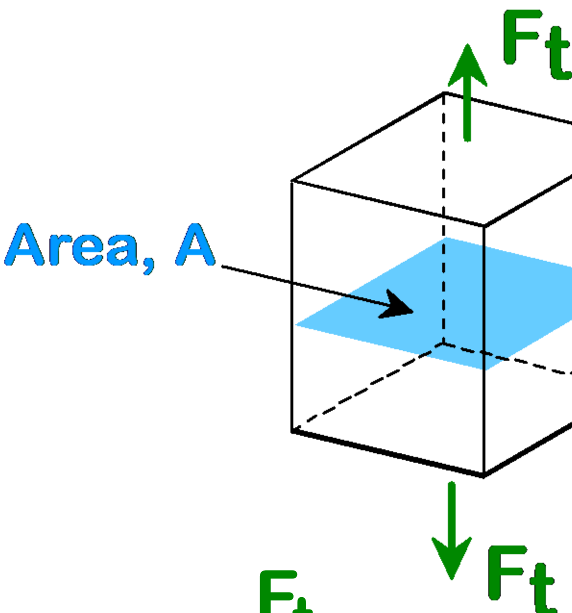
$$e = \frac{\Delta L}{L_o}$$

Engineering Strain



ENGINEERING STRESS

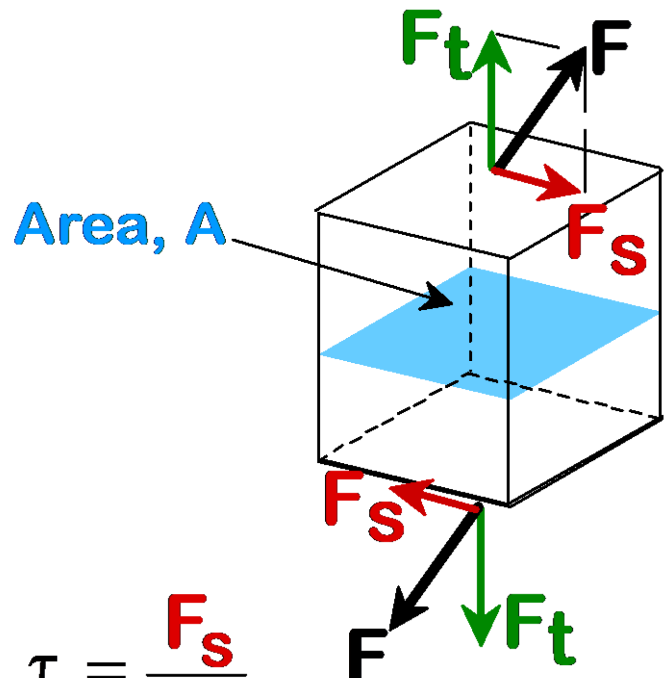
- **Tensile** stress, σ:



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

original area before loading

- **Shear** stress, τ:



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

Stress has units: N/m^2 or lb/in^2

COMMON STATES OF STRESS

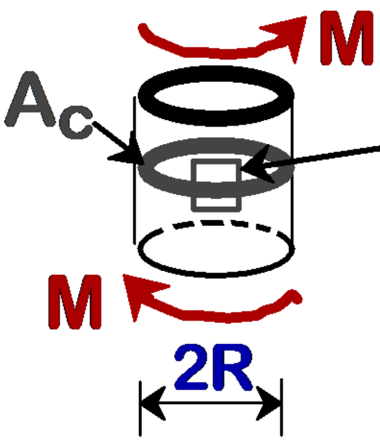
- **Simple tension: cable**

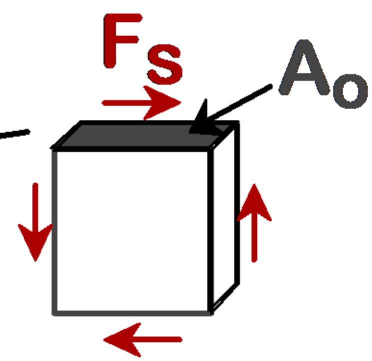
A_o = cross sectional Area (when unloaded)

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

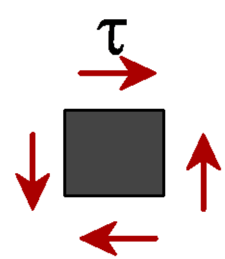
Ski lift (photo courtesy P.M. Anderson)

- **Simple shear: drive shaft**





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

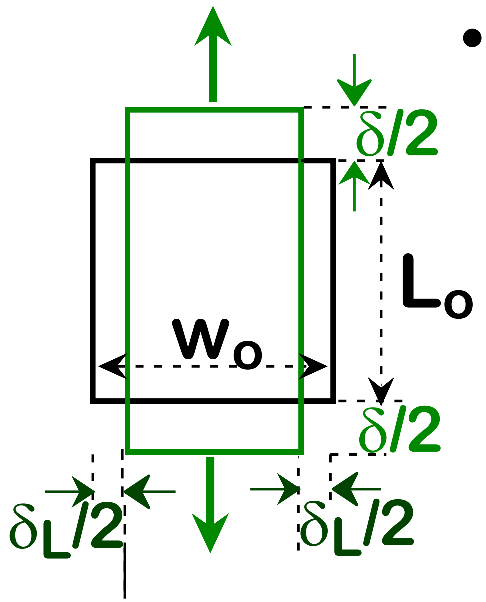


Note: $\tau = M/A_c R$ here.

ENGINEERING STRAIN

- **Tensile strain:**

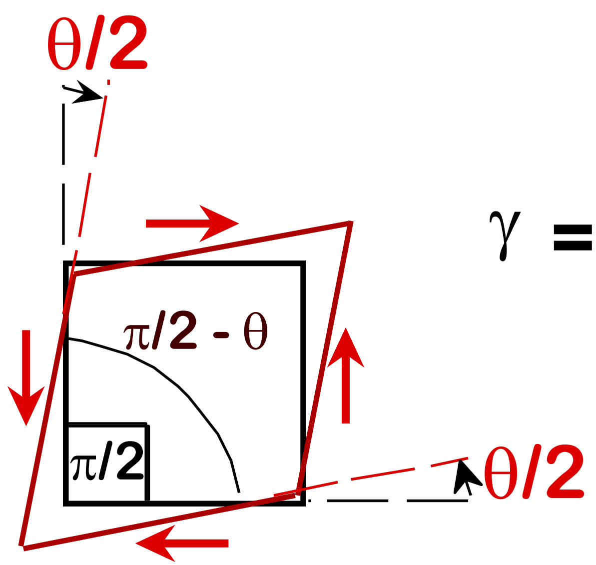
$$\varepsilon = \frac{\delta}{L_o}$$



- **Lateral strain:**

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

- **Shear strain:**

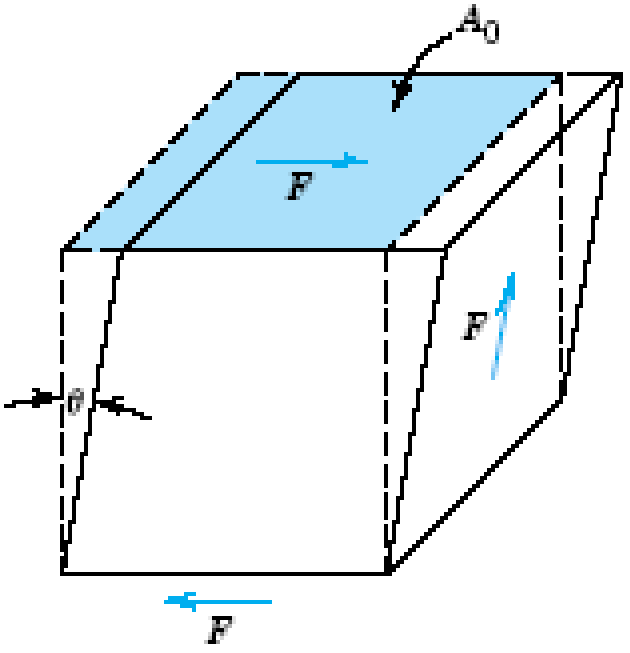


$$\gamma = \tan \theta$$

Strain is always dimensionless.

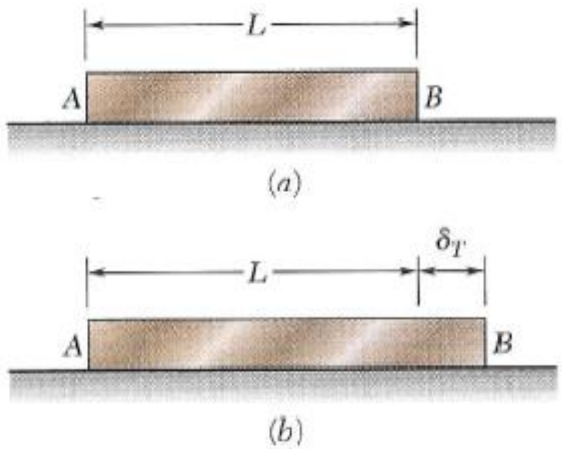
Concepts of Stress and Strain

- **Shear stress** : $\tau = F / A_o$
  - **F:** Load or force imposed parallel to the upper and lower faces
  - **A_o:** shear or parallel area



- **Shear strain** (γ) is defined as the tangent of the strain angle θ.

Thermal Stress/Strain



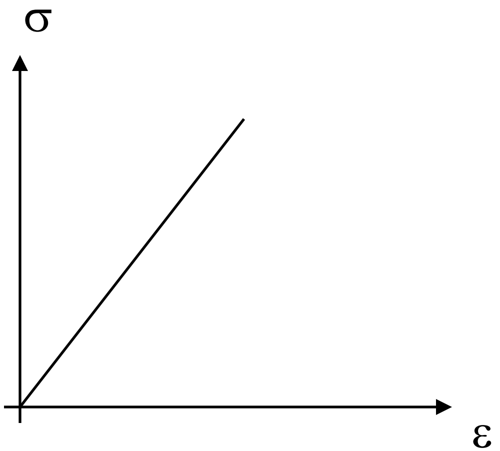
$$\varepsilon_T = \alpha \Delta T$$

Strain caused by temperature changes. α is a material characteristic called the ***coefficient of thermal expansion***.

Hooke's Law and Poission's Ratio

- **Hooke's Law:**

  Stress is proportional to strain



- **Poission's Ratio:**

  Ratio of lateral strain (caused by longitudinal strain) to the longitudinal strain

Modulus of Elasticity

- Constant of proportionality (slope of a line) in elastic range.

$$E = \frac{\sigma}{\varepsilon}$$

Unit: lb/in^2

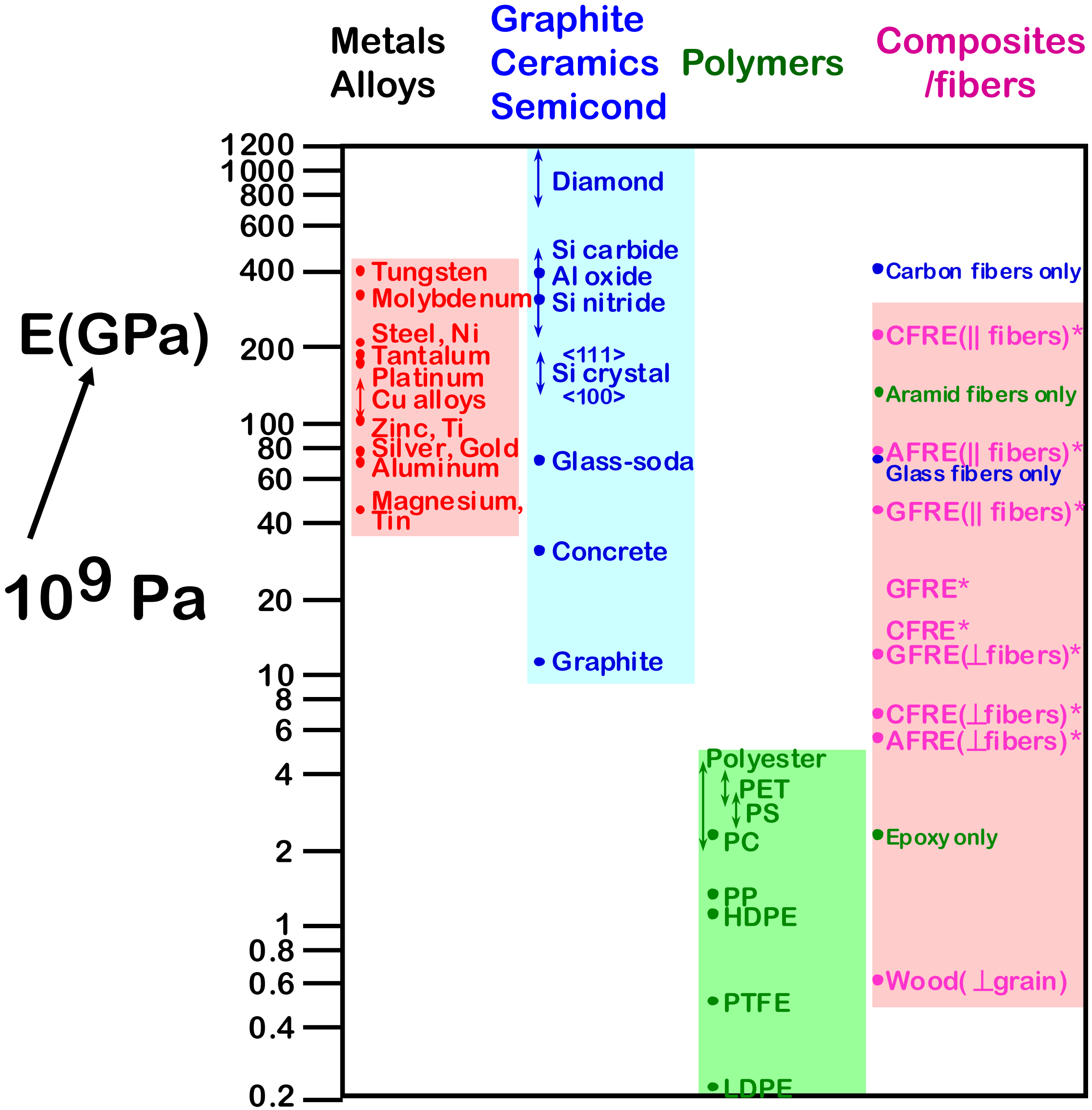
- It is also called as **Young's Modulus**.
- For a linear material, the relationship between stress and strain:

$$\sigma = E\varepsilon$$

and

$$\varepsilon = \frac{\sigma}{E}$$

YOUNG'S MODULI: COMPARISON



$E_{ceramics}$ > E_{metals} >> $E_{polymers}$

Based on data in Table B2, *Callister 6e*.
Composite data based on reinforced epoxy with 60 vol% of aligned carbon (CFRE), aramid (AFRE), or glass (GFRE) fibers.

Mathematical Relationships for Strain and Poisson's Ratio

Longitudinal Strain:

$$\varepsilon_x = \frac{\Delta x}{x} = \frac{x1 - x0}{x0}$$

Lateral Strain:

$$\varepsilon_y = \frac{\Delta y}{y} = \frac{y1 - y0}{y0} \qquad \varepsilon_z = \frac{\Delta z}{z} = \frac{z1 - z0}{z0}$$

Poission's Ratio:

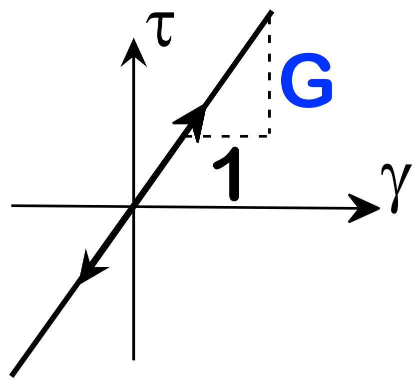
$$\mu_{yx} = \frac{-\varepsilon_y}{\varepsilon_x} \qquad \mu_{zx} = \frac{-\varepsilon_z}{\varepsilon_x}$$

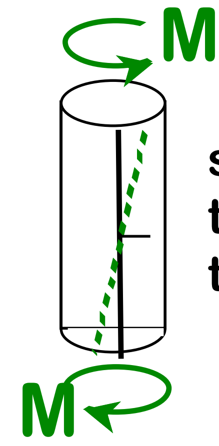
For Isotropic Materials: $\mu_y = \mu_z = \mu$

OTHER ELASTIC PROPERTIES

- Elastic Shear modulus, G:

$$\tau = G\,\gamma$$

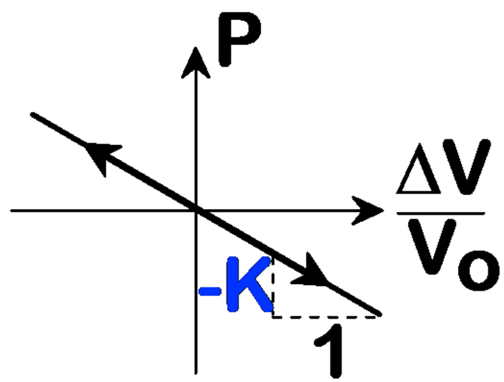


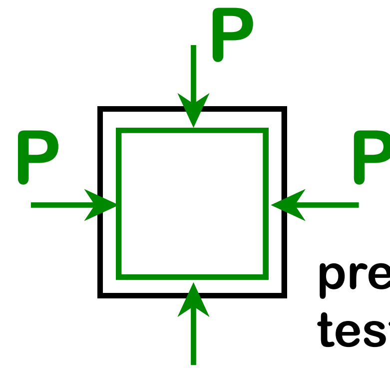


simple torsion test

- Elastic Bulk modulus, K:

$$P = -K\frac{\Delta V}{V_o}$$





pressure test: Init. vol $=V_o$. Vol chg. $=\Delta V$

- Special relations for isotropic materials:

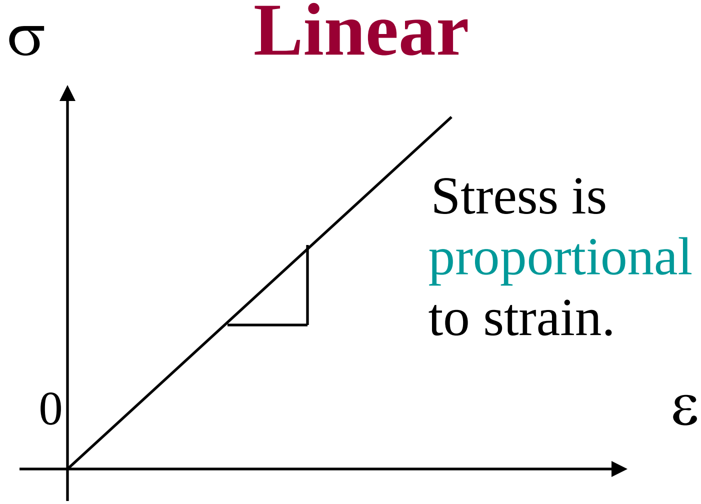
$$G = \frac{E}{2(1+\nu)} \qquad K = \frac{E}{3(1-2\nu)}$$

More Definitions

- **Stress vs. Strain Diagrams**: Plot of stress vs. strain for a given material.
- **Linear (Elastic) Range**: Range of stress-strain diagram in which stress is (generally) proportional to strain.
- **Nonlinear (Plastic) Range**: Range of stress-strain diagram in which stress is **NOT** proportional to strain.

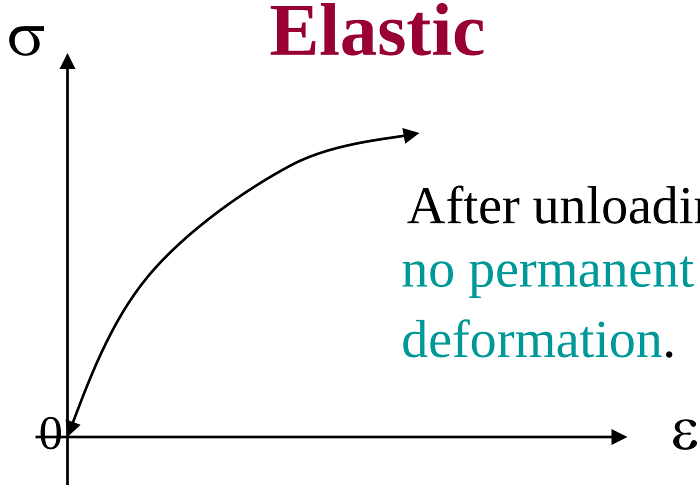
“Linear” and “Elastic”

Linear



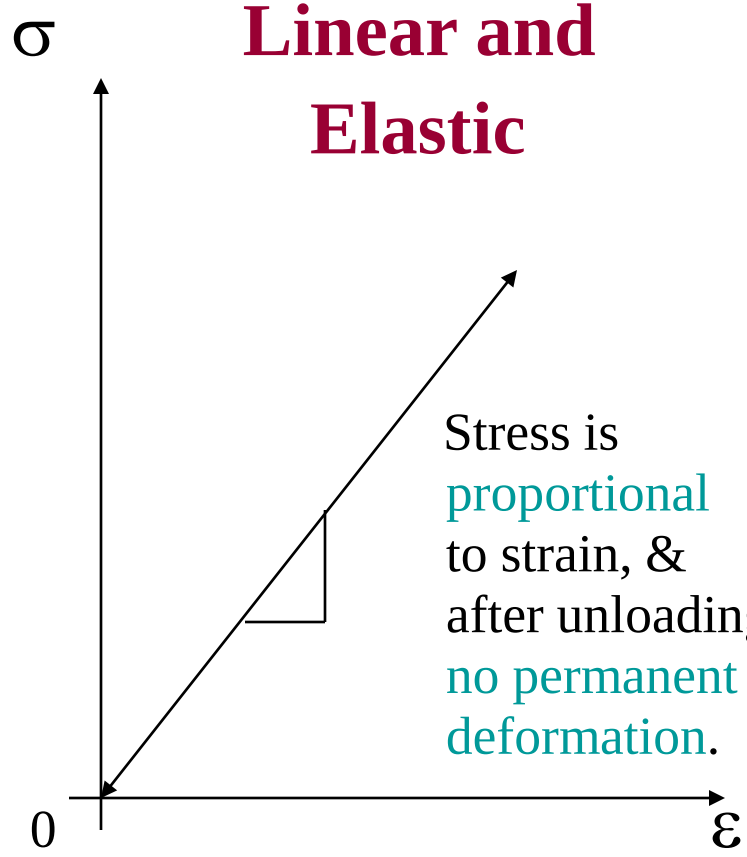
Stress is proportional to strain.

Elastic



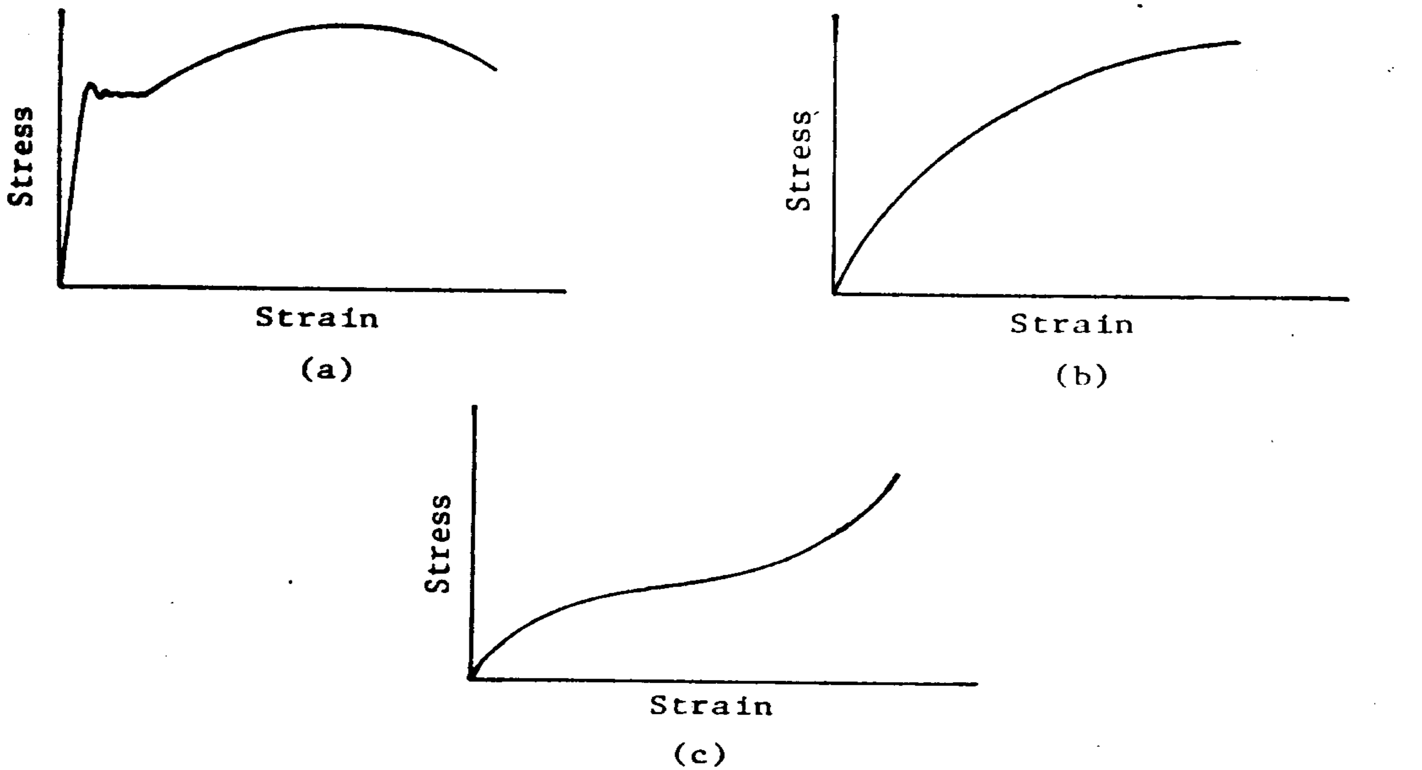
After unloading, no permanent deformation.

Linear and Elastic



Stress is proportional to strain, & after unloading, no permanent deformation.

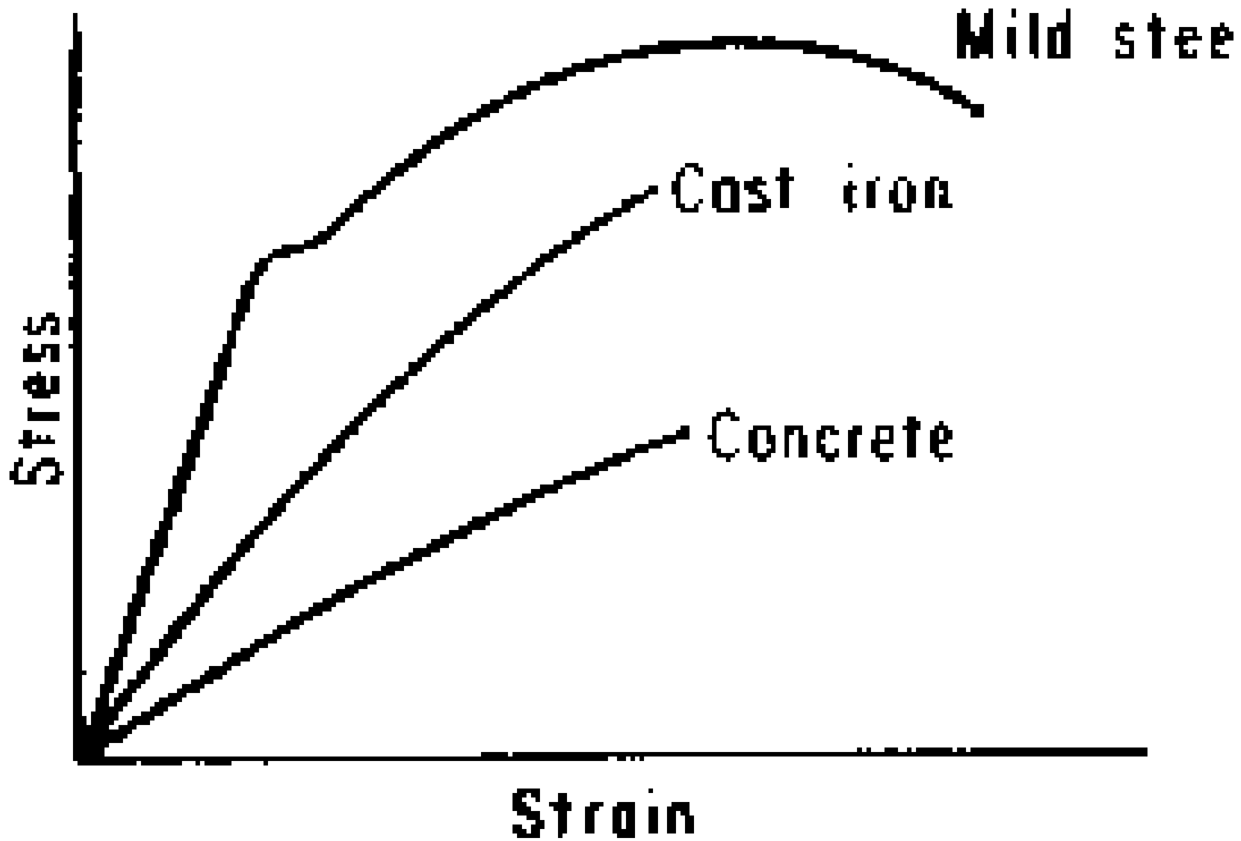
Typical Stress-Strain Curves for Materials



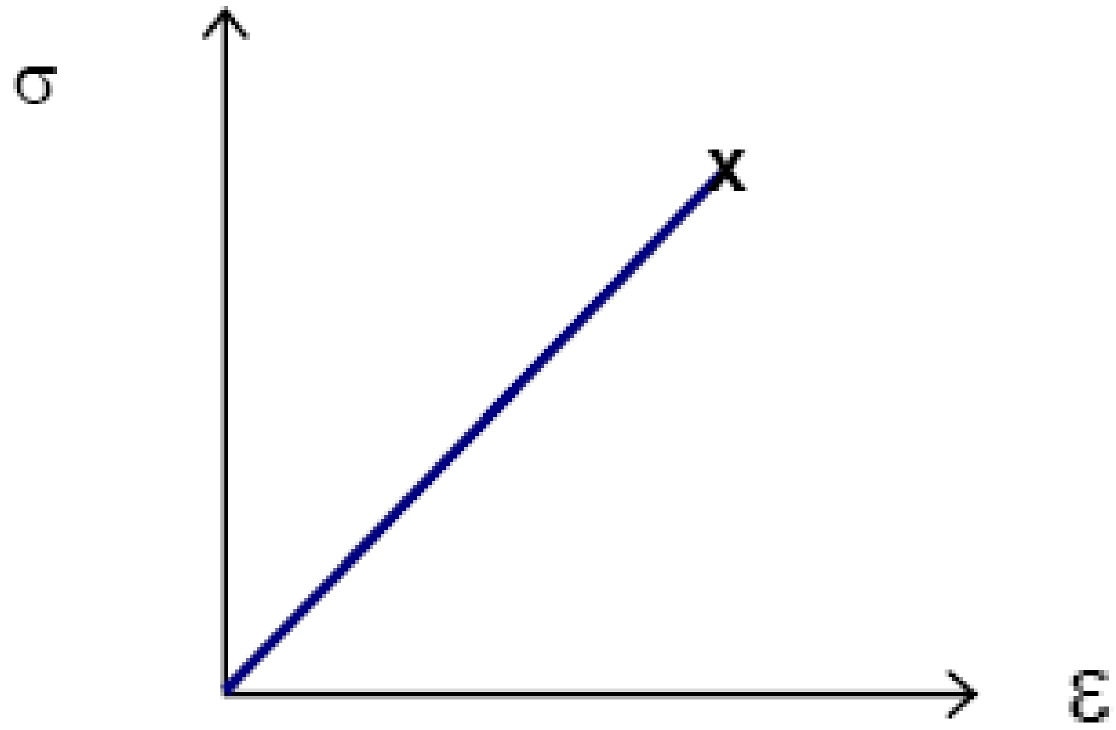
(a) Mild Steel **(b) Iron**

(c) Rubber

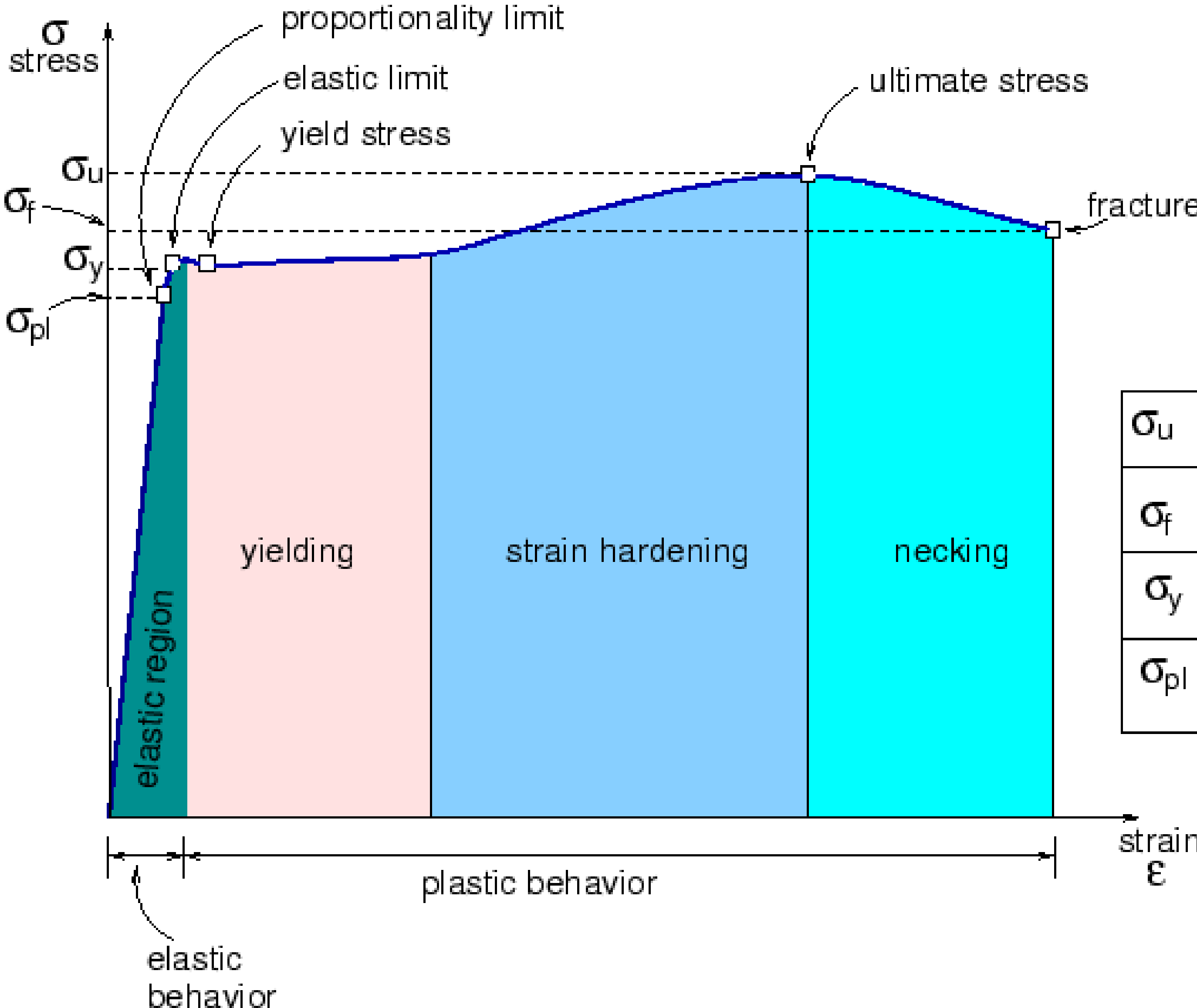
Stress-Strain Curves



Stress-Strain Curve
(brittle material)

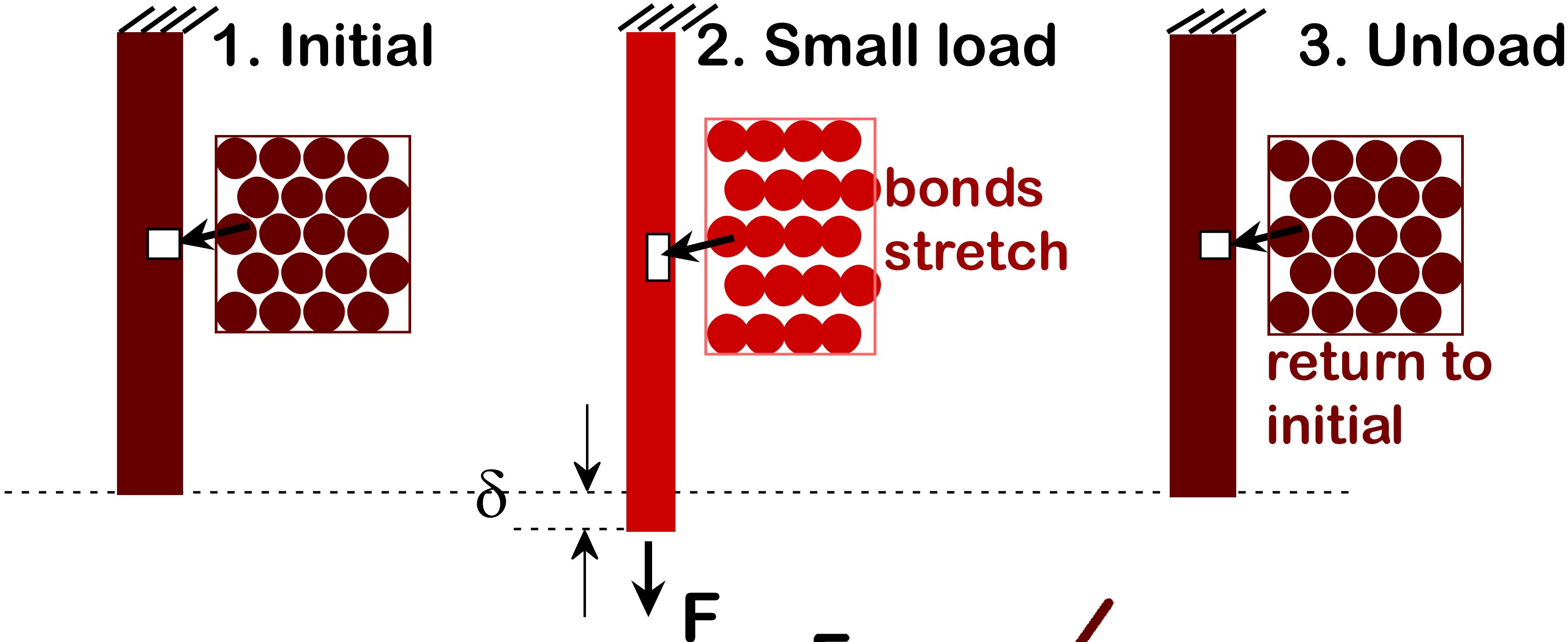


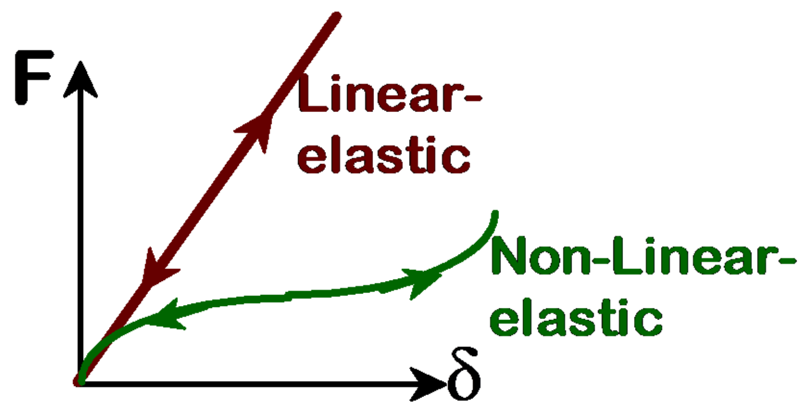
Stress Strain Terminology (Low CS)



σ_u	Ultimate stress
σ_f	Fracture stress
σ_y	Yield stress
σ_{pl}	Proportionality limit

ELASTIC DEFORMATION

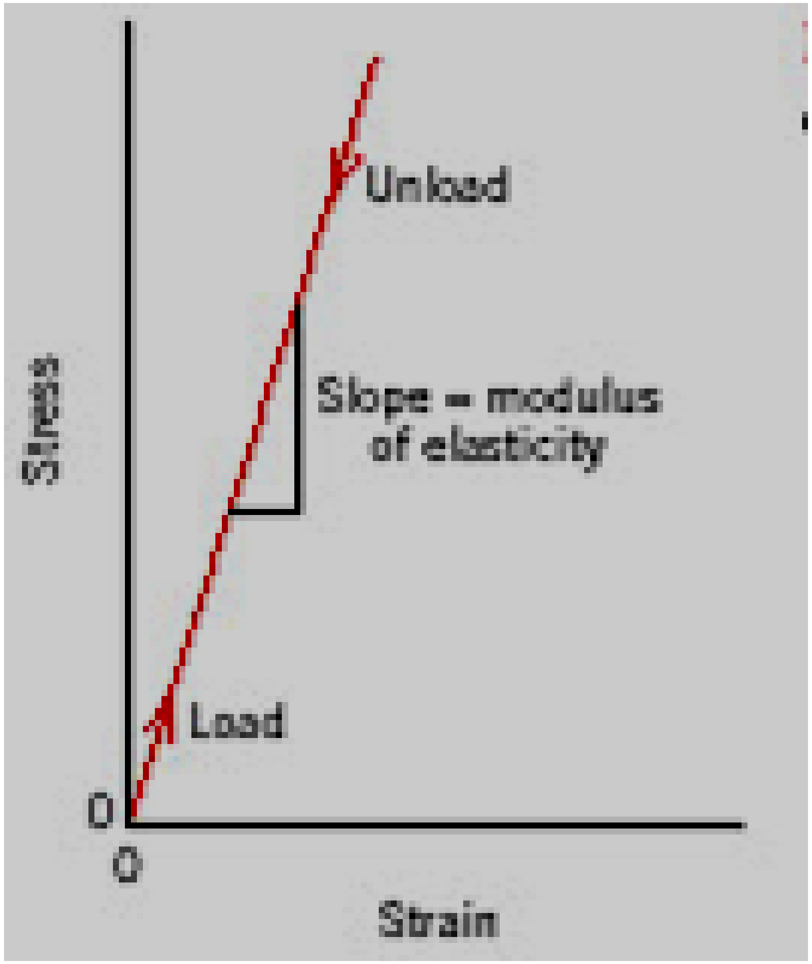




Elastic means reversible!

ELASTIC DEFORMATION

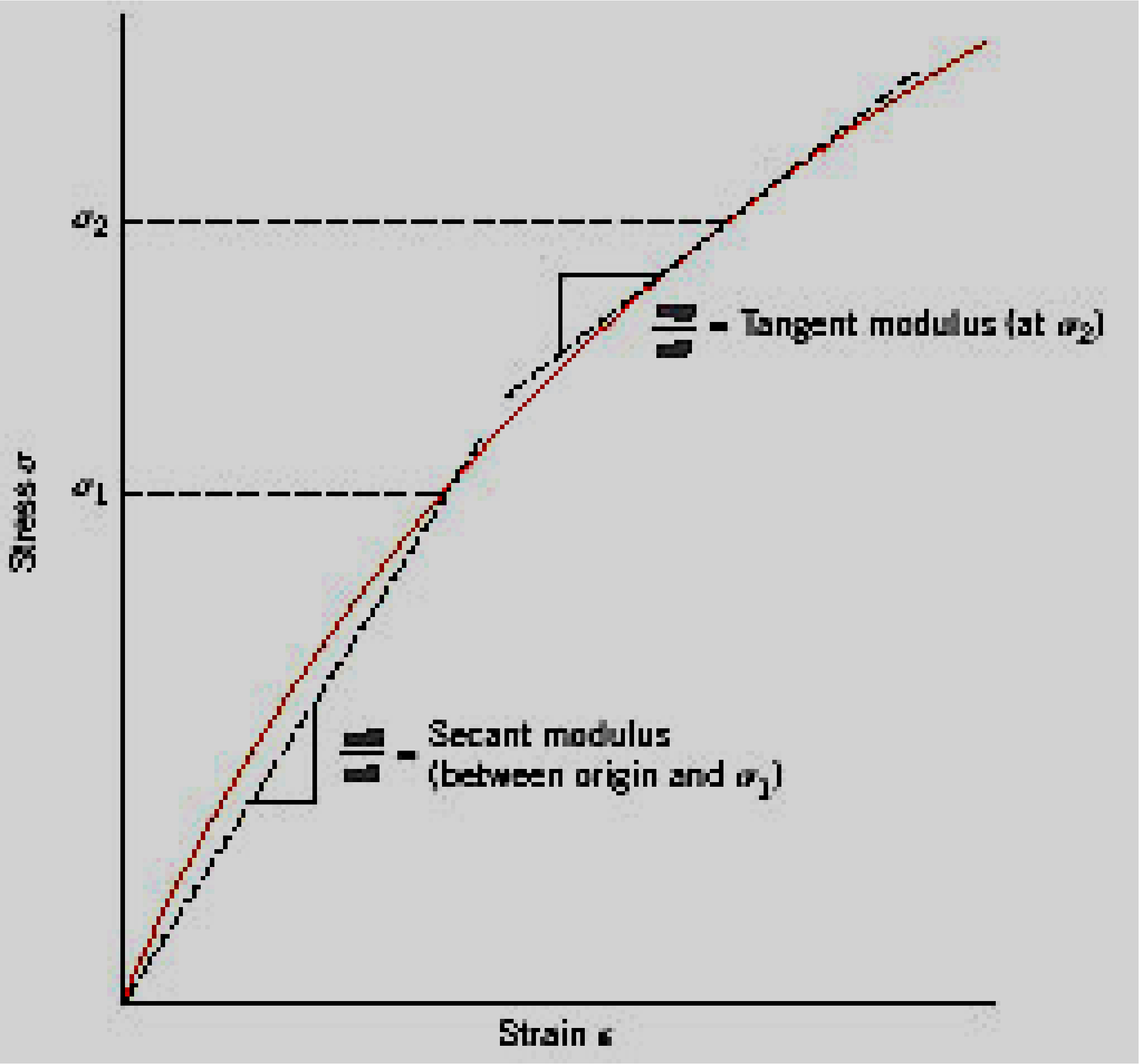
- **Elastic deformation**:
  - Non-permanent, completely reversible, conservative
  - Follow same loading and unloading path
- **Linear elastic deformation**
- Hooke's Law
  - Modulus of elasticity or Young's Modulus ➔ stiffness or a material's resistance to elastic deformation



- **Nonlinear Elastic Behavior**

- Gray cast iron, concrete, many polymers

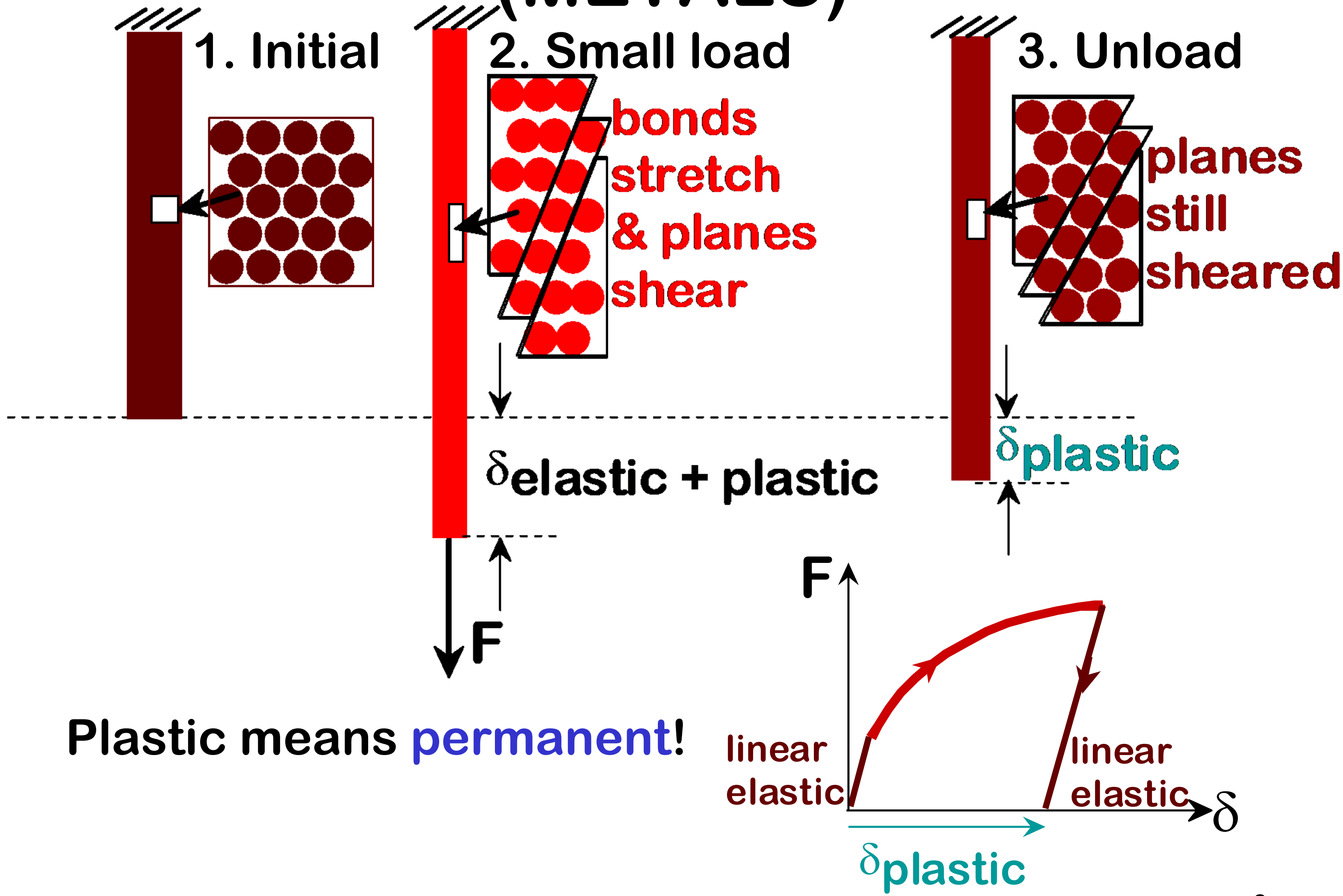
- Not possible to determine a modulus of elasticity
  - Either **tangent** or **secant modulus** is normally used.



PLASTIC DEFORMATION

- For most metals, **elastic deformation** persists only to strains of about 0.005
- **Plastic deformation**
  - – Stress not proportional to strain (Hooke's law cease to be valid)
  - – Permanent
  - – Nonrecoverable
  - – Non-conservative
- **Transition** from elastic to plastic deformation
  - – Gradual for most metals
  - – Some curvature results at the onset of plastic deformation

PLASTIC DEFORMATION (METALS)

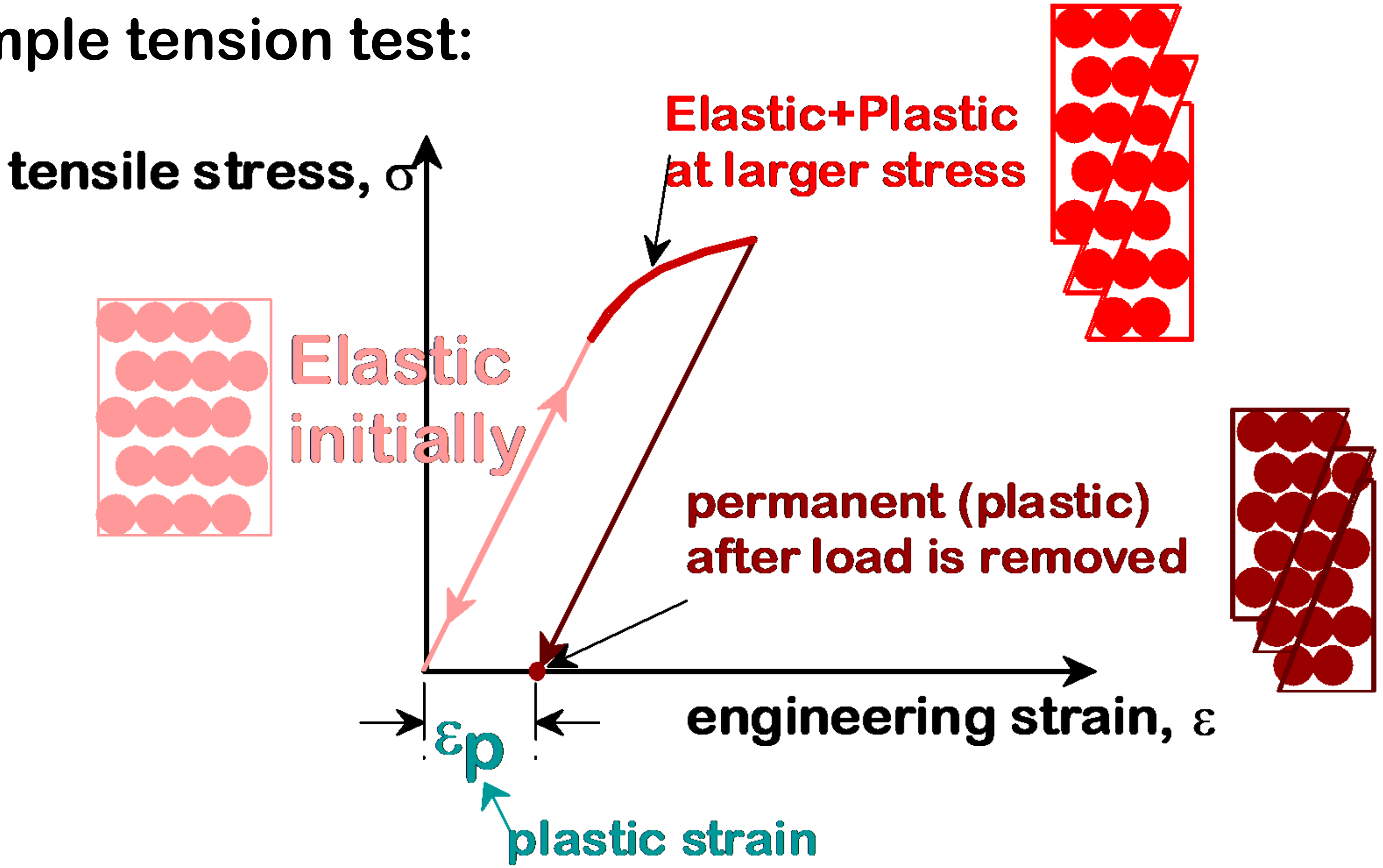


Plastic means **permanent**!

PLASTIC (PERMANENT) DEFORMATION

(at lower temperatures, $T < T_{melt}/3$)

• Simple tension test:

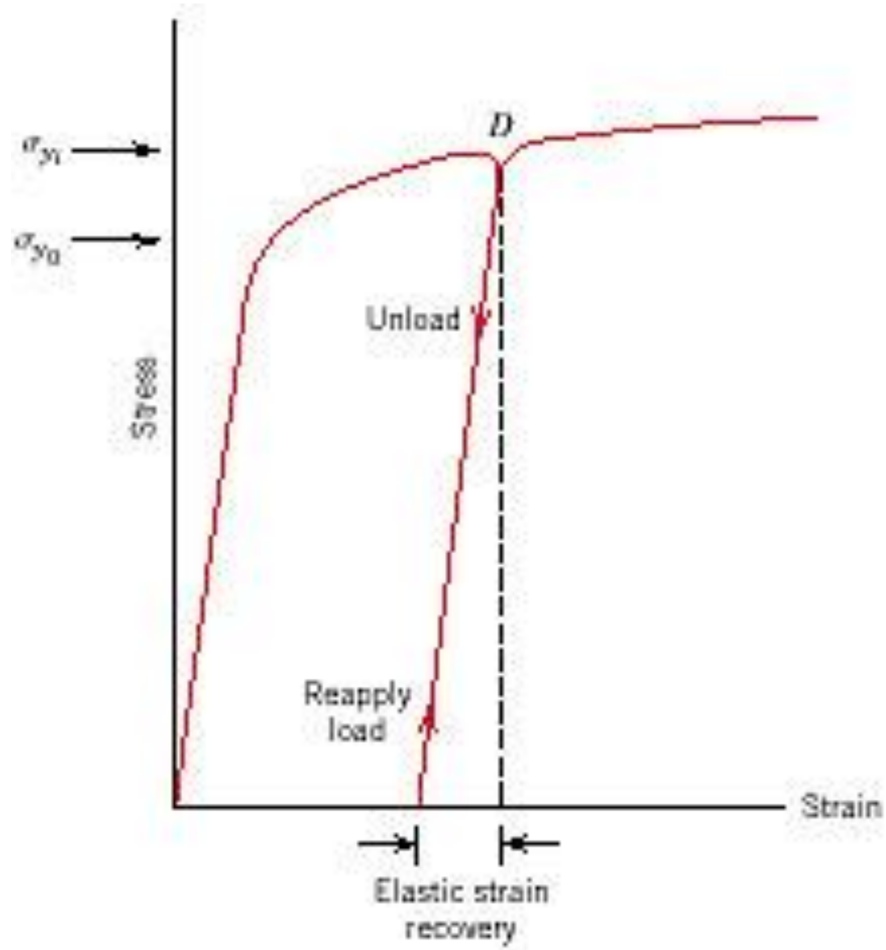


Elastic Recovery During Plastic Deformation

- Upon release of load, some fraction of total strain is recovered as elastic strain

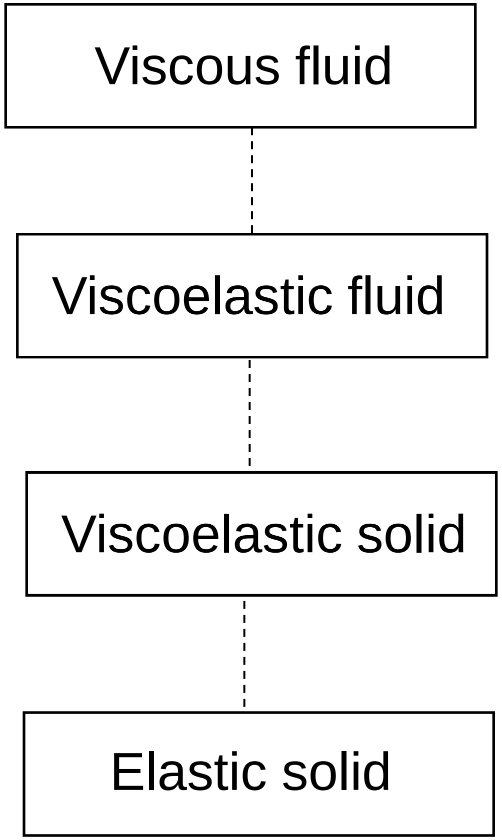
- During unloading, straight path parallel to elastic loading

- Reloading
  - Yielding at new yield strength



Introduction to Viscoelasticity (Viscoelastic Deformation)

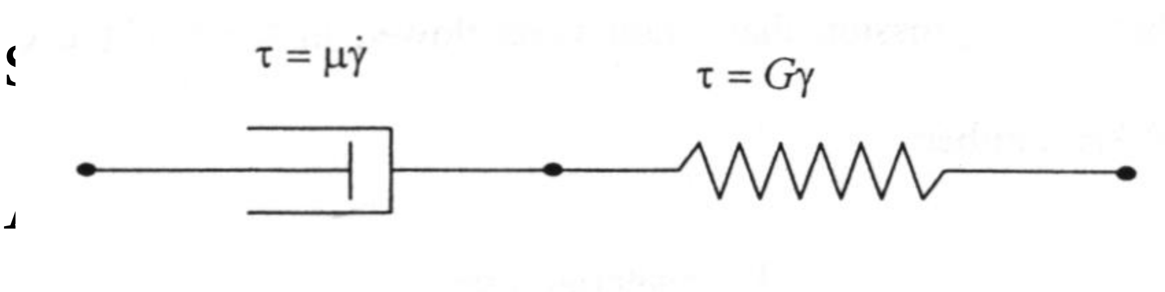
- All viscous liquids deform continuously under the influence of an applied stress – They exhibit viscous behavior.
- Solids deform under an applied stress, but soon reach a position of equilibrium, in which further deformation ceases. If the stress is removed they recover their original shape – They exhibit elastic behavior.
- Viscoelastic materials can exhibit both viscosity and elasticity, depending on the conditions.



➢ Polymers display VISCOELASTIC properties

Viscoelastic Response – Maxwell Element

A viscoelastic material (liquid or solid) will not respond instantaneously when stresses are applied, or the stresses will not respond instantaneously to any imposed deformation. Upon imposing a step input in strain the viscoelastic liquid or solid will



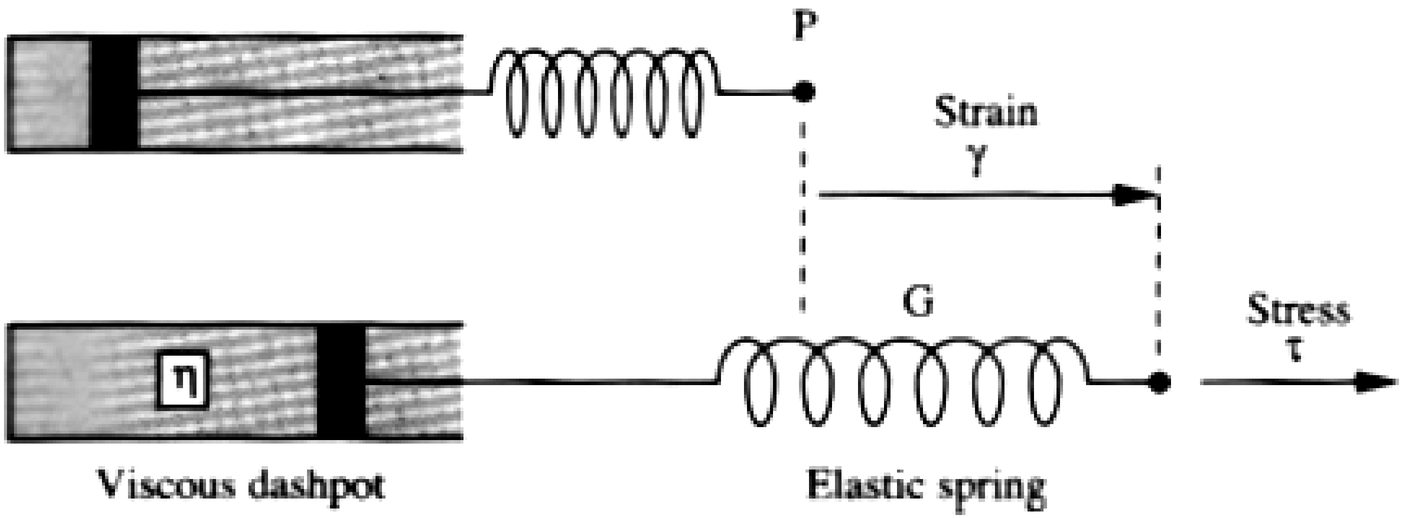
ficant time.

$$\tau(t,\gamma) = G(t,\gamma)\,\gamma$$

ed, one to characterize elastic and the other viscous behavior. One such model is the Maxwell model:

Viscoelastic Response

Let's try to deform the Maxwell element



The deformation rate of the Maxwell model is equal to the sum of the individual deformation rates:

$G(t,\gamma)$ = relaxation modulus.
If $G = G(t)$ only, then we have linear viscoelastic behavior

Maxwell Model Response

1) Stress Relaxation Experiment: If the mechanical model is suddenly extended to a position and held there (γ_o=const., $\dot{\gamma}$=0), from (1):

$$\tau(t) = \tau_o e^{-t/\lambda}$$

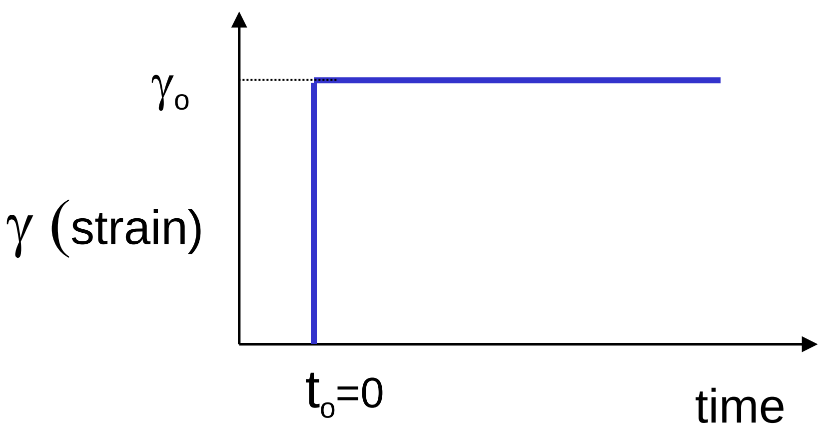
Exponential decay

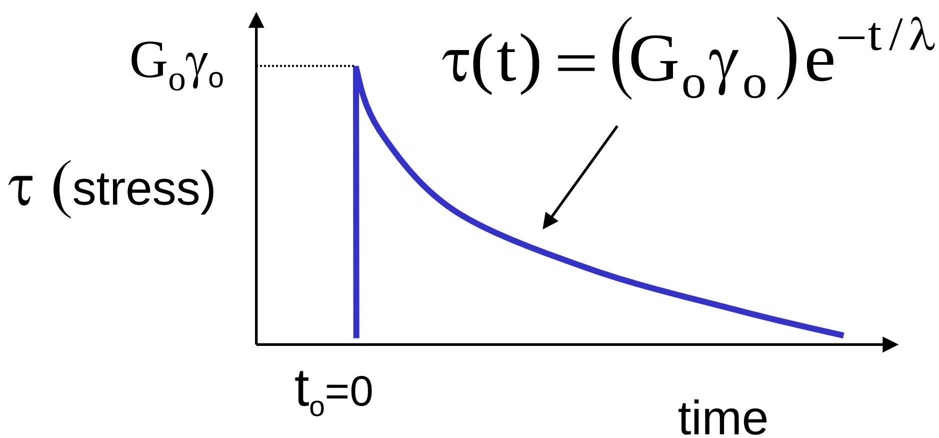
Also recall the definition of the "relaxation" modulus: $G(t) = \dfrac{\tau(t)}{\gamma_o}$

$$\tau(t) = \left(G_o \gamma_o\right) e^{-t/\lambda}$$

and

$$G(t) = G_o e^{-t/\lambda}$$





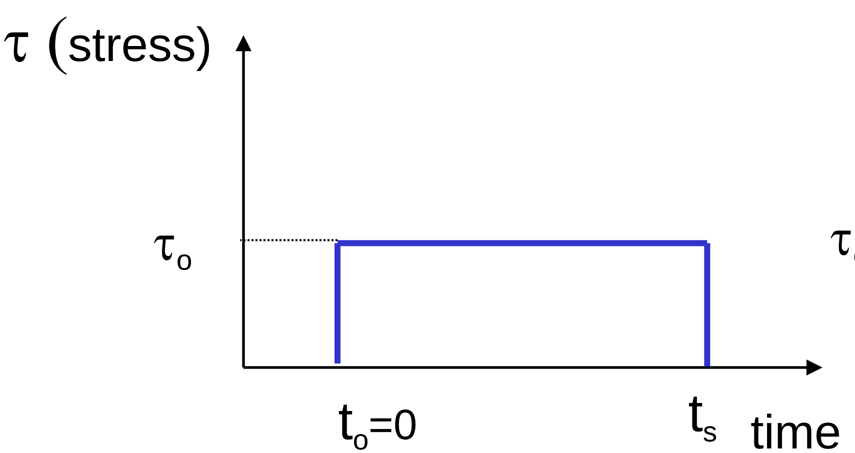
Maxwell Model Response

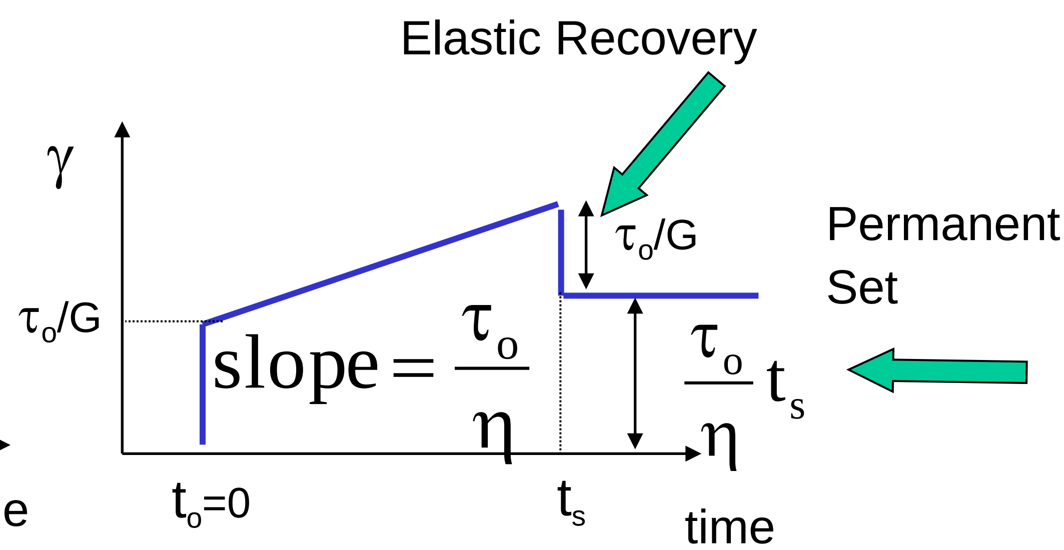
2) Creep Experiment: If a sudden stress is imposed, an instantaneous stretching of the spring will occur, followed by an extension of the dashpot. Deformation after removal of the stress is known as creep recovery:

$$\gamma(t) = \frac{\tau_o}{G} + \frac{\tau_o}{\eta} t$$

Or by defining the “creep compliance”: $J(t) = \frac{\gamma(t)}{\tau_o}$

$$J(t) = \frac{1}{G} + \frac{t}{\eta}$$



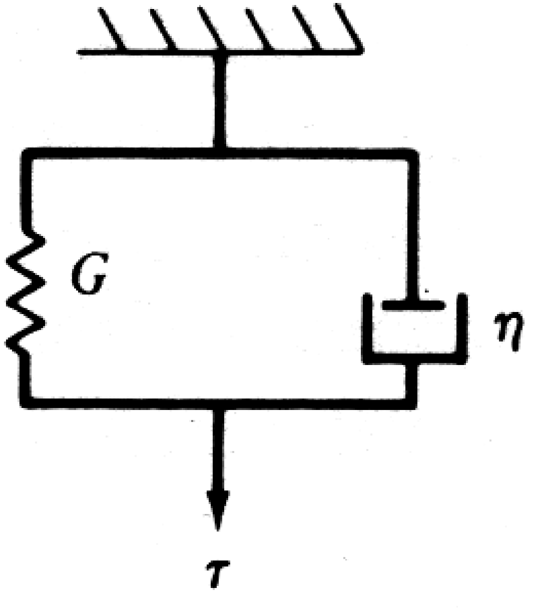


Maxwell Model Response

- The Maxwell model can describe successfully the phenomena of elastic strain, creep recovery, permanent set and stress relaxation observed with real materials
- Moreover the model exhibits relaxation of stresses after a step strain deformation and continuous deformation as long as the stress is maintained. These are characteristics of liquid-like behaviour
- Therefore the Maxwell element represents a VISCOELASTIC FLUID.

Viscoelastic Reponse – Voigt-Kelvin Element

The Voigt-Kelvin element consists of a spring and a dashpot connected in parallel.



$$\gamma = \gamma_{spring} = \gamma_{dashpot}$$

$$\tau = \tau_{spring} + \tau_{dashpot}$$

$$\tau = G\gamma + \eta\dot{\gamma}$$

Voigt-Kelvin Model Response

Creep Experiment (τ_o=const.):

$$\gamma(t) = \frac{\tau_o}{G} + (1 - e^{-t/\lambda})$$

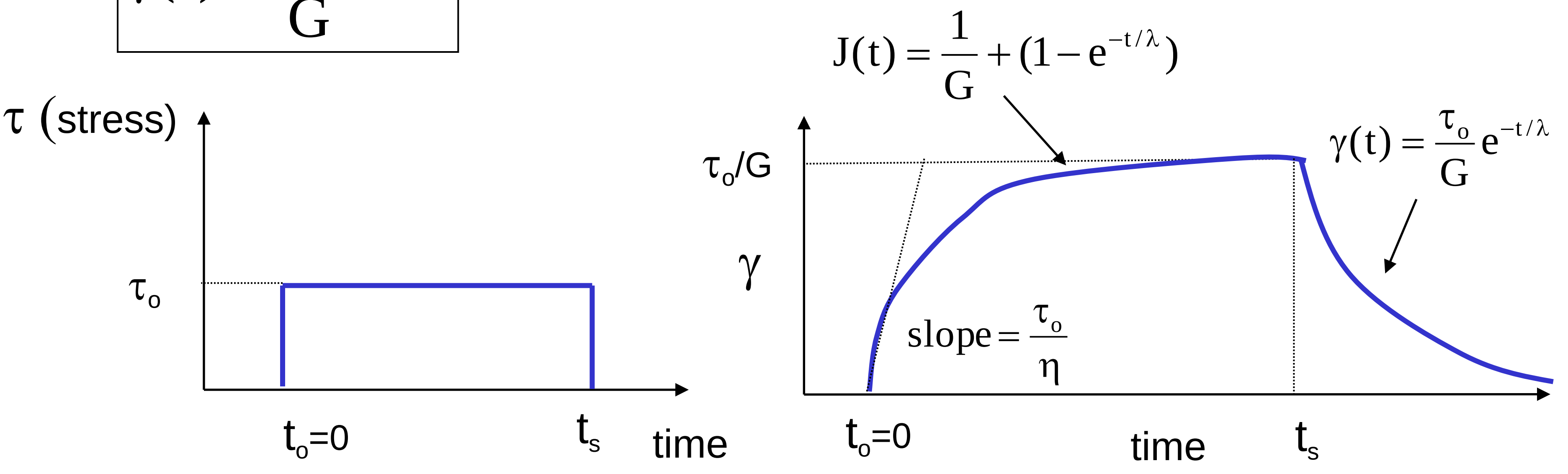
or

$$J(t) = \frac{1}{G} + (1 - e^{-t/\lambda})$$

If the stress is removed after equilibrium has been reached (creep recovery):

$$\gamma(t) = \frac{\tau_o}{G} e^{-t/\lambda}$$

Exponential decay



Voigt-Kelvin Model Response

- The Voigt-Kelvin element does not continue to deform as long as stress is applied, rather it reaches an equilibrium deformation. It does not exhibit any permanent set. These resemble the response of cross-linked rubbers and are characteristics of solid-like behaviour
- Therefore the Voigt-Kelvin element represents a VISCOELASTIC SOLID.

➢ The Voigt-Kelvin element cannot describe stress relaxation.

➢ Both Maxwell and Voigt-Kelvin elements can provide only a qualitative description of the response

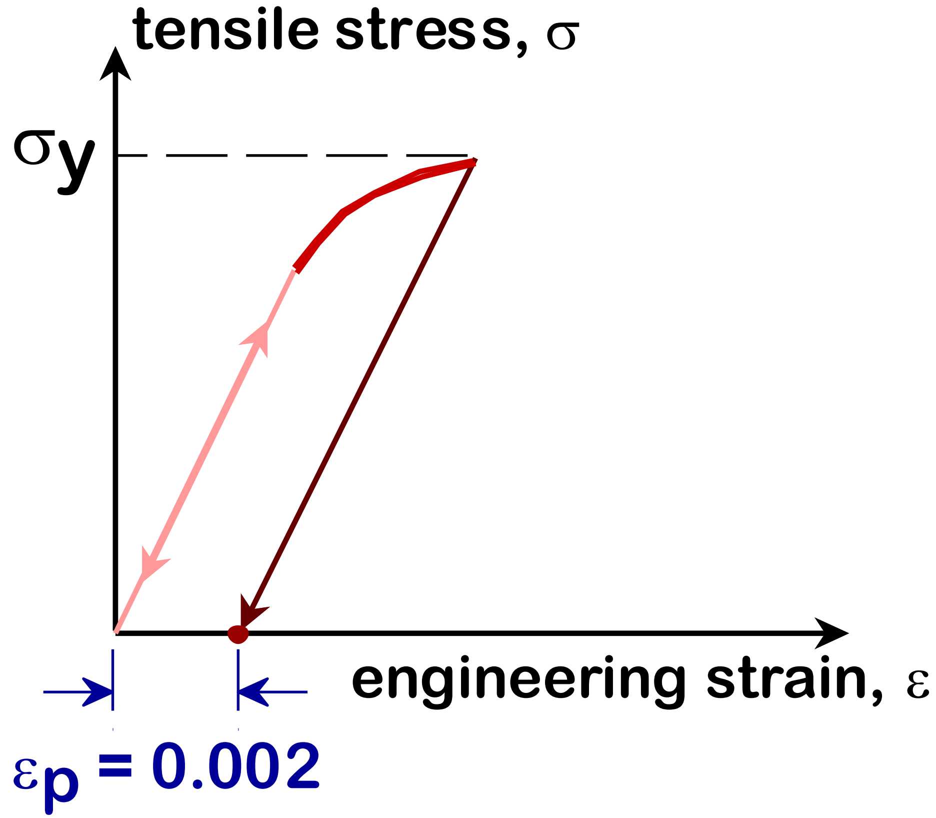
➢ Various other spring/dashpot combinations have been proposed.

IMPORTANT PROPERTIES OF MATERIALS

YIELD STRENGTH, σ_y

- Stress at which *noticeable* plastic deformation has occurred.

when $\varepsilon_p = 0.002$



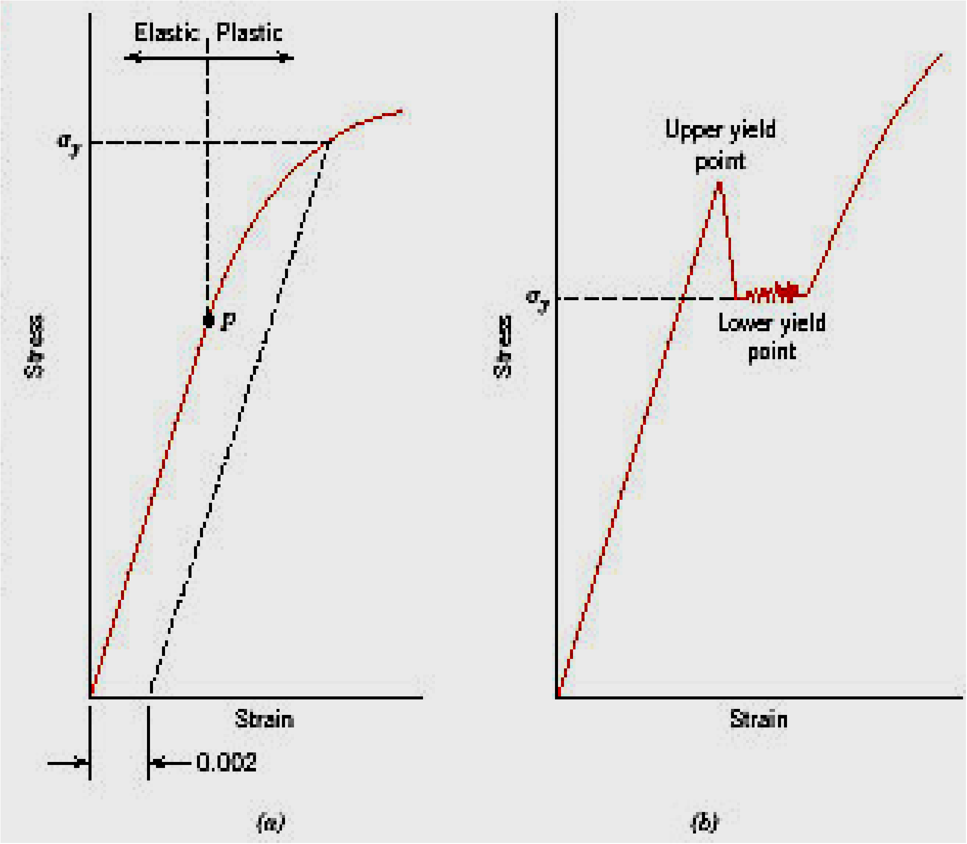
- **YIELDING and YIELD STRESS**

Typical stress strain behavior (Figure)

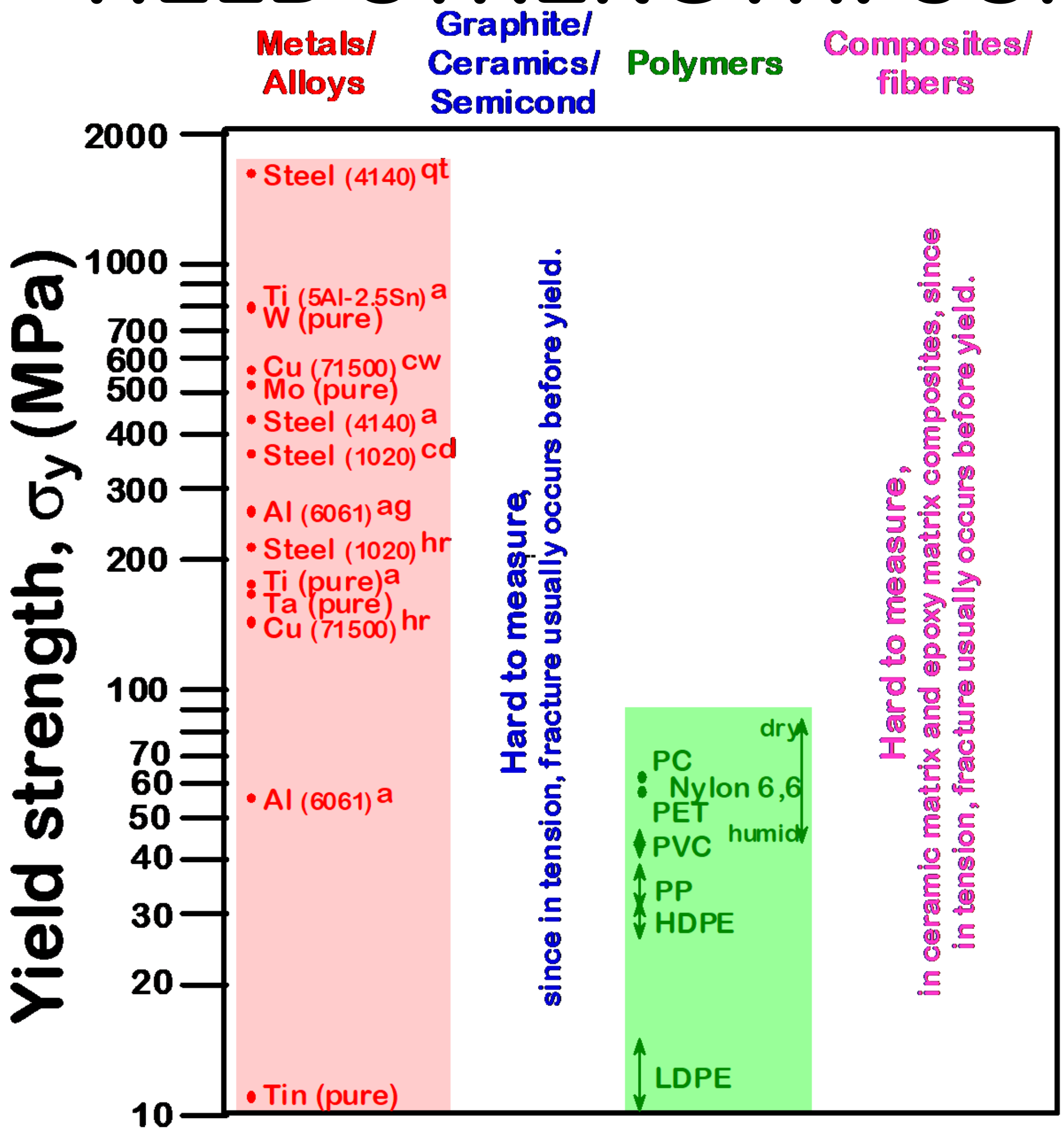
- **Proportional Limit (P)**
- **Yielding**
- **Yield strength**

In most cases, the position of yield point may not be determined precisely.

- **Established convention**: a straight line is constructed parallel to the elastic portion at some specified **strain offset**, usually 0.002 (0.2%) Fig. 6.10a ➔ corresponding intersection point gives **yield strength**.



YIELD STRENGTH: COMPARISON



σ_y(ceramics)

>> σ_y(metals)

>> σ_y(polymers)

Room T values

Based on data in Table B4, *Callister 6e*.

a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered

- **TENSILE STRENGTH**

- **Tensile** strength TS (MPa or psi) is the stress at the maximum on the engineering stress-strain curve

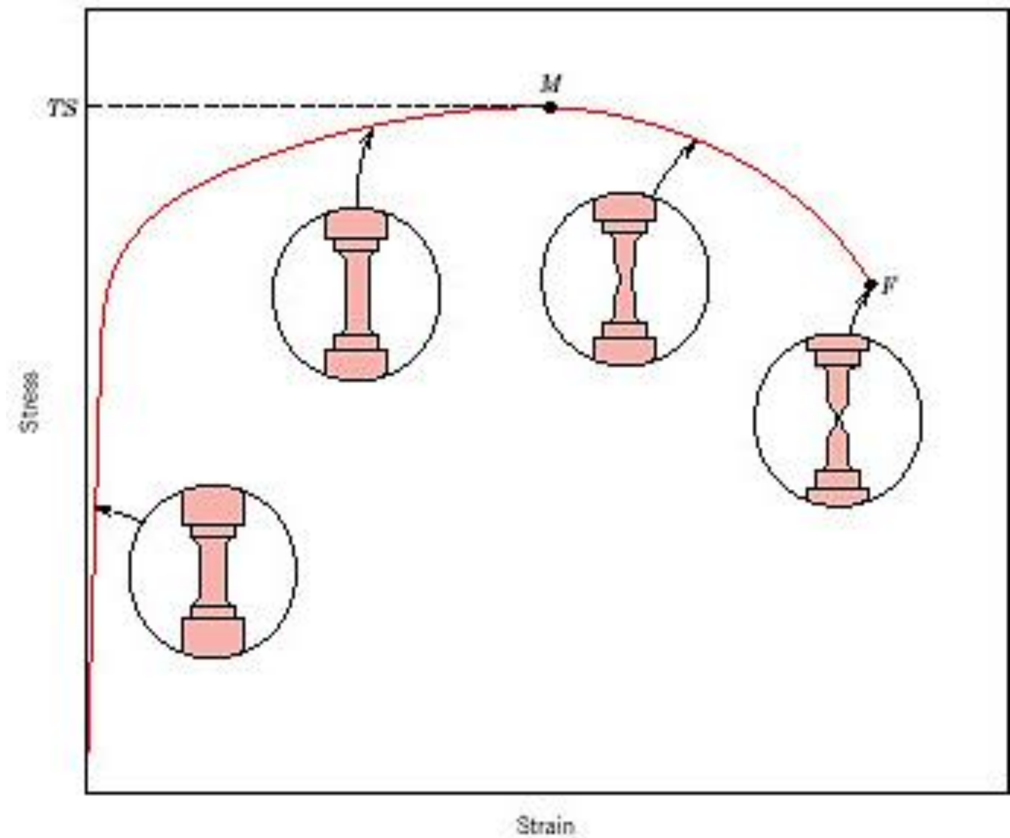
- All deformation up to this point is **uniform**.

- Onset of **necking** at this stress at some point → all subsequent deformation at this neck.

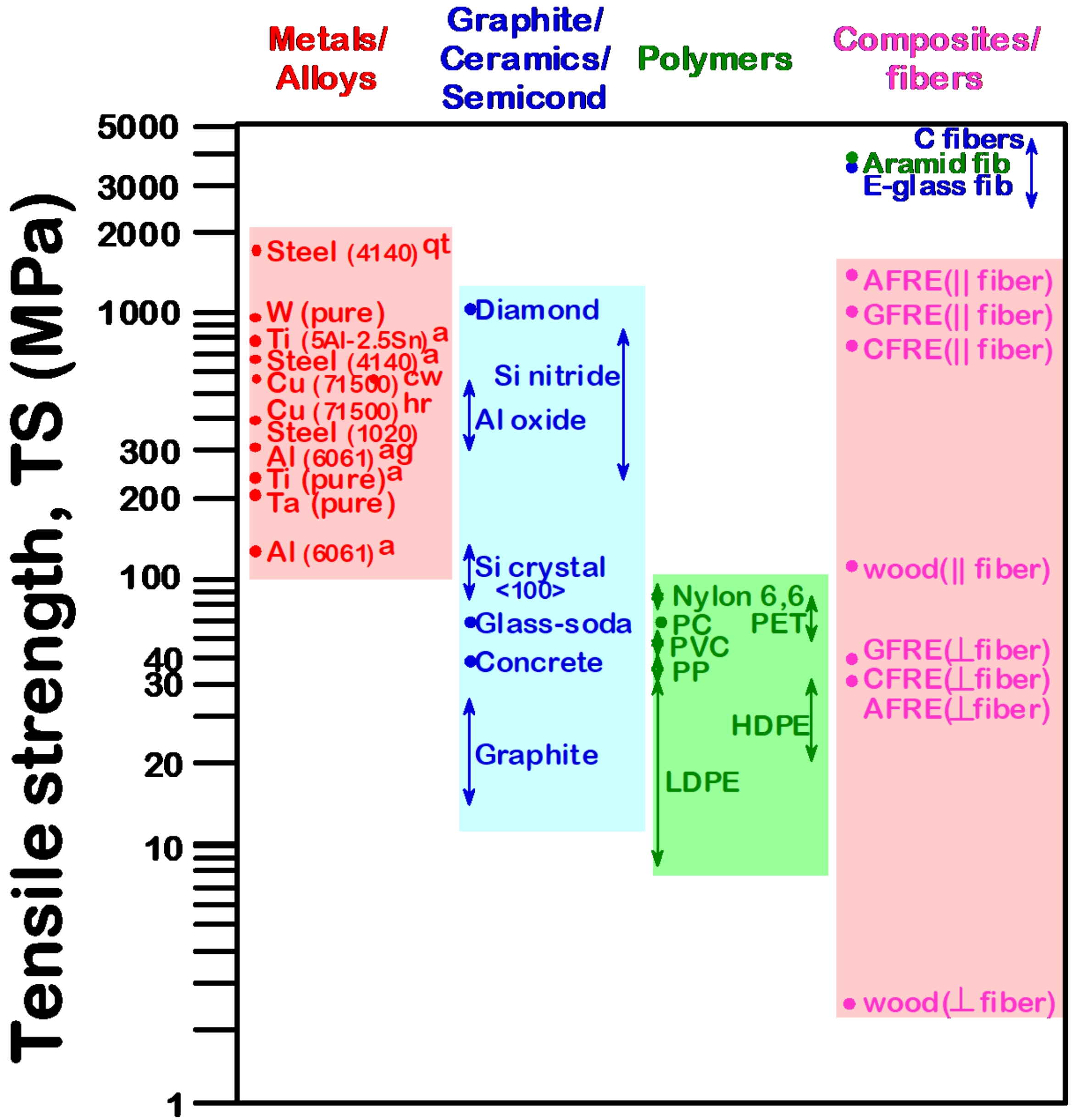
- **Range: 50 - 3000 MPa**

  50 MPa for aluminum

  3000 MPa for high strength steel



TENSILE STRENGTH: COMPARISON



TS(ceram)
~TS(met)
~ TS(comp)
>> TS(poly)

Room T values

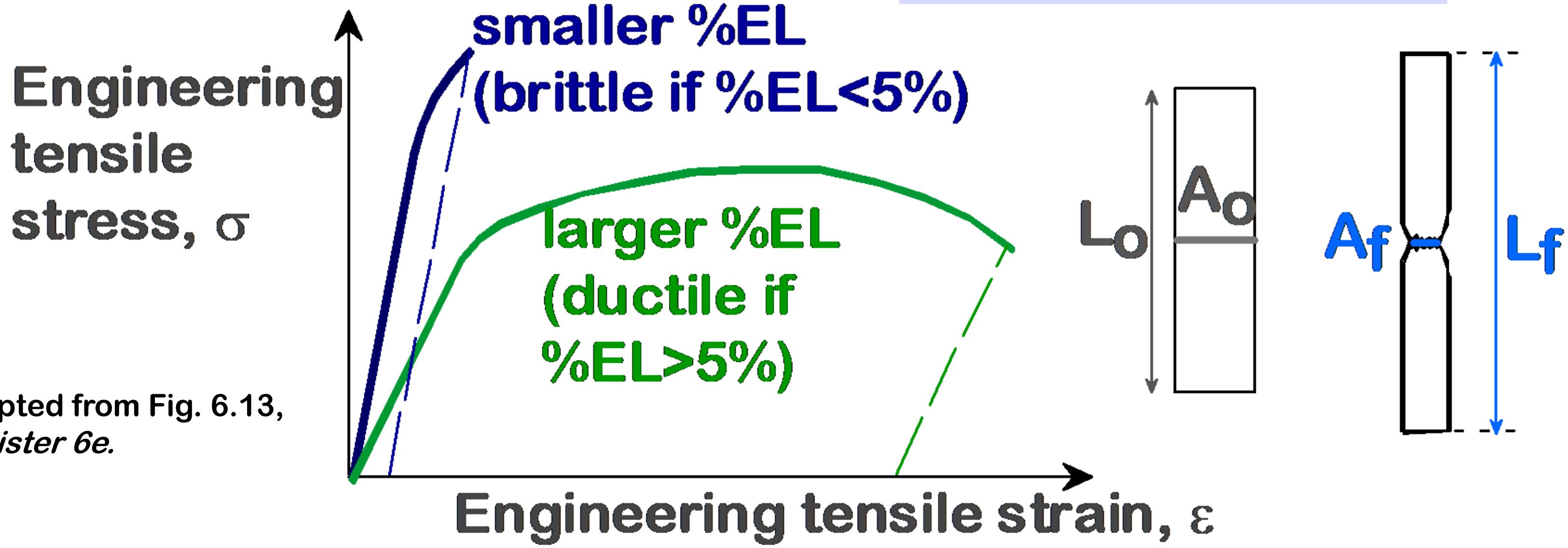
Based on data in Table B4, *Callister 6e*.

a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered

AFRE, GFRE, & CFRE = aramid, glass, & carbon fiber-reinforced epoxy composites, with 60 vol% fibers.

DUCTILITY, %EL

- **Plastic tensile strain at failure:** $$\%EL = \frac{L_f - L_o}{L_o} x100$$



Adapted from Fig. 6.13, *Callister 6e.*

- **Another ductility measure:** $$\%AR = \frac{A_o - A_f}{A_o} x100$$

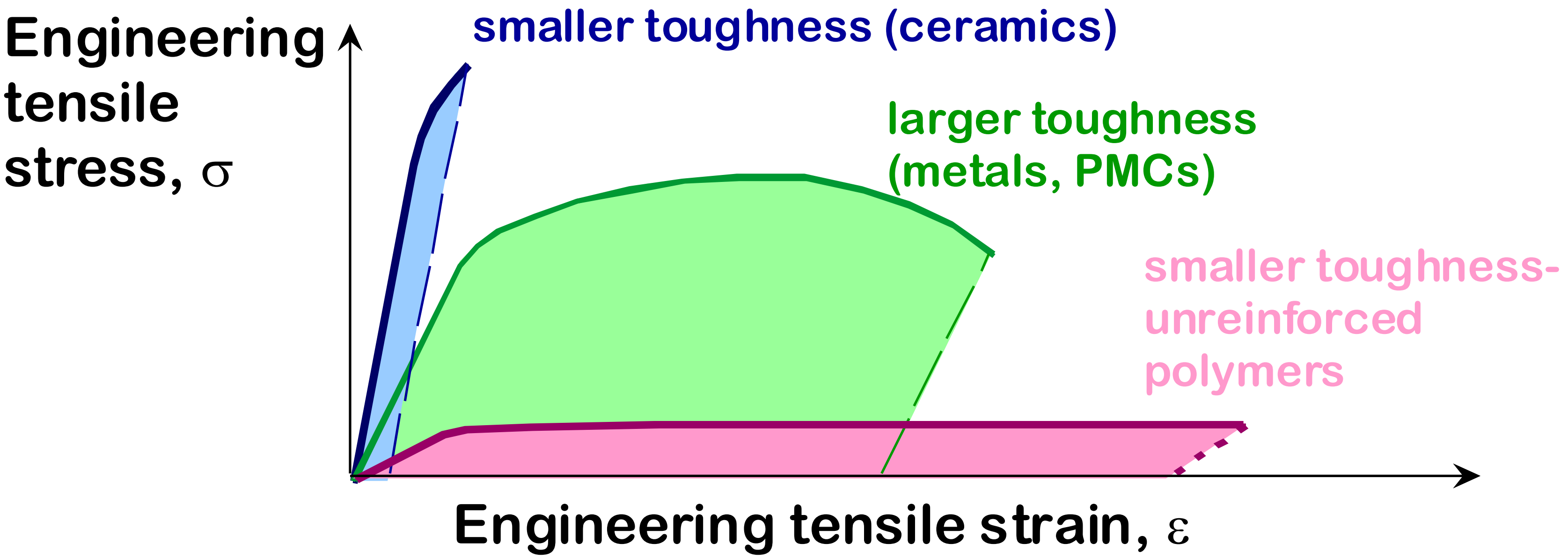
- **Note: %AR and %EL are often comparable.**
  --Reason: crystal slip does not change material volume.
  --%AR > %EL possible if internal voids form in neck.

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

TOUGHNESS

- Energy to break a unit volume of material
- Approximate by the area under the stress-strain curve.



TOUGHNESS

- A measure of the ability of a material to absorb energy up to fracture.
- Specimen geometry and the manner of load application are important in toughness determination:
  - Notch toughness: dynamic (high strain rate) loading, specimen with notch (or point of stress concentration) (Sec 8.6)
  - Fracture toughness: property indicative of a materials resistance to fracture when crack is present (Sec 8.5)

- For static (low strain rate) condition, modulus of toughness is equal to the total area under the stress-strain curve (up to fracture):

For Ductile Material :

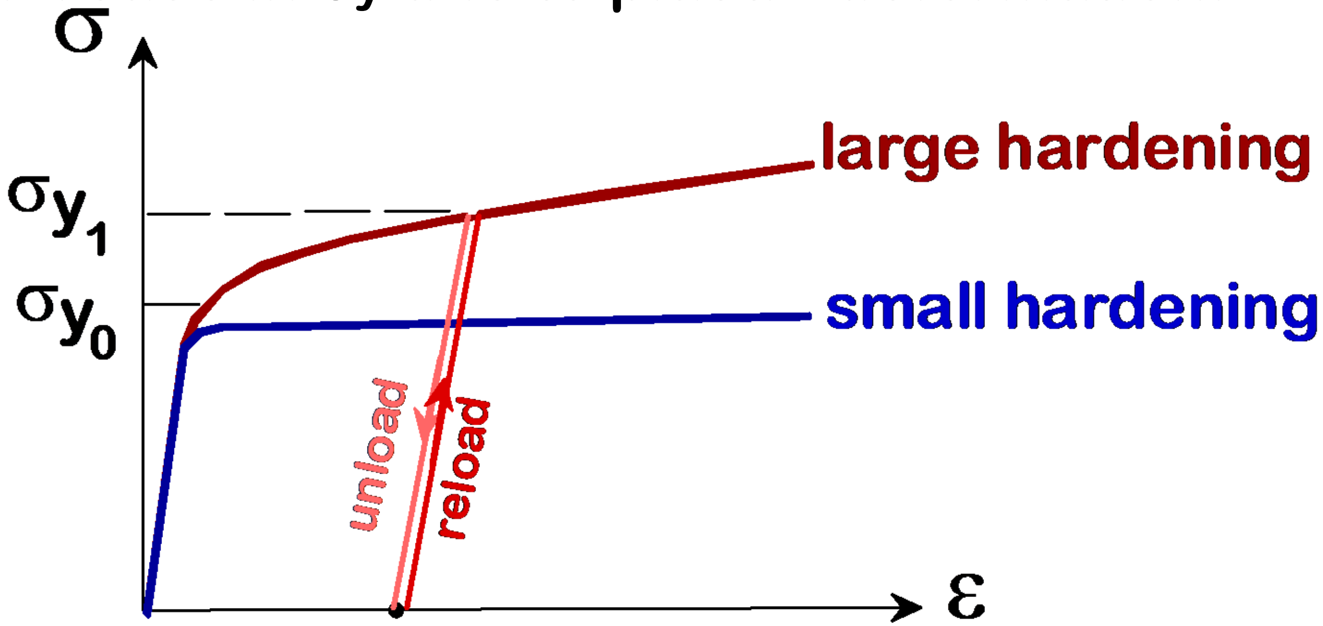
$$U_T \approx \sigma_u \varepsilon_f \approx \frac{1}{2}\left(\sigma_{y(0.2\%)} + \sigma_u\right)\varepsilon_f$$

For Brittle Material:

$$U_T \approx \frac{2}{3}\sigma_u \varepsilon_f$$

HARDENING

- An increase in σ_y due to plastic deformation.



- Curve fit to the stress-strain response:

$$\sigma_T = C(\varepsilon_T)^n$$

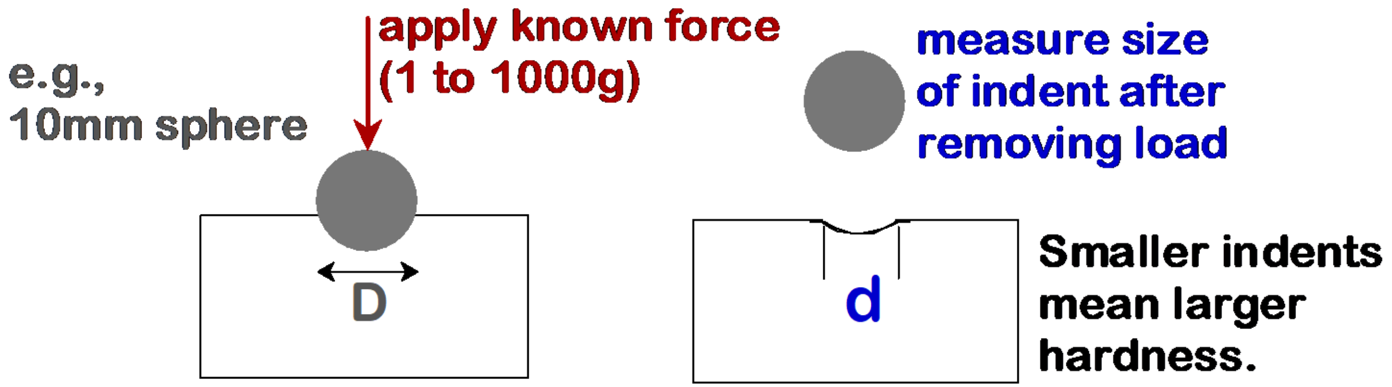
"true" stress (F/A)

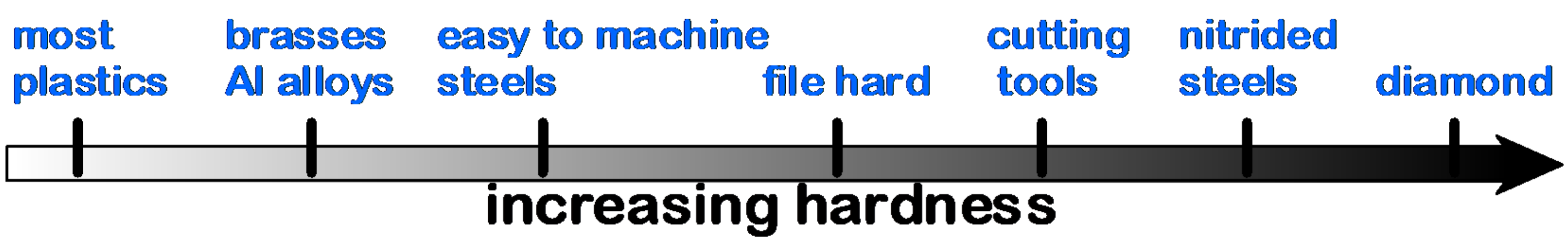
"true" strain: $\ln(L/L_o)$

hardening exponent:
n=0.15 (some steels)
to n=0.5 (some copper)

HARDNESS

- Resistance to permanently indenting the surface.
- Large hardness means:
  - --resistance to plastic deformation or cracking in compression.
  - --better wear properties.



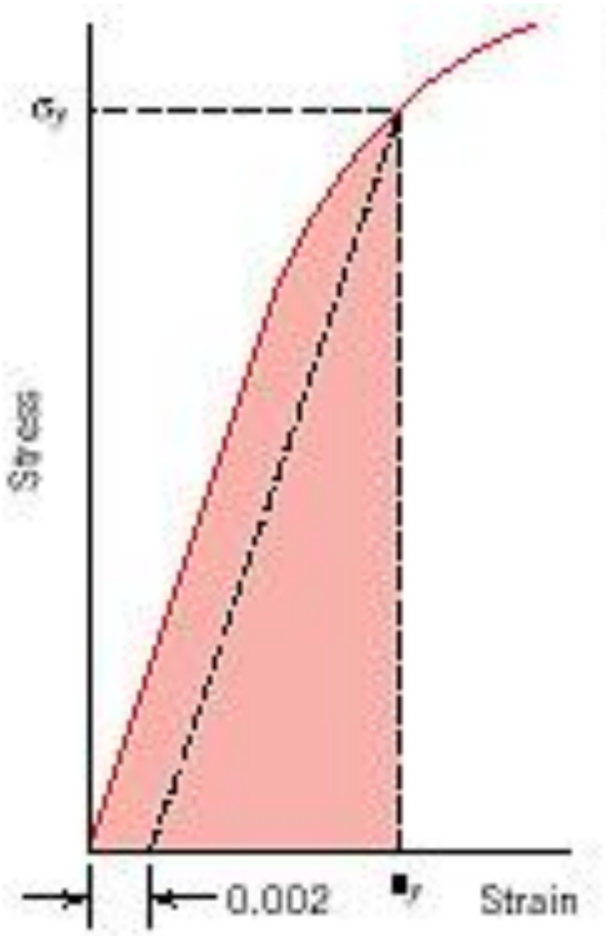


Adapted from Fig. 6.18, *Callister 6e.* (Fig. 6.18 is adapted from G.F. Kinney, *Engineering Properties and Applications of Plastics*, p. 202, John Wiley and Sons, 1957.)

RESILIENCE

- **Resilience** is the capacity of a material to **absorb energy** when it is deformed **elastically** and then, upon unloading, to have this energy recovered.

- **Modulus of resilience (Ur)**
  - Associated property
  - Area under the engineering stress-strain curve
  - **Strain energy per unit volume** required to stress from an unloaded state to yielding



DESIGN OR SAFETY FACTORS

- Design uncertainties mean we do not push the limit.
- Factor of safety, N

$$\sigma_{working} = \frac{\sigma_y}{N}$$

Often N is between 1.2 and 4

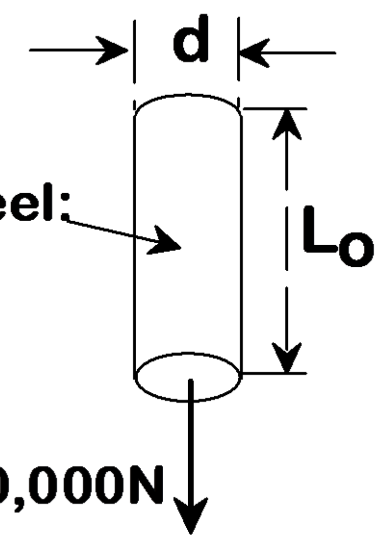
- Ex: Calculate a diameter, d, to ensure that yield does not occur in the 1045 carbon steel rod below. Use a factor of safety of 5.

$$\sigma_{working} = \frac{\sigma_y}{N}$$

$$\frac{220{,}000\text{N}}{\pi\left(d^2/4\right)}$$

5

1045 plain carbon steel:
σ_y=310MPa
TS=565MPa



F = 220,000N

SUMMARY - I

- Stress and strain: These are size-independent measures of load and displacement, respectively.
- Elastic behavior: This reversible behavior often shows a linear relation between stress and strain. To minimize deformation, select a material with a large elastic modulus (E or G).
- Plastic behavior: This permanent deformation behavior occurs when the tensile (or compressive) uniaxial stress reaches σy.
- Toughness: The energy needed to break a unit volume of material.
- Ductility: The plastic strain at failure.

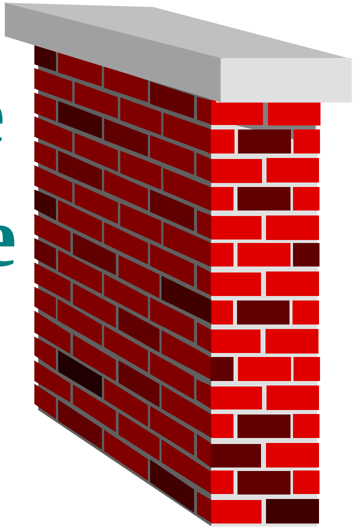
Mechanical Failure:
How do materials break ?

- Fracture: crack growth to rupture at a critical load
  - Ductile vs Brittle fracture
  - Principles of Fracture Mechanics
    - Stress Concentration
  - Impact Fracture Testing
- Fatigue: crack growth due to cycling loads
  - Cyclic stresses, the S-N curve
  - Crack initiation and propagation
  - Factors that effect fatigue behavior
- Creep: high temperature plastic deformation
  - Stress and temperature effects
  - Alloys for hi-temperature usage

Fracture

Brittle Fracture

Ductile Fracture

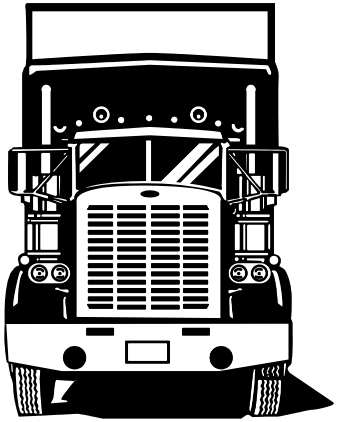


Parameters Affecting Fracture

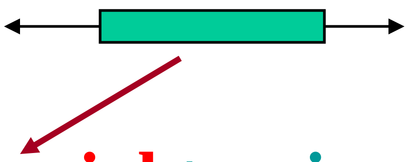
Load Rate
Nature of Loading
- Triaxiality
- Cyclic

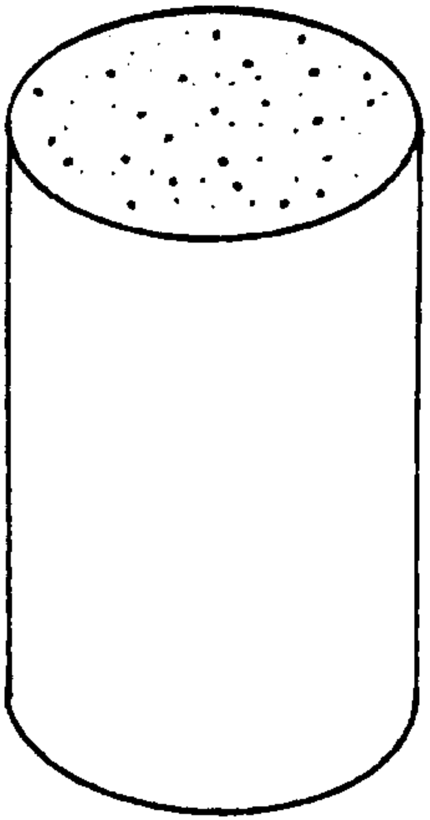
Material
Temperature
Corrosion

Fabrication Cracks
Design Features
- Notches
- Holes
- Fillets
- Uneven surface
- Roughness



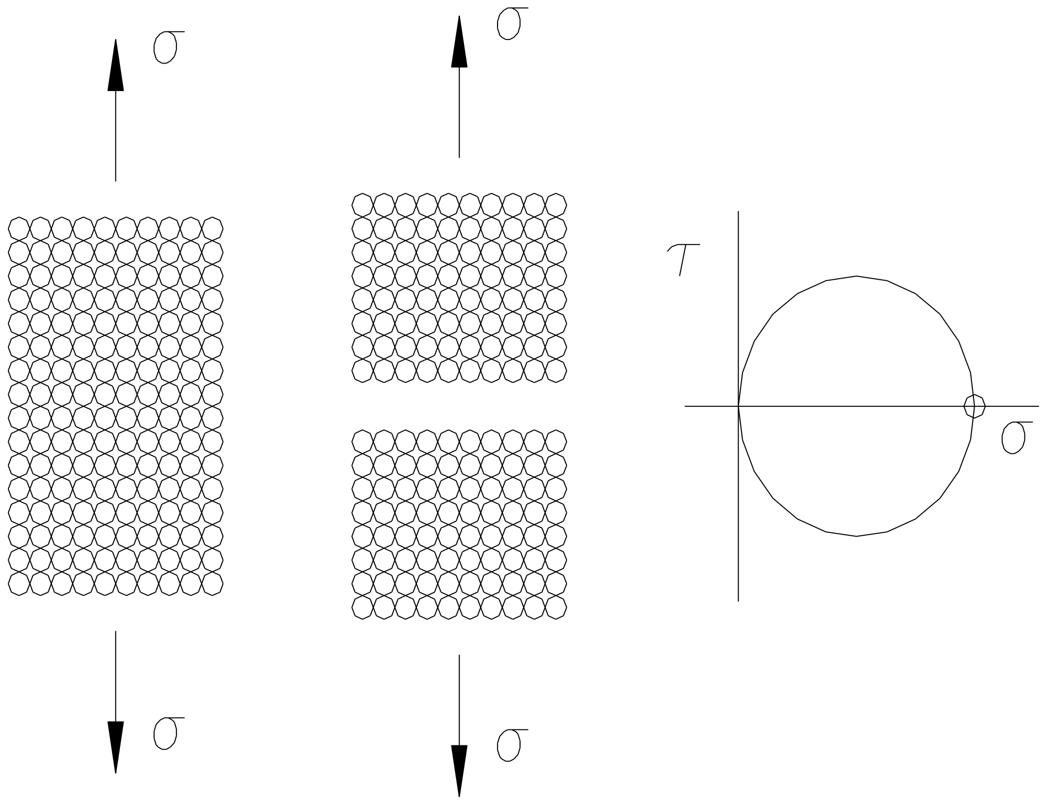
Characteristics of Brittle Fracture in Tension





- Under uniaxial tension loading, fracture occurs at 90 degrees with the axis of loading.
- There is no plastic deformation (i.e. there is no necking).
- The failure plane has a granular appearance.

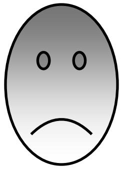
Mechanics of Brittle Material Fracture in Tension



Mechanics of Brittle Material Fracture in Tension

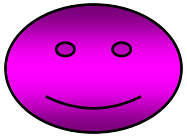
- The **tensile** component of stress "pulls" the crystal apart:

$$\sigma = [\sigma]$$



- **Shear strength** of the material is **relatively higher**.

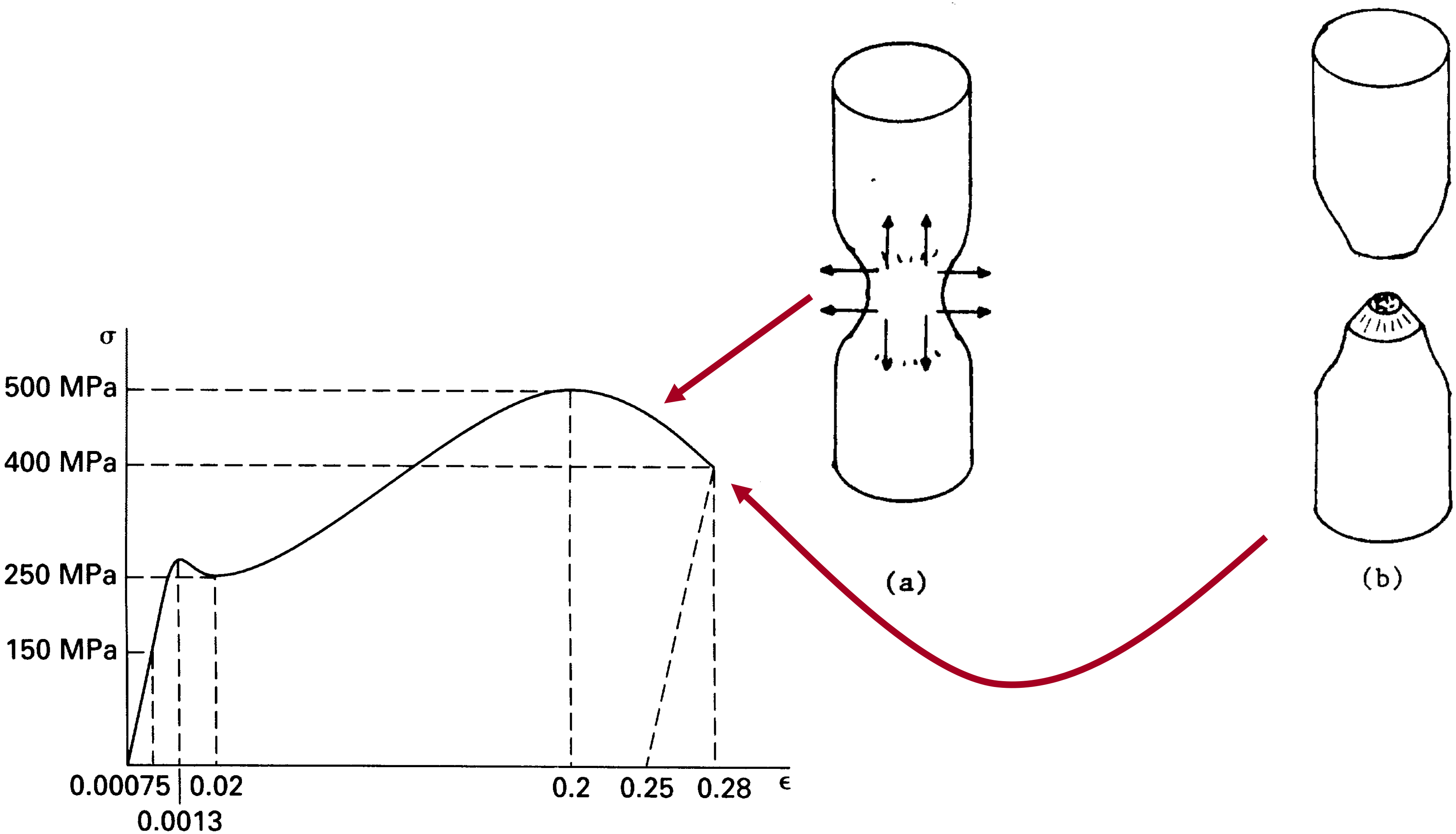
$$\tau < [\tau]$$



- **Fracture surface** is orthogonal to the direction of maximum principle tensile stress.

EXAMPLE

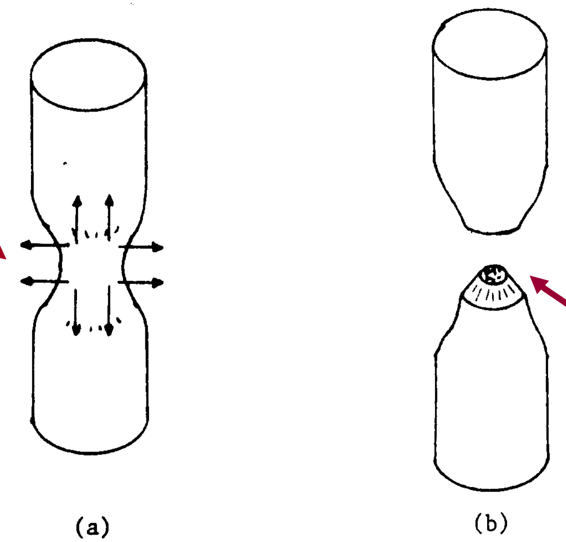
Ductile Fracture



Characteristics of Ductile Fracture

- Necking in round specimens:

  As necking occurs, a **tri**-axial state of stress develops in the region of necking. This is most popular in round specimens.

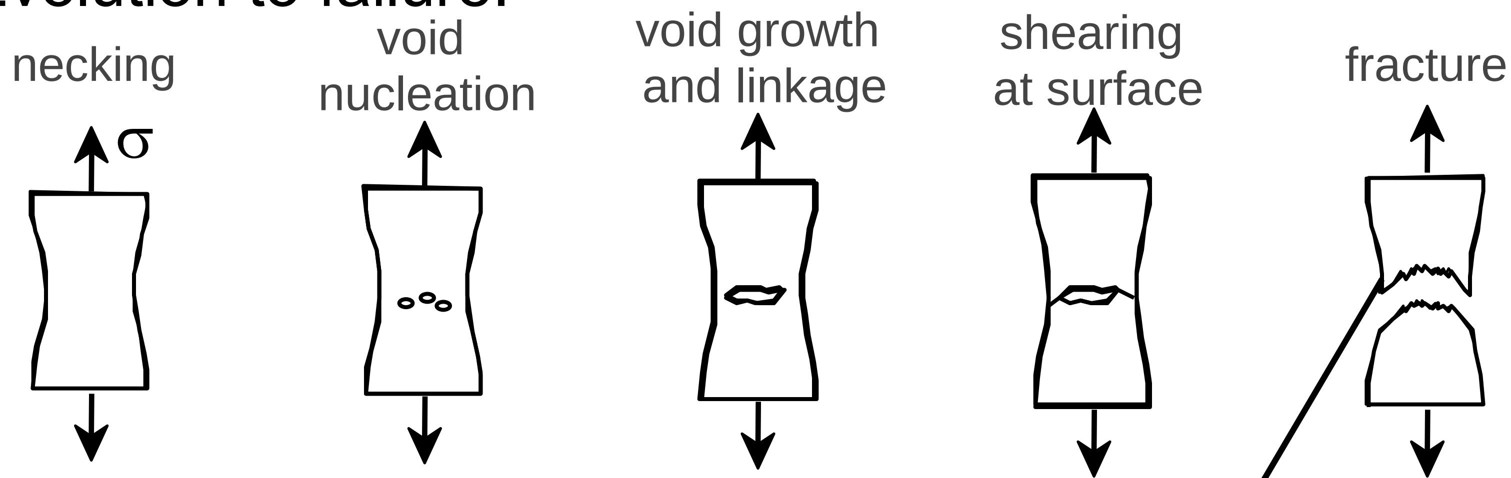


- Failure:

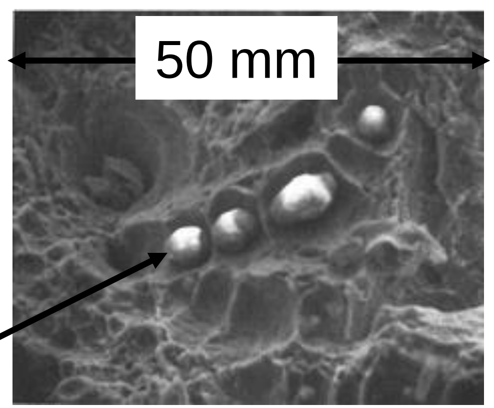
  Failure begins when micro-cracking causing a fibrous surface to develop. This is followed by a rapid fracture oriented **at 45º** with the axis of loading.

Moderately Ductile Failure

- Evolution to failure:

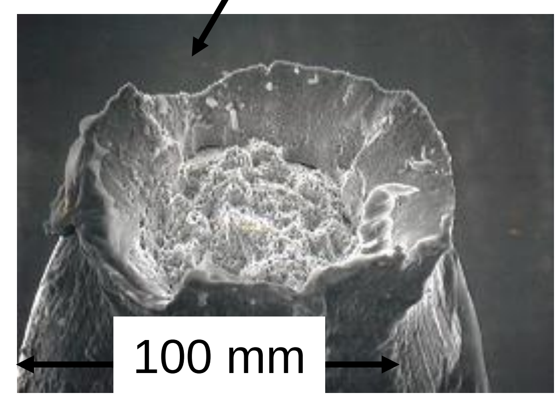


- Resulting fracture surfaces (steel)



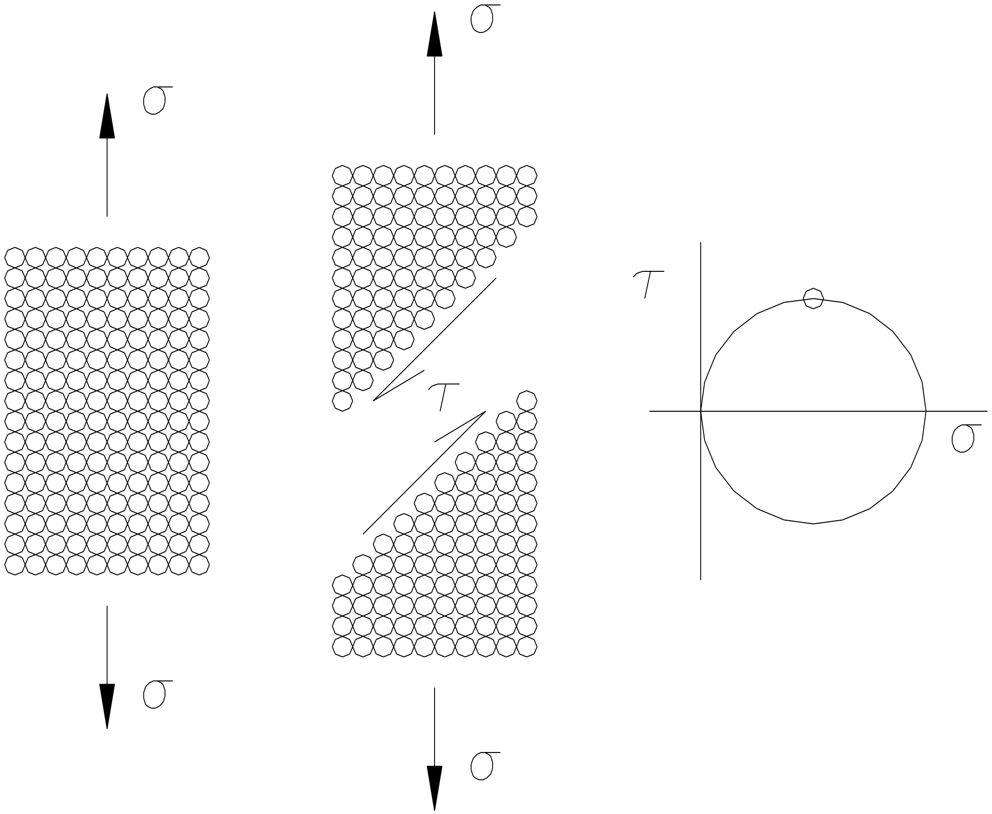
particles serve as void nucleation sites.

From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 11.28, p. 294, John Wiley and Sons, Inc., 1987. (Orig. source: P. Thornton, *J. Mater. Sci.*, Vol. 6, 1971, pp. 347-56.)



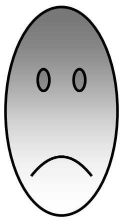
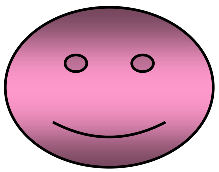
Fracture surface of tire cord wire loaded in tension. Courtesy of F. Roehrig, CC Technologies, Dublin, OH. Used with permission.

Mechanics of Ductile Material Fracture in Tension



Mechanics of Ductile Material Fracture in Tension

- The SHEAR component of stress "shears" the crystal apart:

$\tau = [\tau]$  $\sigma < [\sigma]$ Ok 

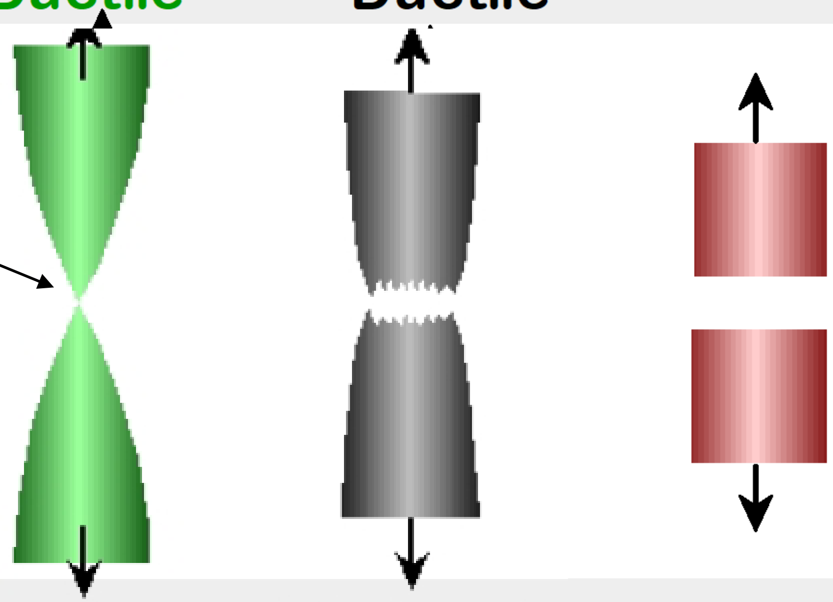
- Shear strength of the material is relatively lower.
- Fracture surface is 45º to the direction of maximum principle tensile stress.

DUCTILE VS BRITTLE FAILURE

- **Classification:**

Fracture behavior:	Very Ductile	Moderately Ductile	Brittle

Substantial plastic deformation
Absorb high amounts of energy before fracture
What is the reduction in x-sectional area ?



Adapted from Fig. 8.1, ***Callister 6e.***

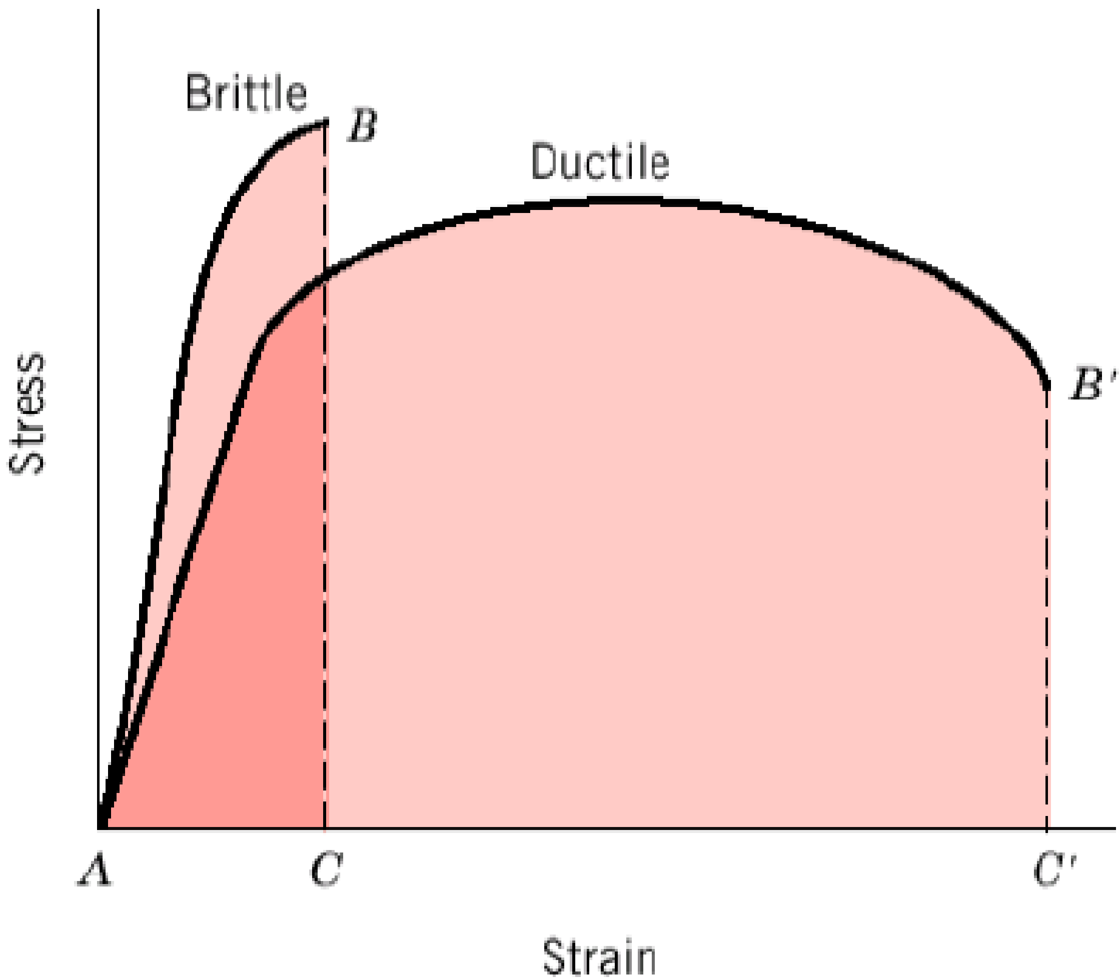
%AR or %EL:	Large	Moderate	Small

- **Ductile fracture is desirable!**

Ductile:
warning before fracture

Brittle:
No warning
Failure is catastrophi

Ductile vs Brittle



Q1:What is ductility ?

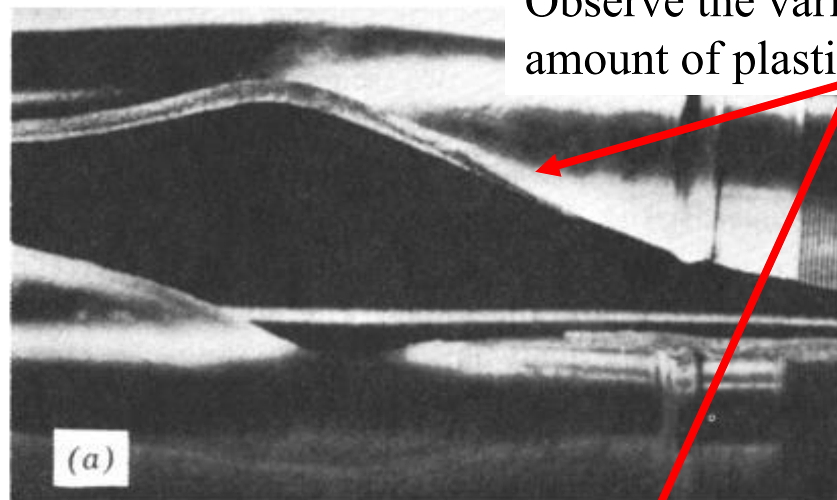
Q2: What is toughness?

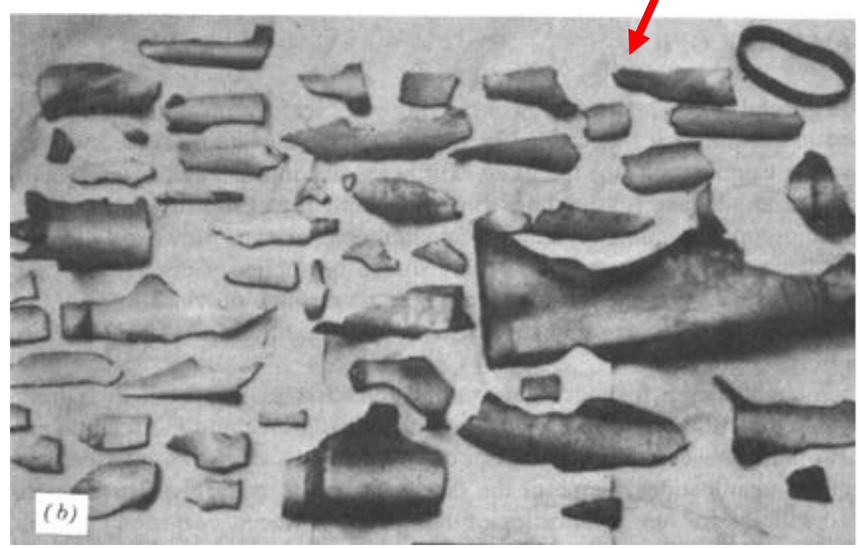
Example: Failure of a Pipe

- **Ductile failure:**
  --one piece
  --large deformation

- **Brittle failure:**
  --many pieces
  --small deformation

Observe the variation in the amount of plastic deformation



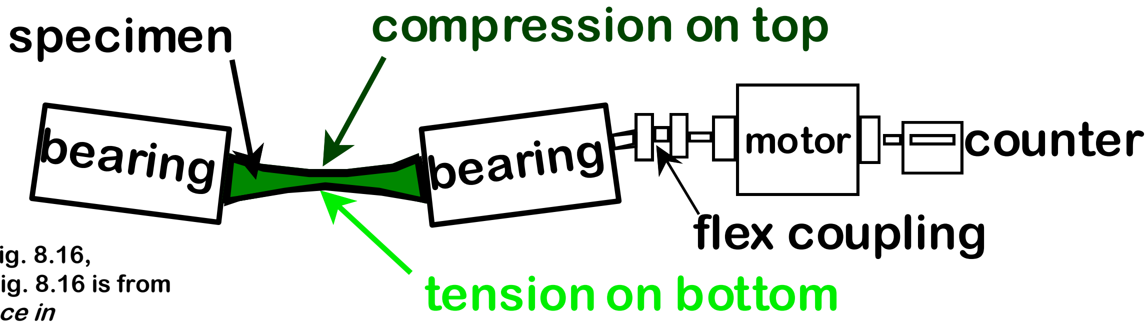


Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

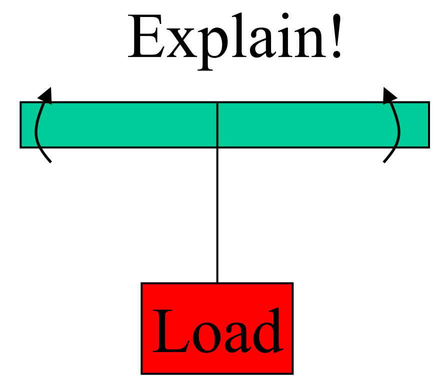
FATIGUE

FATIGUE

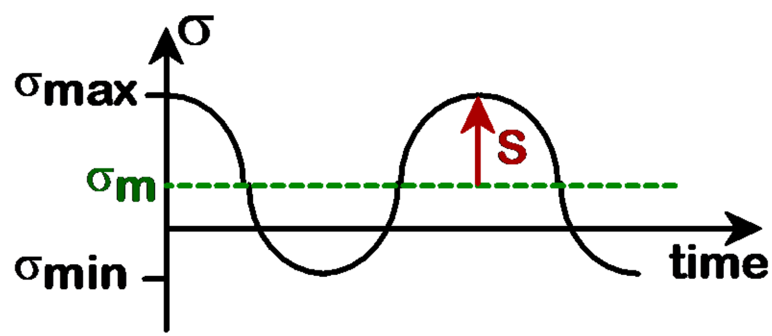
- **Fatigue** = failure under cyclic stress.



Adapted from Fig. 8.16, *Callister 6e.* (Fig. 8.16 is from *Materials Science in Engineering*, 4/E by Carl. A. Keyser, Pearson Education, Inc., Upper Saddle River, NJ.)



- Stress varies with time.
  --key parameters are S and σ_m



- Key points: Fatigue...
  --can cause part failure, even though $\sigma_{max} < \sigma_{critical}$.
  --causes ~ 90% of mechanical engineering failures.

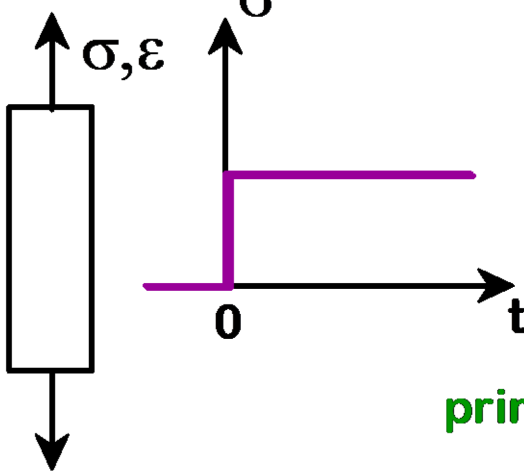
FATIGUE

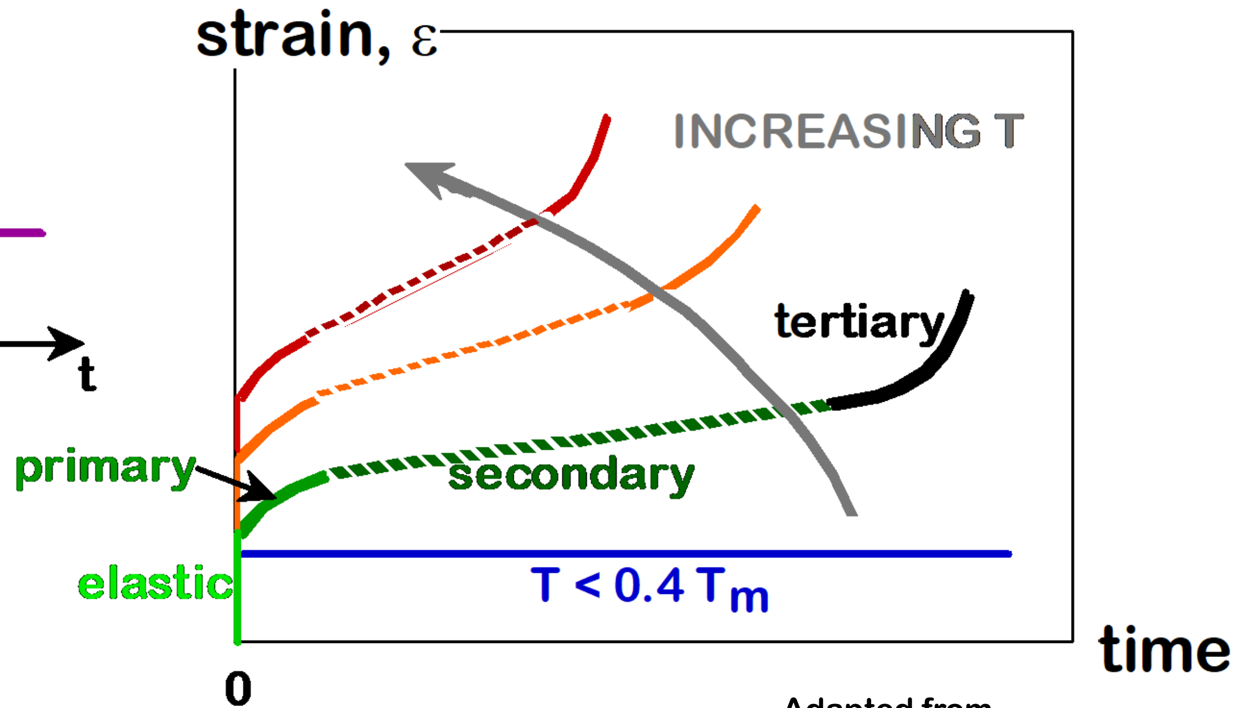
- **How ?**
  - Under fluctuating / cyclic stresses, failure can occur at loads considerably lower than tensile or yield strengths of material under a static load:
- **Important ?**
  - Estimated to causes 90% of all failures of metallic structures (bridges, aircraft, machine components, etc.)
- **What is the failure type ?**
  - Fatigue failure is brittle-like (relatively little plastic deformation) - even in normally ductile materials. Thus sudden and catastrophic!
- Applied stresses causing fatigue may be axial (tension or compression), flextural (bending) or torsional (twisting).
- Fatigue failure proceeds in three distinct stages:
  - Crack initiation in the areas of stress concentration (near stress raisers),
  - incremental crack propagation,
  - final catastrophic failure.

CREEP

CREEP

- Occurs at elevated temperature, $T > 0.4\ T_{melt}$
- Deformation changes with time.





Adapted from
Figs. 8.26 and 8.27,
Callister 6e.

SECONDARY CREEP

- Most of component life spent here.
- Strain rate is constant at a given T, σ
  --strain hardening is balanced by recovery

$$\dot{\varepsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

stress exponent (material parameter)

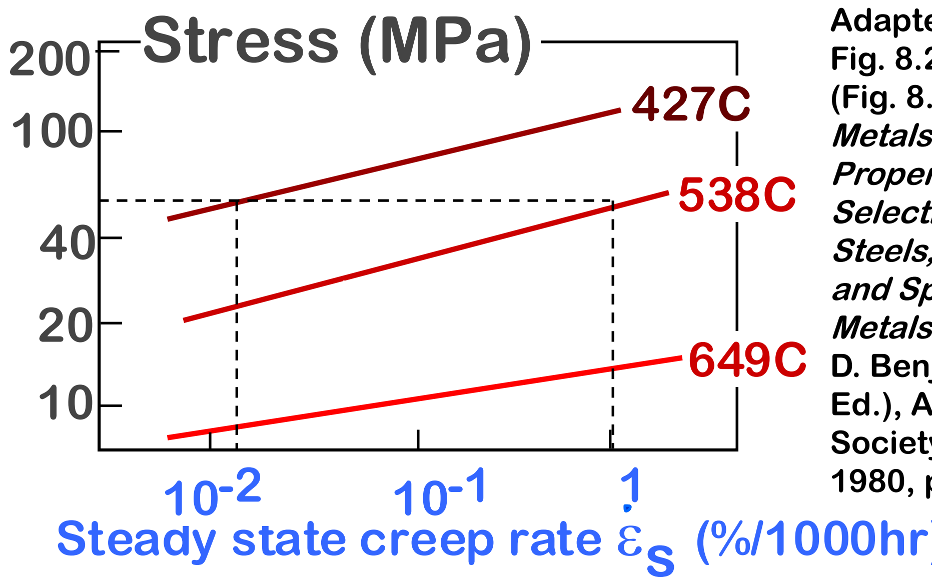
activation energy for creep (material parameter)

strain rate

material const.

applied stress

- Strain rate increases for larger T, σ

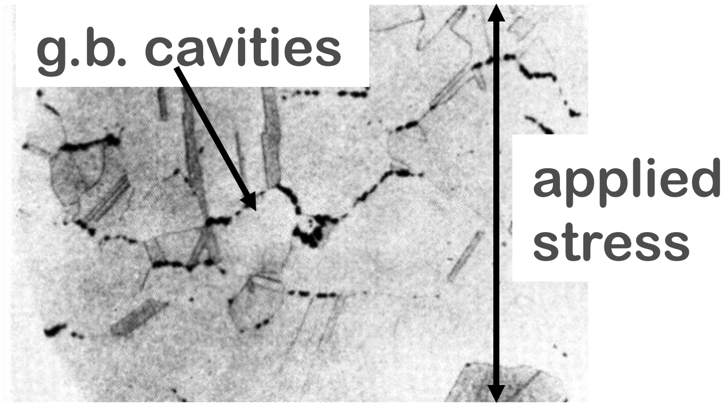


Adapted from Fig. 8.29, *Callister 6e.* (Fig. 8.29 is from *Metals Handbook: Properties and Selection: Stainless Steels, Tool Materials, and Special Purpose Metals*, Vol. 3, 9th ed., D. Benjamin (Senior Ed.), American Society for Metals, 1980, p. 131.)

CREEP FAILURE

- **Failure:**

  along grain boundaries.



From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.32, p. 87, John Wiley and Sons, Inc., 1987. (Orig. source: Pergamon Press, Inc.)

- **Time to rupture, t_r**

$$T(20 + \log t_r) = L$$

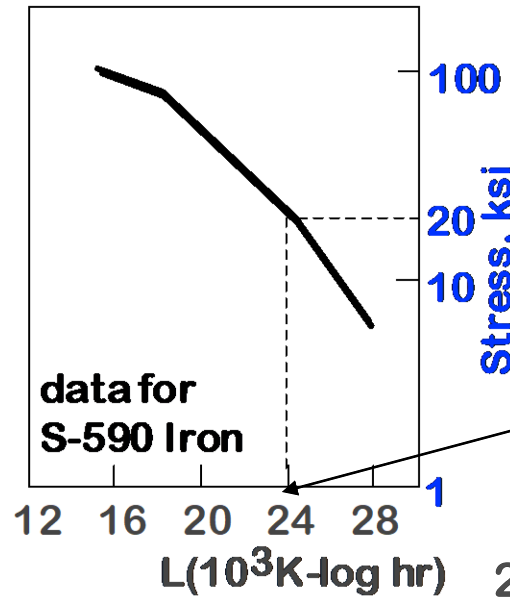
temperature (T)

time to failure (rupture) (t_r)

function of applied stress (L)

- **Estimate rupture time**

  S 590 Iron, T = 800C, σ = 20 ksi



Adapted from Fig. 8.45, *Callister 6e.* (Fig. 8.45 is from F.R. Larson and J. Miller, *Trans. ASME*, **74**, 765 (1952).)

24×10^3 K-log hr

$$T(20 + \log t_r) = L$$

1073K

Ans: t_r = 233hr

SUMMARY (II)

Failure Type	Description	Characteristic property
Generalized yielding (Ch. 7)	Dislocation motion at $\sigma \geq \sigma_y$	σ_y, TS
Fracture	Crack growth to rupture at: $\sigma <$ TS (ductile) $\sigma < \sigma_y$ (brittle)	K_c
Fatigue	Cyclic crack growth at $\sigma < \sigma_{fracture}$ ($K_{max} < K_c$)	S-N_f, da/dN vs ΔK
Creep	High temperature deformation ($T > 0.4\ T_m$) by diffusion at $\sigma < \sigma_y$	Q_c, n