NDT-Deflection Measurement Devices: Benkelman Beam (BB)

Sri Atmaja P. Rosyidi, Ph.D., P.E.
Associate Professor

NDT-Deflection Measurement Devices on Pavement Structure

- NDT measurement of pavement surface deflections provides information that can be used for the structural evaluation of new or in-service pavements.
- These deflection measurements may be used to determine the following pavement characteristics:
  - Modulus of each layer.
  - Overall stiffness of the pavement system.
  - Load transfer efficiency of PCC pavement joints.
  - Modulus of subgrade reaction.
  - Effective thickness, structural number, or soil support value.
  - Bearing capacity or load carrying capacity of a pavement.

NDT-Deflection Measurement Devices:

- *Non-continuous Static Device,*
- *Semi-continuous Static Device,*
- *Steady-State Dynamic Device,*
- *Impulse Device.*

Concept of Deflection Measurement and related Engineering Properties

- Keyword = Deflection Measurement
- **What is the deflection ? And its implementation on pavement investigation (assessment) ?**

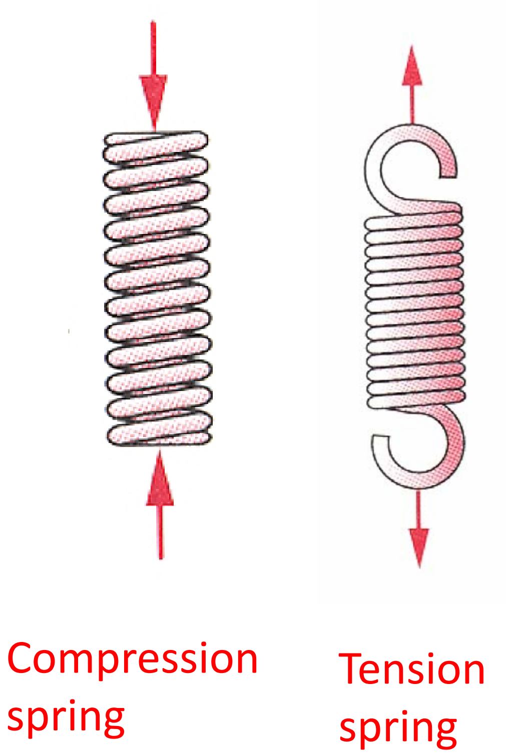
Questions to Think About

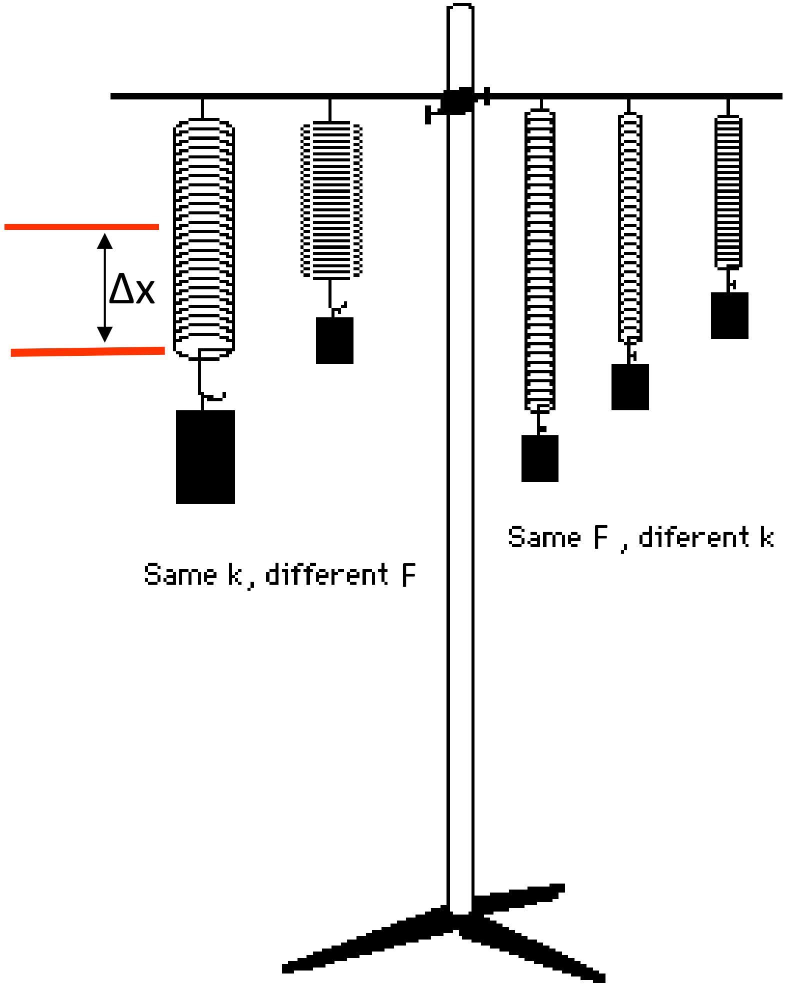
- Deflection ?
- Stiffness ?
- Elastic Modulus ?
  - How do these parameters correlate each other ?

Questions to Think About

- 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?

Spring Stiffness





$$F = k\ (\Delta x)$$

where

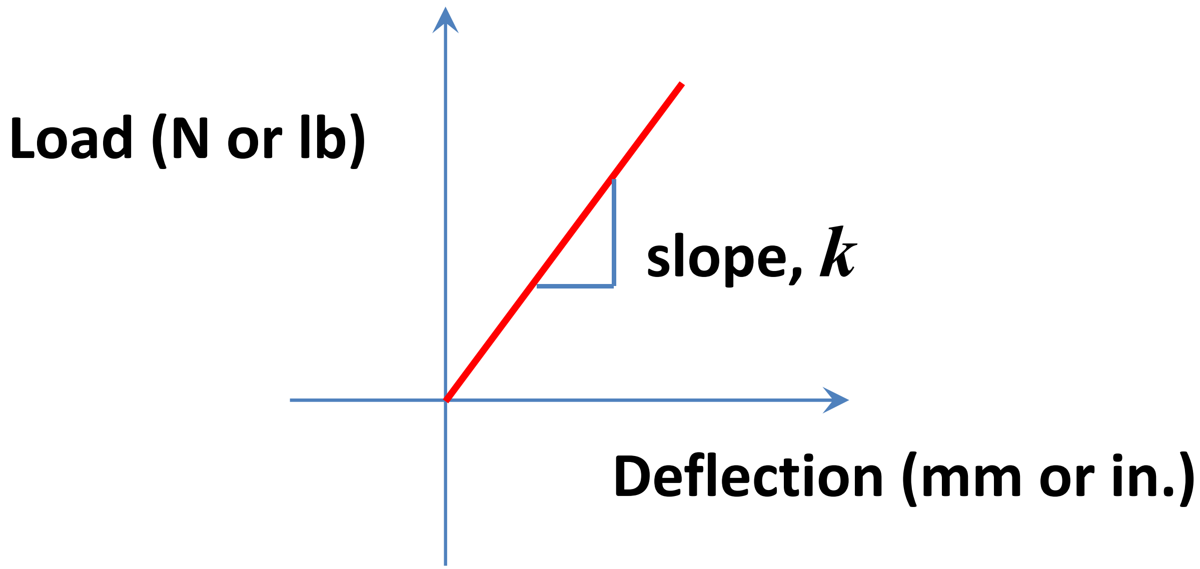
k = **spring constant**

Δx = **spring stretch**

F = **applied force**

Stiffness (Spring)

- Deflection is proportional to load, $F = k\,(\Delta x)$



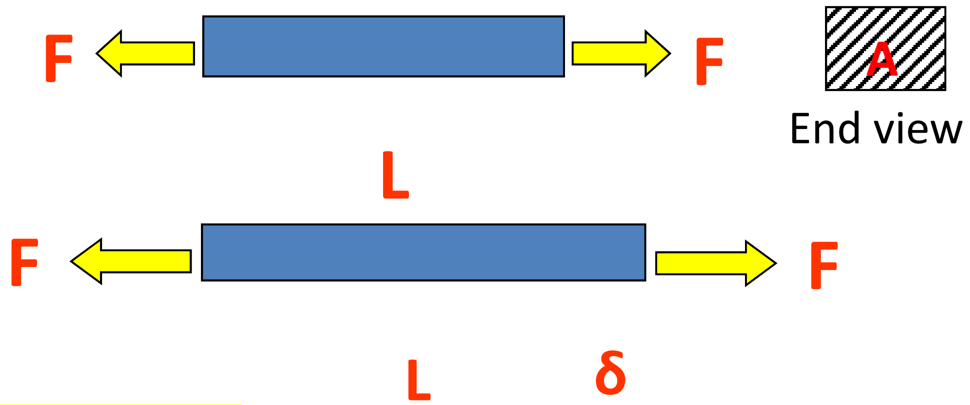
$$k = \frac{load}{deflection}$$

Slope of Load-Deflection curve:

The "Stiffness"

Stiffness (Solid Bar)

- Stiffness in tension and compression
  - Applied Forces *F*, length *L*, cross-sectional area, *A*, and material property, *E* (Young's modulus)



E is constant for a given material

$$k = \frac{F}{\delta}$$

$$\delta = \frac{FL}{AE}$$

$$k = \frac{AE}{L}$$

Stiffness for components in tension-compression

E (steel) = 30 x 10^6 psi

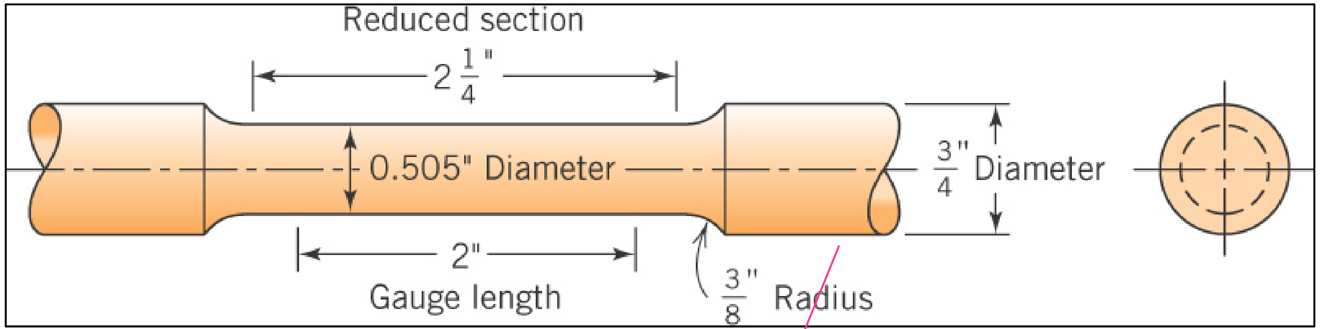
E (Al) = 10 x 10^6 psi

E (concrete) = 3.4 x 10^3 psi

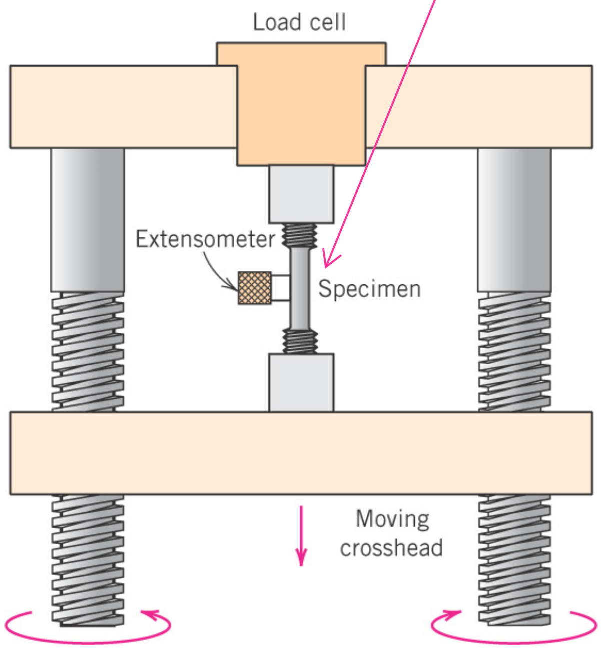
E (Kevlar, plastic) = 19 x 10^3 psi

E (rubber) = 100 psi

Stress-Strain Test

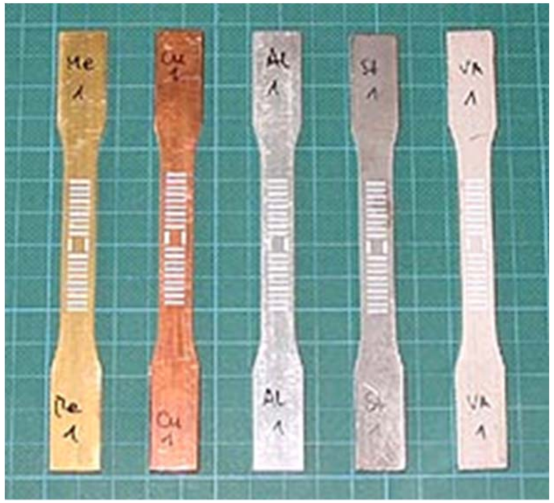


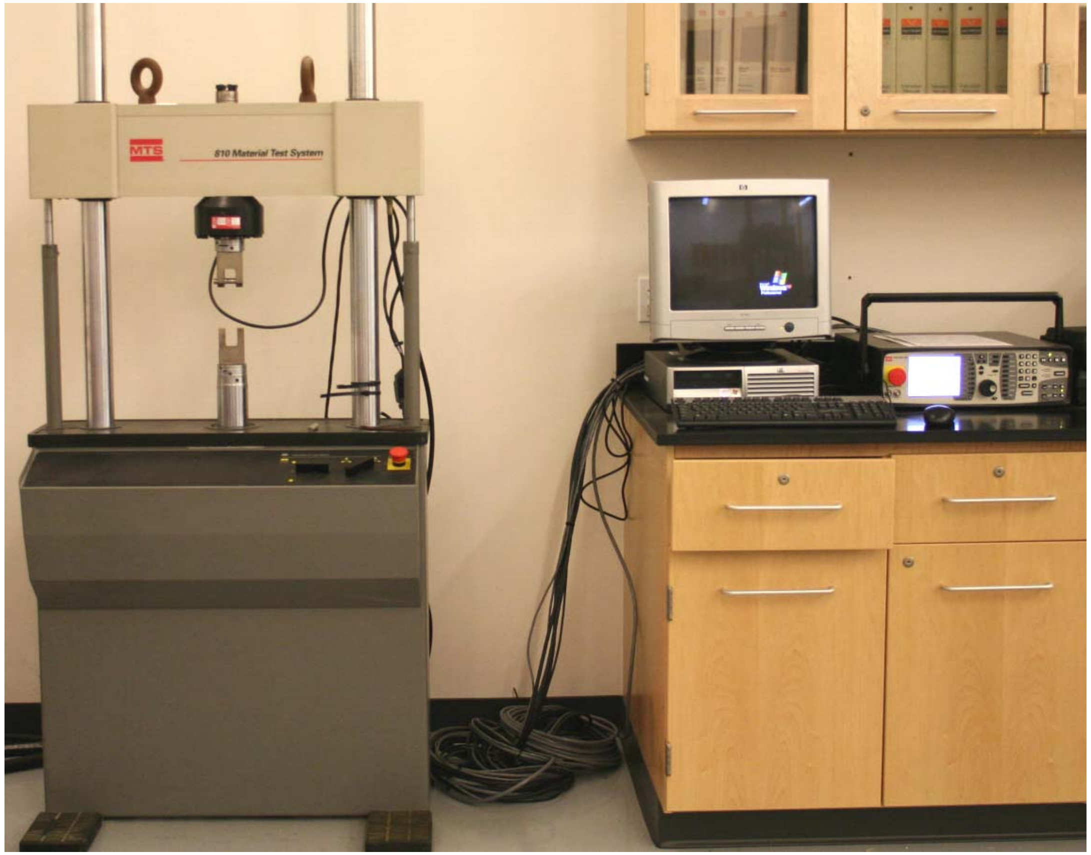
specimen

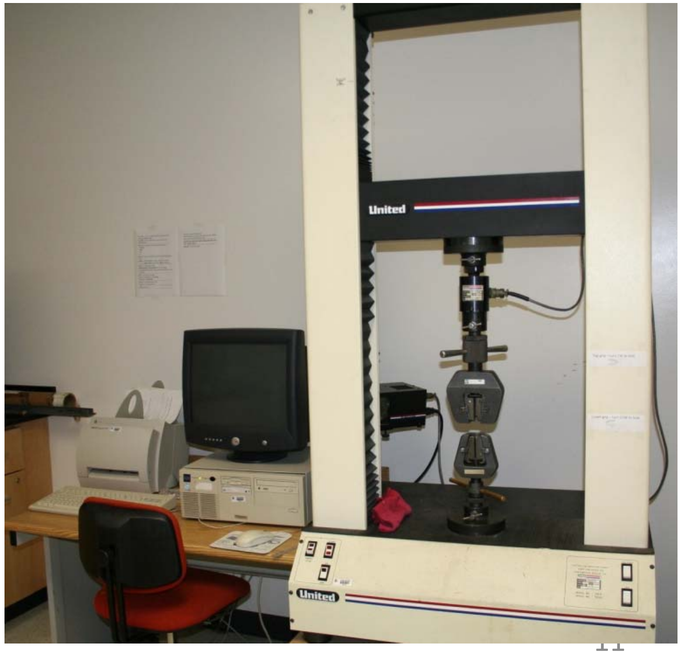


machine

Tensile Test







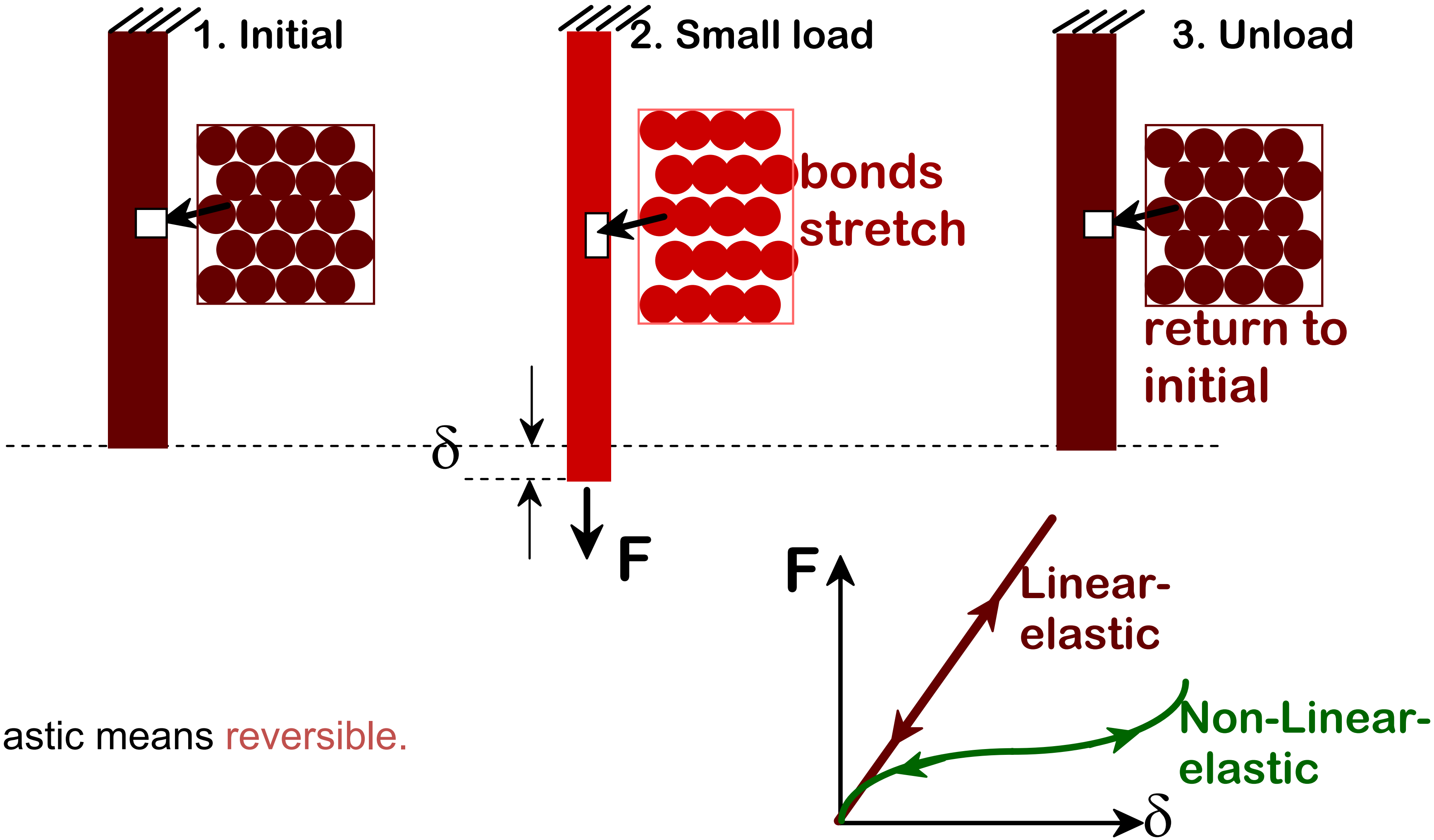
Important Mechanical Properties from a Tensile Test

- **Young's Modulus**: This is the slope of the linear portion of the stress-strain curve, it is usually specific to each material; a constant, known value.
- **Yield Strength**: This is the value of stress at the yield point, calculated by plotting young's modulus at a specified percent of offset (usually offset = 0.2%).
- **Ultimate Tensile Strength**: This is the highest value of stress on the stress-strain curve.
- **Percent Elongation**: This is the change in gauge length divided by the original gauge length.

Terminology

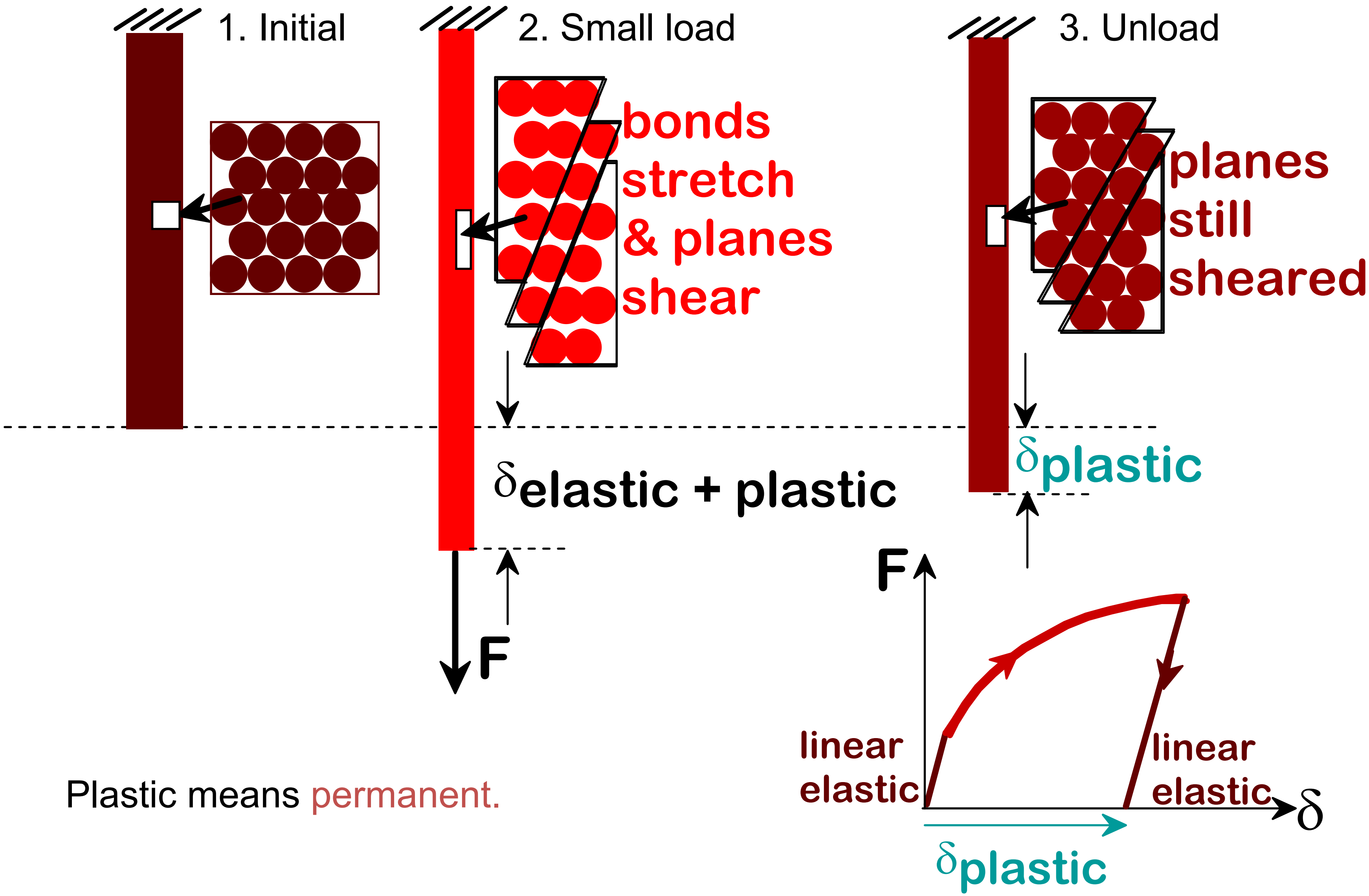
- Load - The force applied to a material during testing.
- Strain gage or Extensometer - A device used for measuring change in length (strain).
- Engineering stress - The applied load, or force, divided by the original cross-sectional area of the material.
- Engineering strain - The amount that a material deforms per unit length in a tensile test.

Elastic Deformation



Elastic means reversible.

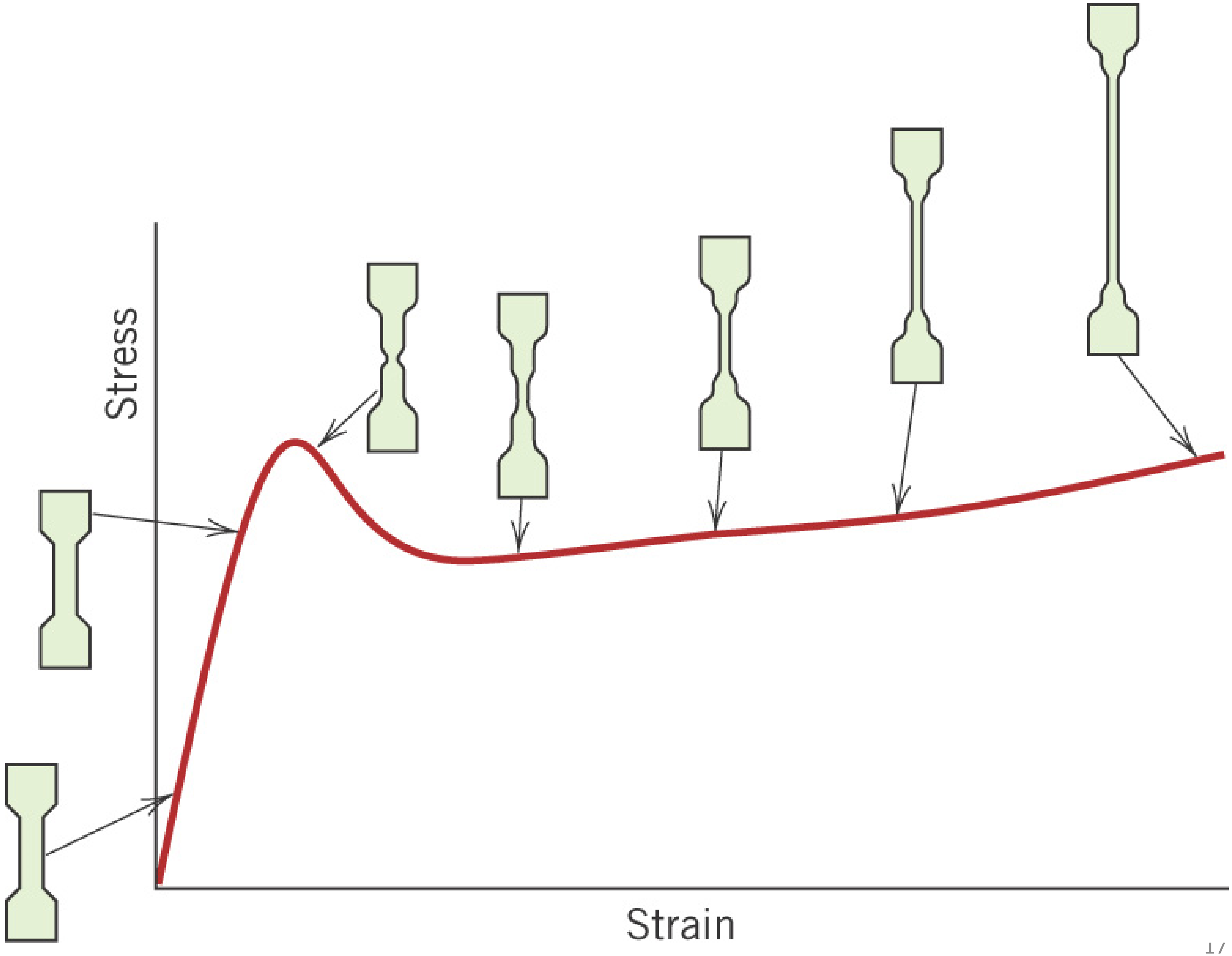
Plastic Deformation (Metals)



Plastic means permanent.

Plastic Deformation (permanent)

- From an atomic perspective, plastic deformation corresponds to the breaking of bonds with original atom neighbors and then reforming bonds with new neighbors.
- After removal of the stress, the large number of atoms that have relocated, do not return to original position.
- Yield strength is a measure of resistance to plastic deformation.

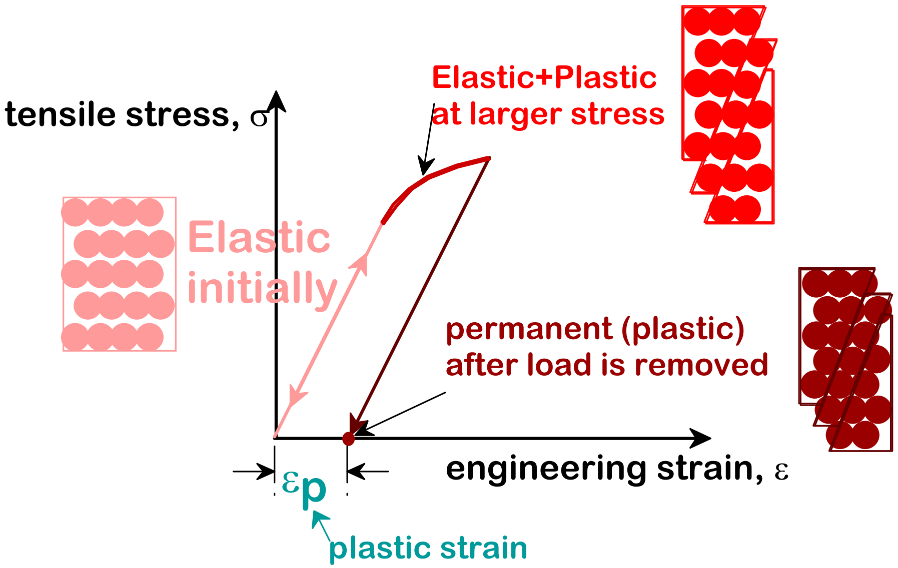


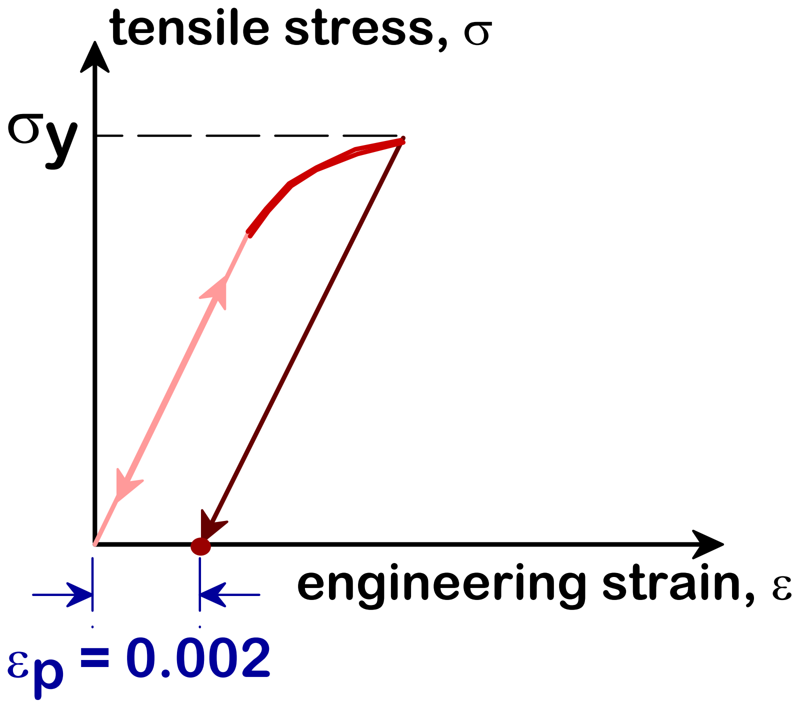
Stress
Strain

Permanent Deformation

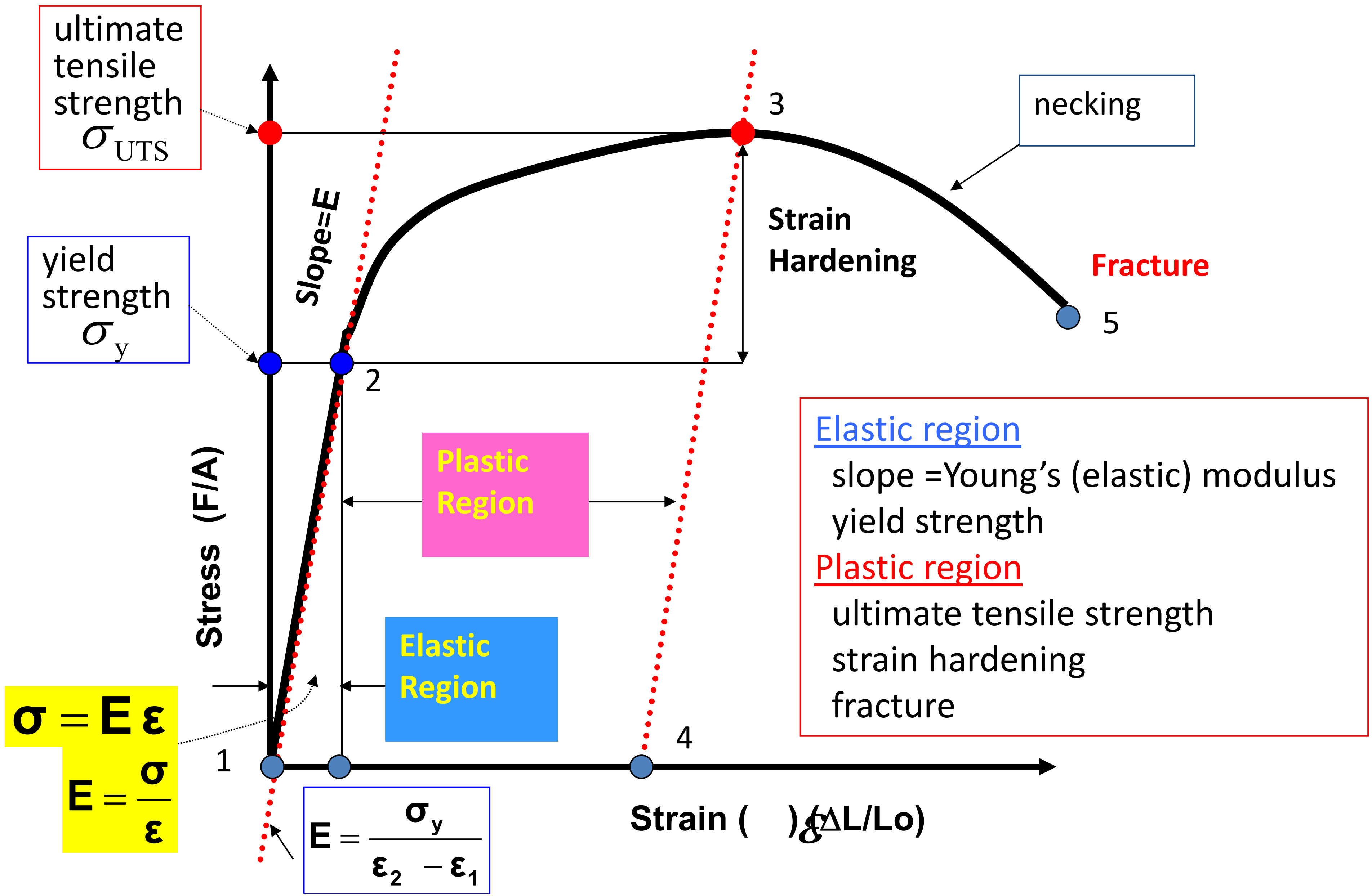
- Permanent deformation for metals is accomplished by means of a process called slip, which involves the motion of dislocations.
- Most structures are designed to ensure that only elastic deformation results when stress is applied.
- A structure that has plastically deformed, or experienced a permanent change in shape, may not be capable of functioning as intended.

Yield Strength, σ_y





Stress-Strain Diagram



Stress-Strain Diagram *(cont)*

- **Elastic Region (Point 1 –2)**

  - The material will return to its original shape after the material is unloaded(like a rubber band).

  - The stress is linearly proportional to the strain in this region.

$$\sigma = E\,\varepsilon \quad \text{or} \quad E = \frac{\sigma}{\varepsilon}$$

σ : Stress(psi)

E : *Elastic modulus* (*Young's Modulus*) (psi)

ε : Strain (in/in)

- Point 2 : <u>Yield Strength</u> : a point where permanent deformation occurs. (If it is passed, the material will no longer return to its original length.)

Stress-Strain Diagram *(cont)*

- **Strain Hardening**

  - If the material is loaded again from Point 4, the curve will follow back to Point 3 with the same Elastic Modulus (slope).

  - The material now has a higher yield strength of Point 4.

  - Raising the yield strength by permanently straining the material is called <u>Strain Hardening.</u>

Stress-Strain Diagram *(cont)*

- **Tensile Strength (Point 3)**

  - The largest value of stress on the diagram is called Tensile Strength(TS) or Ultimate Tensile Strength *(UTS)*

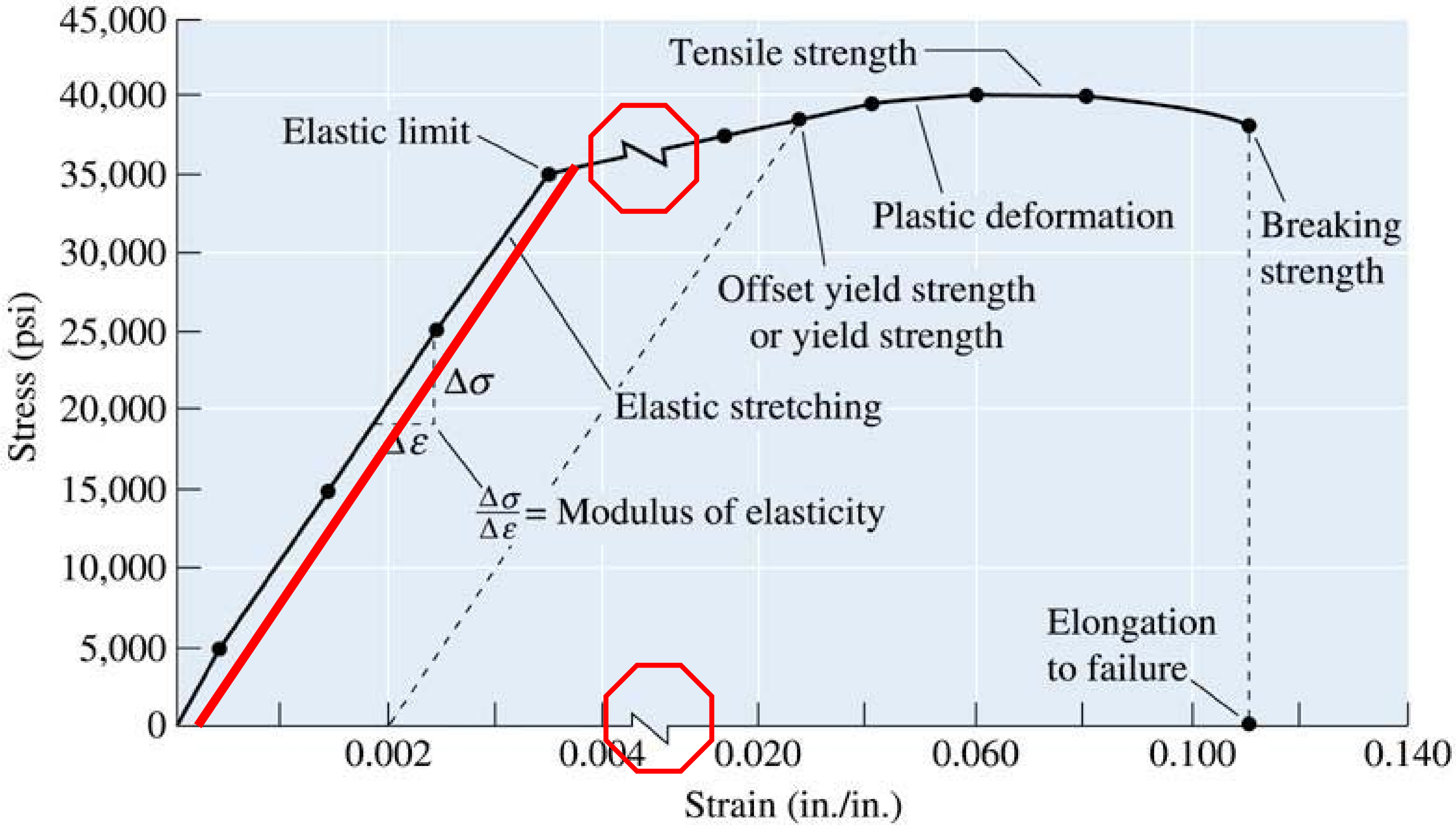
  - It is the maximum stress which the material can support without breaking.

- **Fracture (Point 5)**

  - If the material is stretched beyond Point 3, the stress decreases as necking and non-uniform deformation occur.

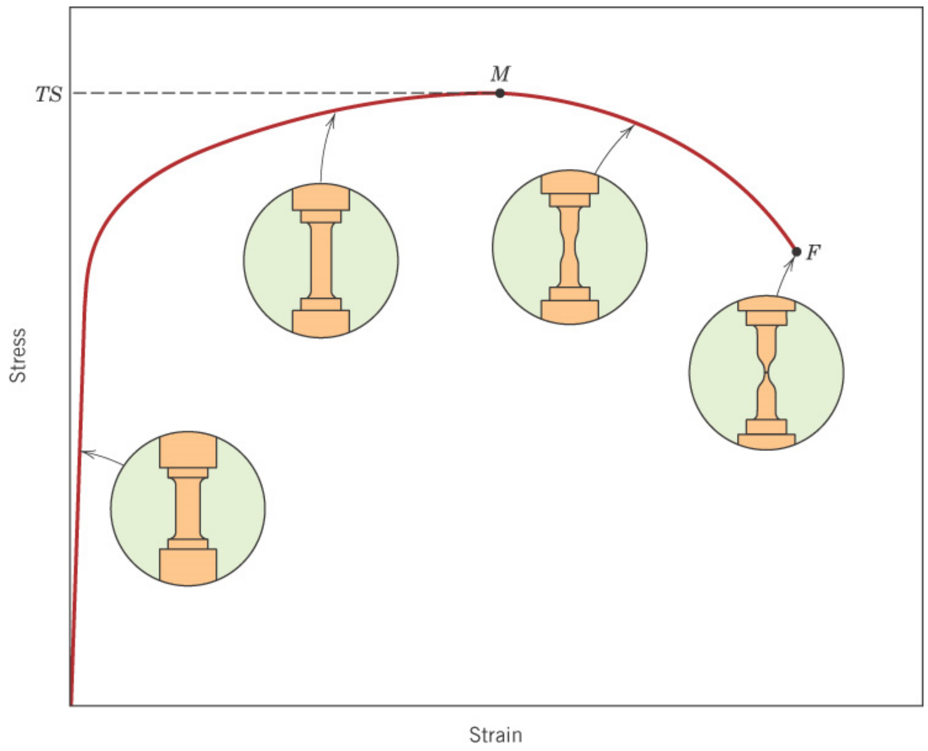
  - Fracture will finally occur at Point 5.

The stress-strain curve for an aluminum alloy.



Tensile Strength, TS

• After yielding, the stress necessary to continue plastic deformation in metals increases to a maximum point (M) and then decreases to the eventual fracture point (F).
• All deformation up to the maximum stress is uniform throughout the tensile sample.
• However, at max stress, a small constriction or neck begins to form.
• Subsequent deformation will be confined to this neck area.
• Fracture strength corresponds to the stress at fracture.

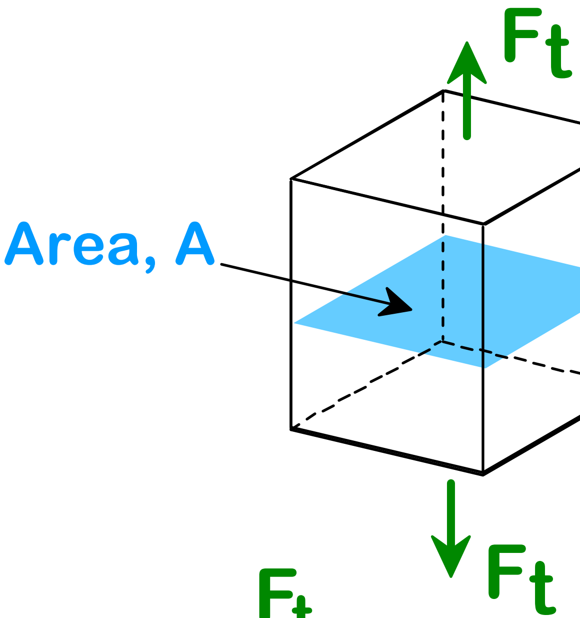


Region between M and F:

- Metals: occurs when noticeable necking starts.
- Ceramics: occurs when crack propagation starts.
- Polymers: occurs when polymer backbones are aligned and about to break.

Engineering Stress

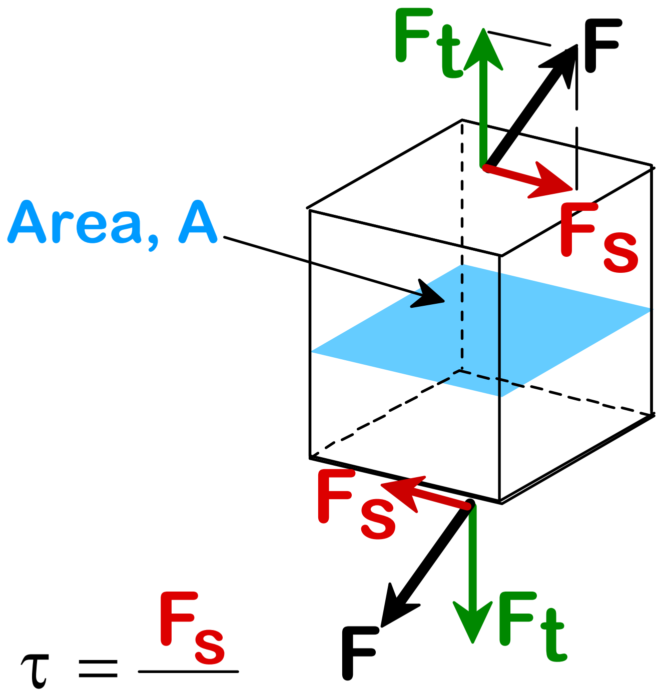
- **Tensile stress, σ:**



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

original area
before loading

- **Shear stress, τ:**



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

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

Example 1

Tensile Testing of Aluminum Alloy

Convert the change in length data in the table to engineering stress and strain and plot a stress-strain curve.

The results of a tensile test of a 0.505-in. diameter aluminum alloy test bar, initial length (l_0) = 2 in.

Measured Change in Length (Δl)		Calculated	
Load (lb)	**(in.)**	**Stress (psi)**	**Strain (in./in.)**
0	0.000	0	0
1000	0.001	5,000	0.0005
3000	0.003	15,000	0.0015
5000	0.005	25,000	0.0025
7000	0.007	35,000	0.0035
7500	0.030	37,500	0.0150
7900	0.080	39,500	0.0400
8000 (maximum load)	0.120	40,000	0.0600
7950	0.160	39,700	0.0800
7600 (fracture)	0.205	38,000	0.1025

Example 1 SOLUTION

For the 1000-lb load:

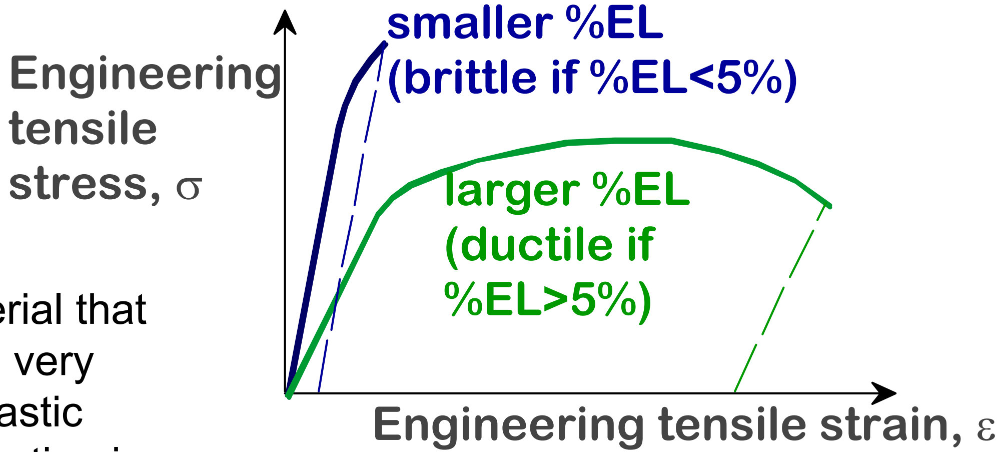
$$\sigma = \frac{F}{A_0} = \frac{1000 \text{ lb}}{(\pi/4)(0.505 \text{ in.})^2} = \frac{1000 \text{ lb}}{0.2 \text{ in.}^2} = 5000 \text{ psi}$$

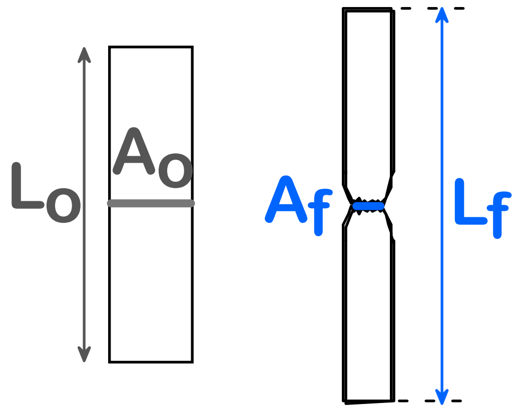
$$\varepsilon = \frac{\Delta l}{l_0} = \frac{0.001 \text{ in.}}{2.000 \text{ in.}} = 0.0005 \text{ in./in.}$$

Ductility, %EL

Ductility is a measure of the plastic deformation that has been sustained at fracture:

$$\% EL = \frac{l_f - l_o}{l_o} x100$$





A material that suffers very little plastic deformation is brittle.

- Another ductility measure:

$$\% AR = \frac{A_o - A_f}{A_o} x100$$

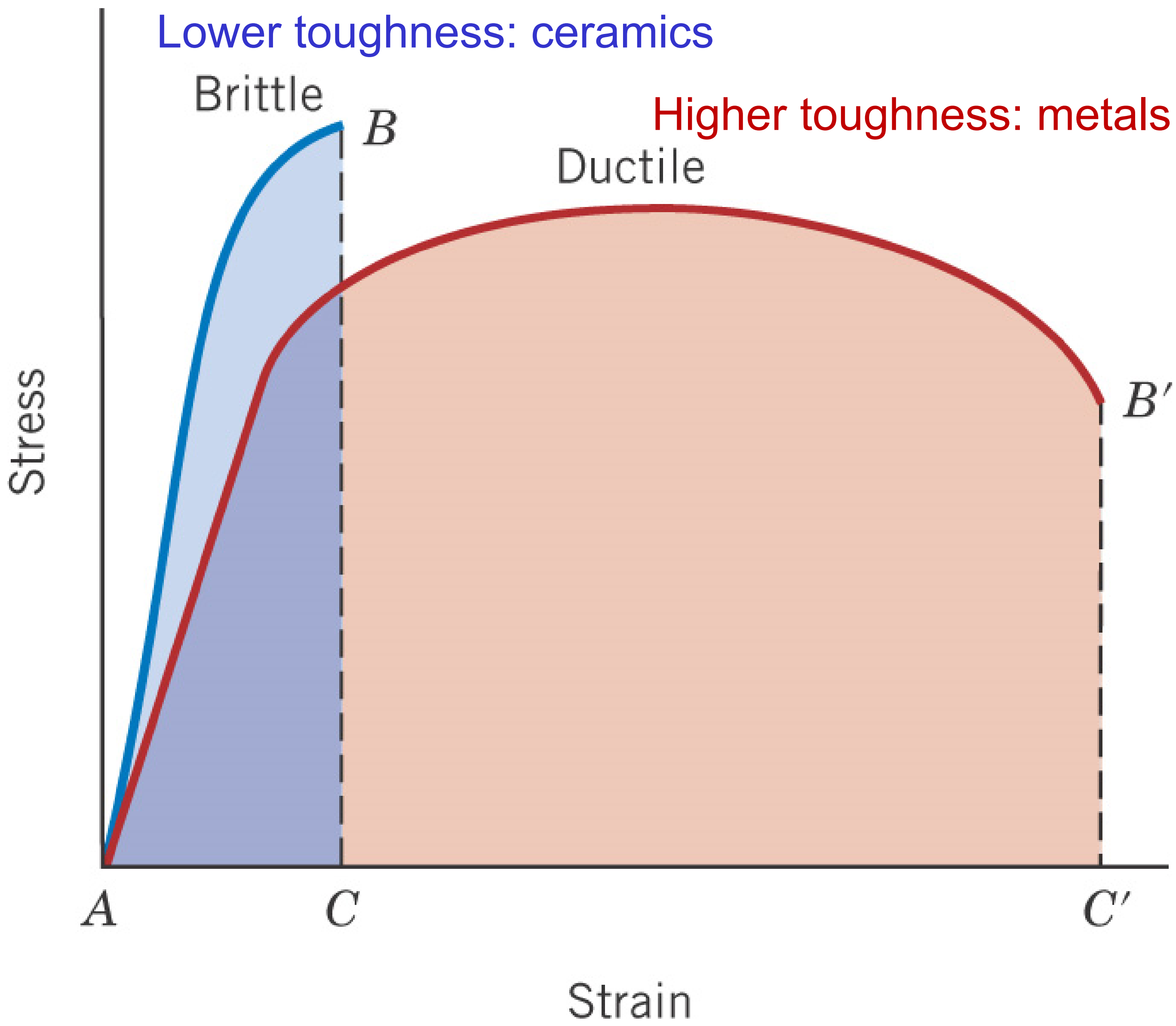
- Ductility may be expressed as either percent elongation (% plastic strain at fracture) or percent reduction in area.
- %AR > %EL is possible if internal voids form in neck.

Toughness

Toughness is the ability to absorb energy up to fracture (energy per unit volume of material).

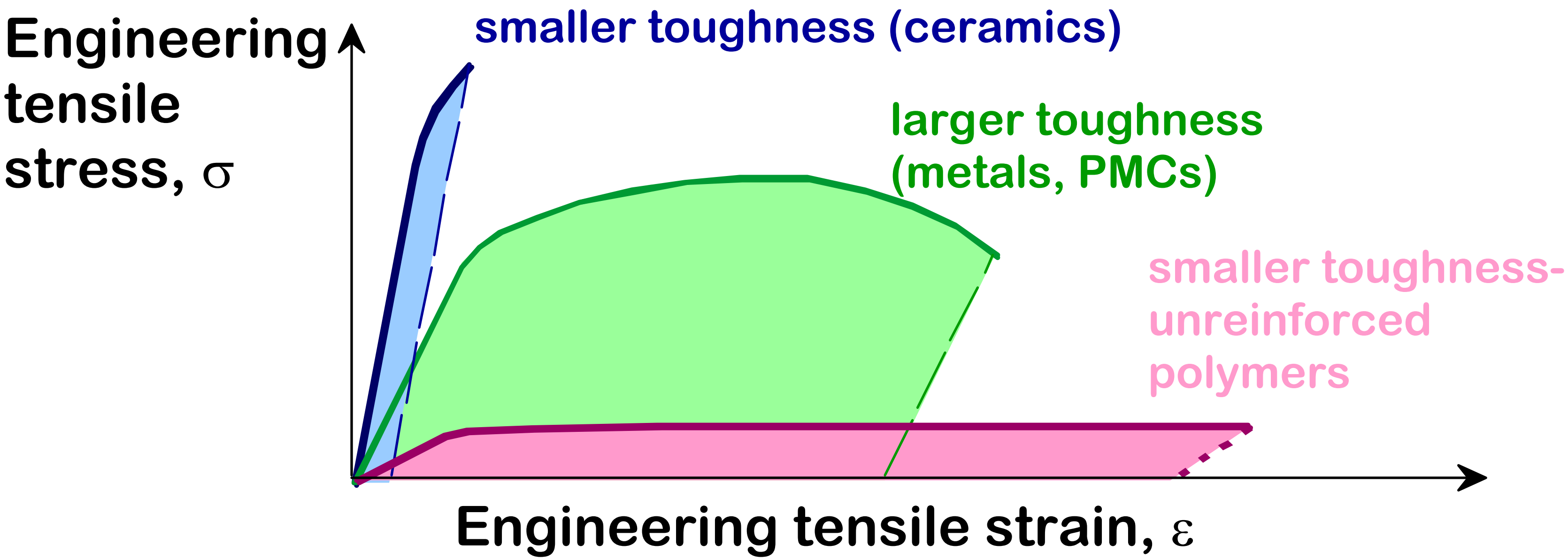
A "tough" material has strength and ductility.

Approximated by the area under the stress-strain curve.



Toughness

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

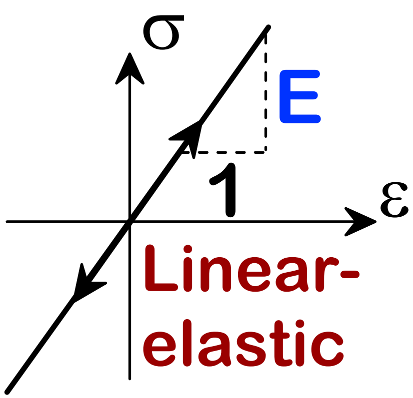


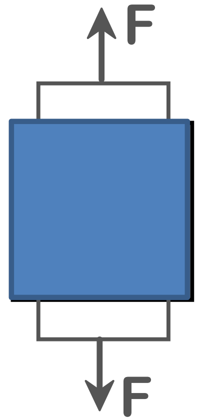
Linear Elastic Properties

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

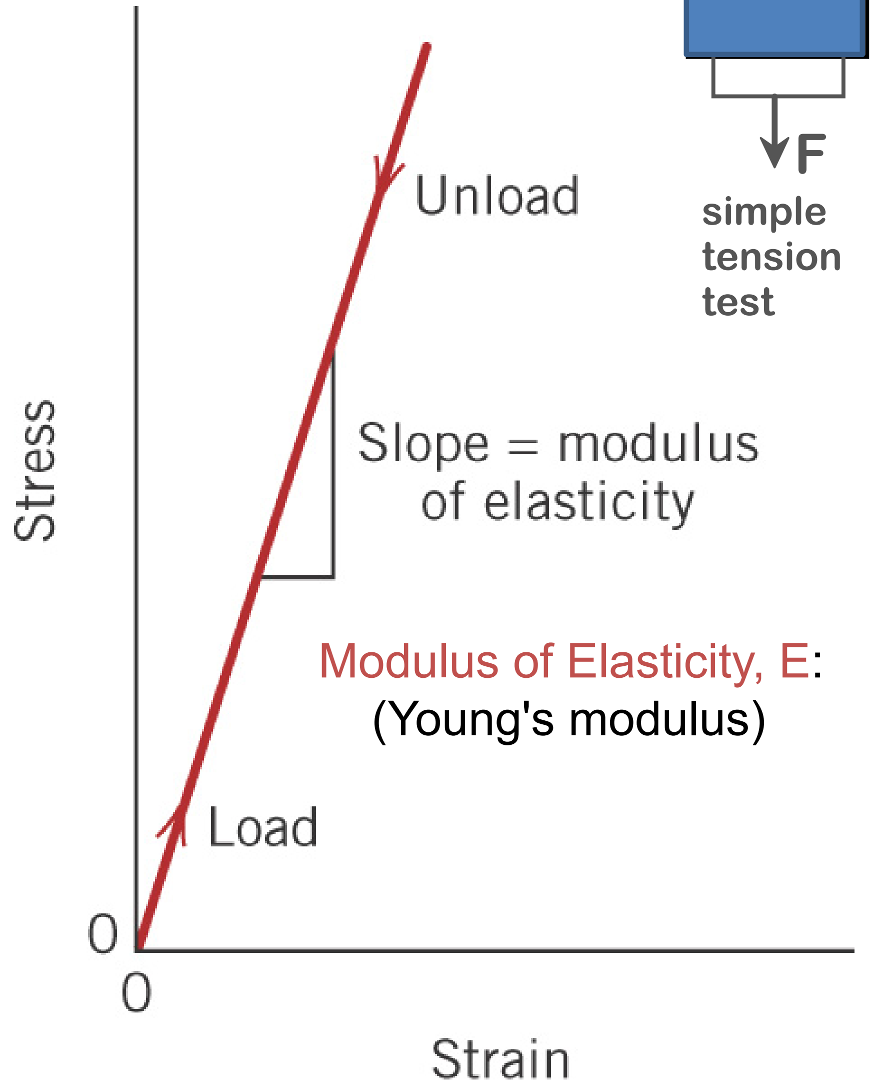
- **Poisson's ratio:** $\nu = \varepsilon_x / \varepsilon_y$

  metals: $\nu \sim 0.33$
  ceramics: $\nu \sim 0.25$
  polymers: $\nu \sim 0.40$





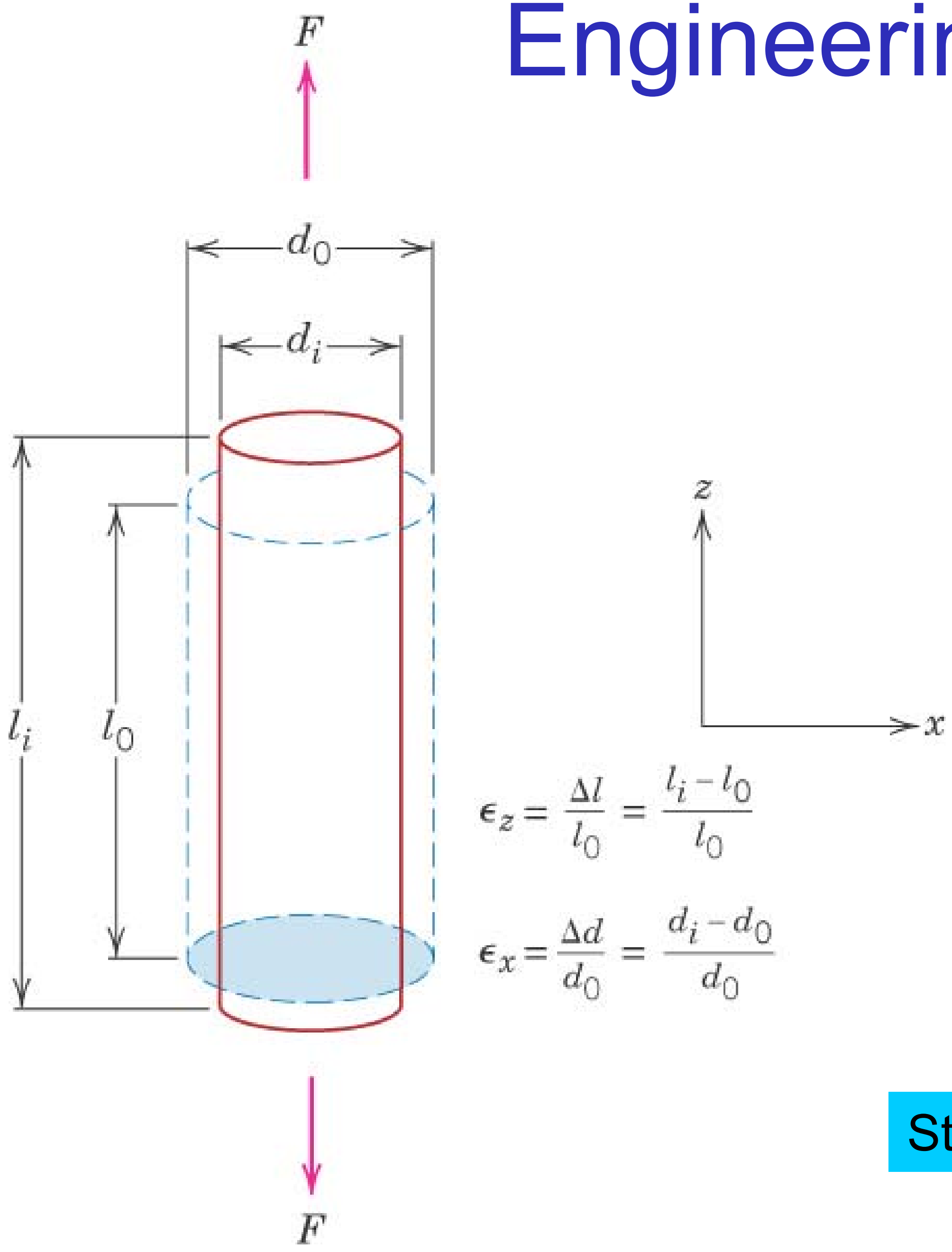
simple tension test



Modulus of Elasticity, E:
(Young's modulus)

Units:
E: [GPa] or [psi]
ν: dimensionless

Engineering Strain

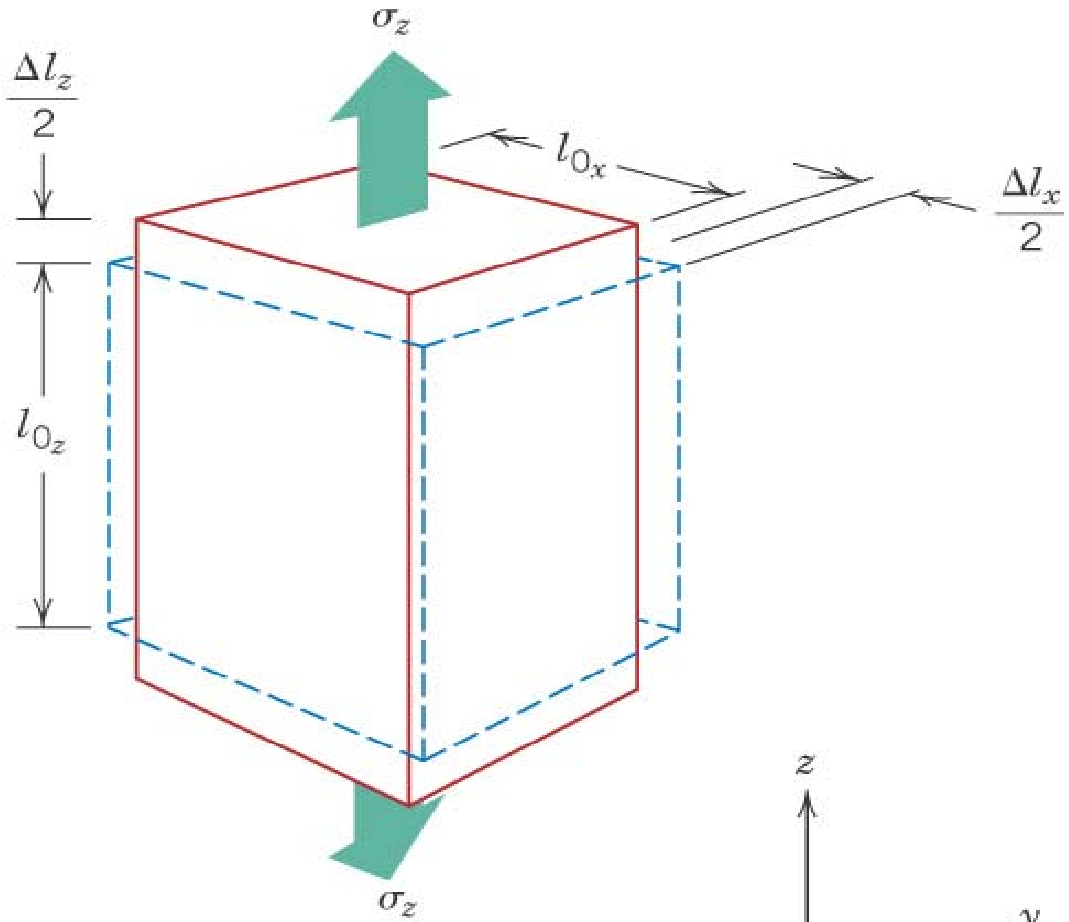


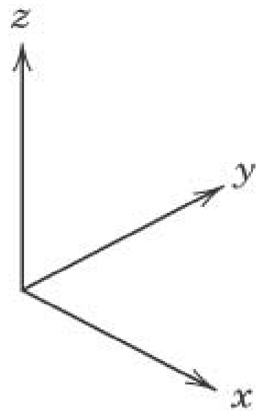
$$\epsilon_z = \frac{\Delta l}{l_0} = \frac{l_i - l_0}{l_0}$$

$$\epsilon_x = \frac{\Delta d}{d_0} = \frac{d_i - d_0}{d_0}$$

Strain is dimensionless.

Axial (z) elongation (positive strain) and lateral (x and y) contractions (negative strains) in response to an imposed tensile stress.



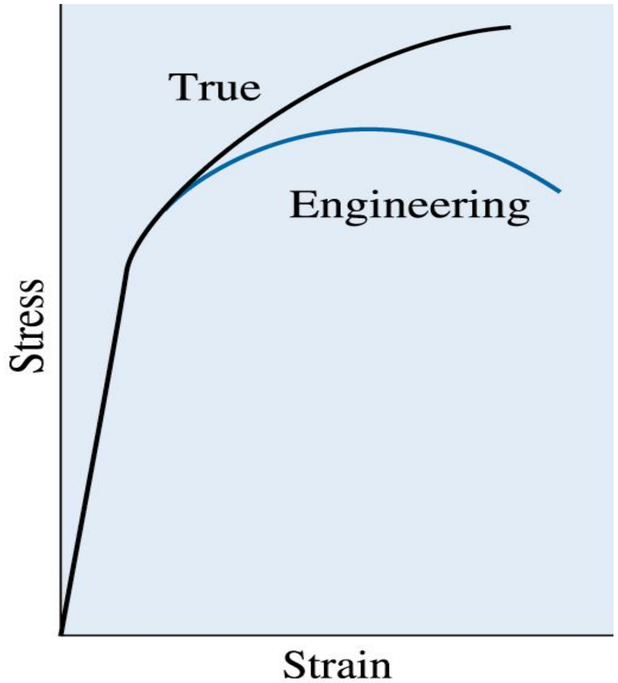


$$\frac{\epsilon_z}{2} = \frac{\Delta l_z/2}{l_{0_z}}$$

$$-\frac{\epsilon_x}{2} = \frac{\Delta l_x/2}{l_{0_x}}$$

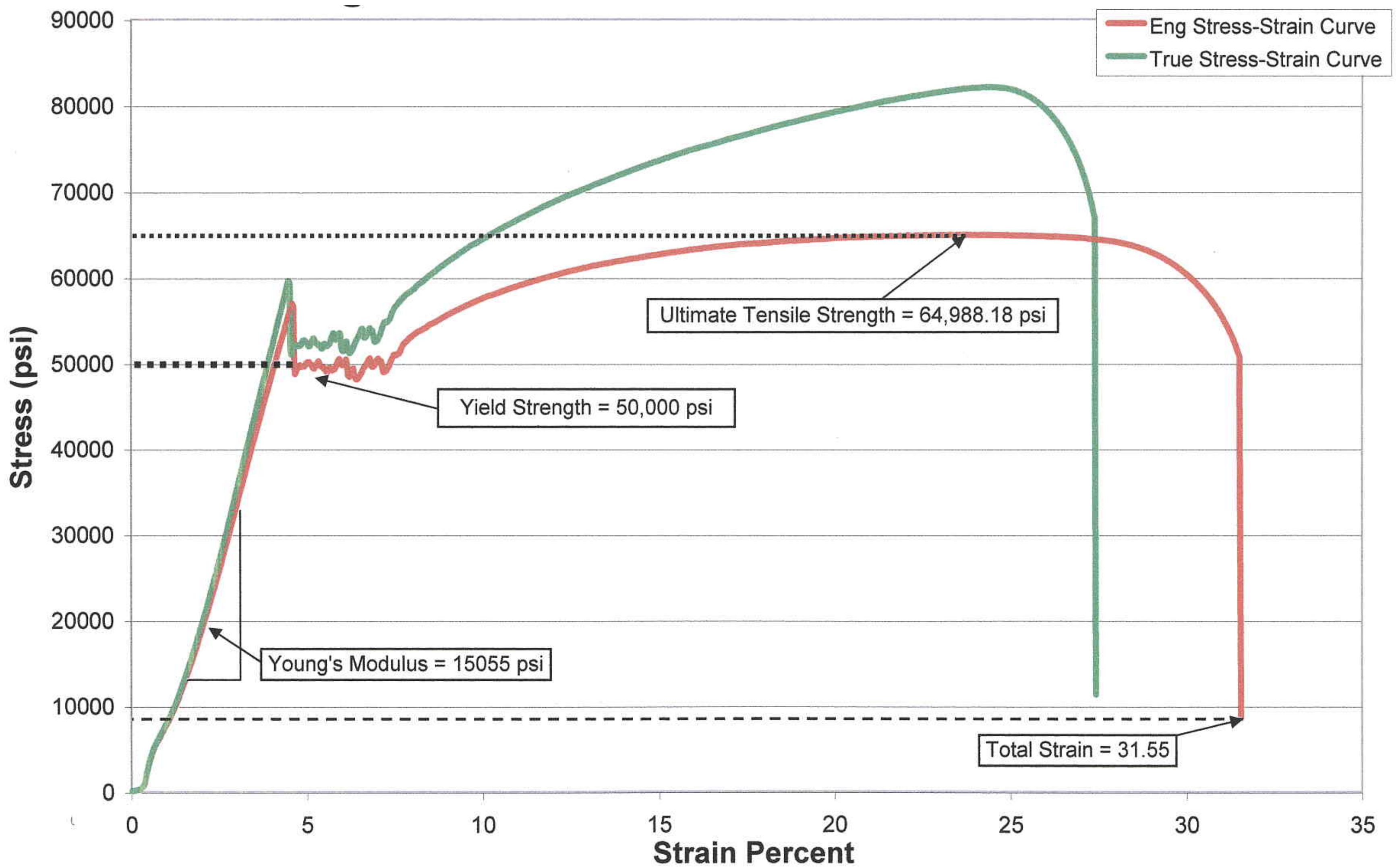
True Stress and True Strain

- **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 $\varepsilon_t \ln(l/l_0)$.



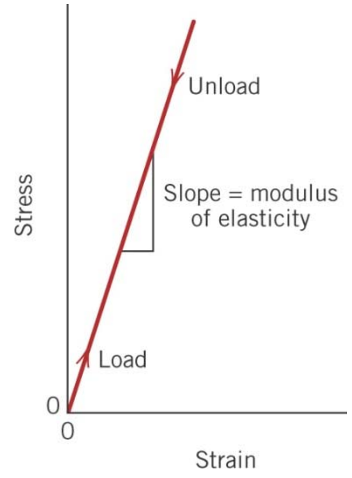
•The relation between the true stress-true strain diagram and engineering stress-engineering strain diagram.
•The curves are identical to the yield point.

Stress-Strain Results for Steel Sample



Example 2:
Young's Modulus - Aluminum Alloy

From the data in Example 1, calculate the modulus of elasticity of the aluminum alloy.



Measured Change in Length (Δl)		Calculated	
Load (lb)	(in.)	Stress (psi)	Strain (in./in.)
0	0.000	0	0
1000	0.001	5,000	0.0005
3000	0.003	15,000	0.0015
5000	0.005	25,000	0.0025
7000	0.007	35,000	0.0035
7500	0.030	37,500	0.0150

When a stress of 35,000 psi is applied, a strain of 0.0035 in./in. is produced.

$$\text{Modulus of elasticity} = E = \frac{\sigma}{\varepsilon} = \frac{35{,}000 \text{ psi}}{0.0035} = 10 \times 10^6 \text{ psi}$$

Example 2: Young's Modulus - Aluminum Alloy - continued

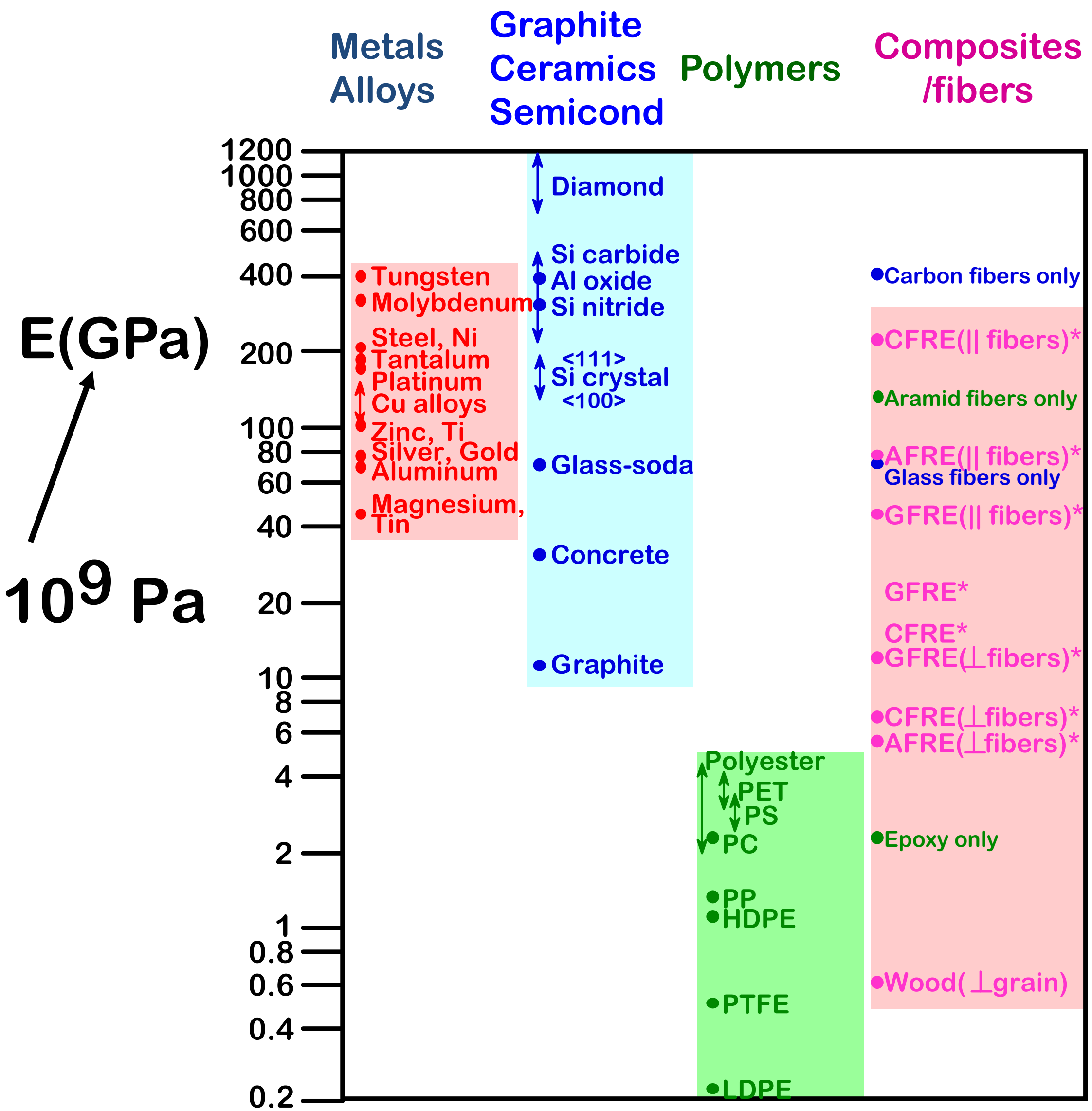
- Use the modulus to determine the length after deformation of a bar of initial length of 50 in.
- Assume that a level of stress of 30,000 psi is applied.

From Hooke's law:

$$\varepsilon = \frac{\sigma}{E} = \frac{30{,}000 \text{ psi}}{10 \times 10^6} = 0.003 = \text{in./in.} = \frac{l - l_0}{l_0}$$

$$l = l_0 + \varepsilon l_0 = 50 + (0.003)(50) = 50.15 \text{ in.}$$

Young's Moduli: Comparison



$E_{ceramics}$

$> E_{metals}$

$>> E_{polymers}$

Composite data based on reinforced epoxy with 60 vol% of aligned carbon (CFRE), aramid (AFRE), or glass (GFRE) fibers.

Example 3: True Stress and True Strain Calculation

Compare engineering stress and strain with true stress and strain for the aluminum alloy in Example 1 at (a) the maximum load. The diameter at maximum load is 0.497 in. and at fracture is 0.398 in.

Example 3 SOLUTION

At the tensile or maximum load:

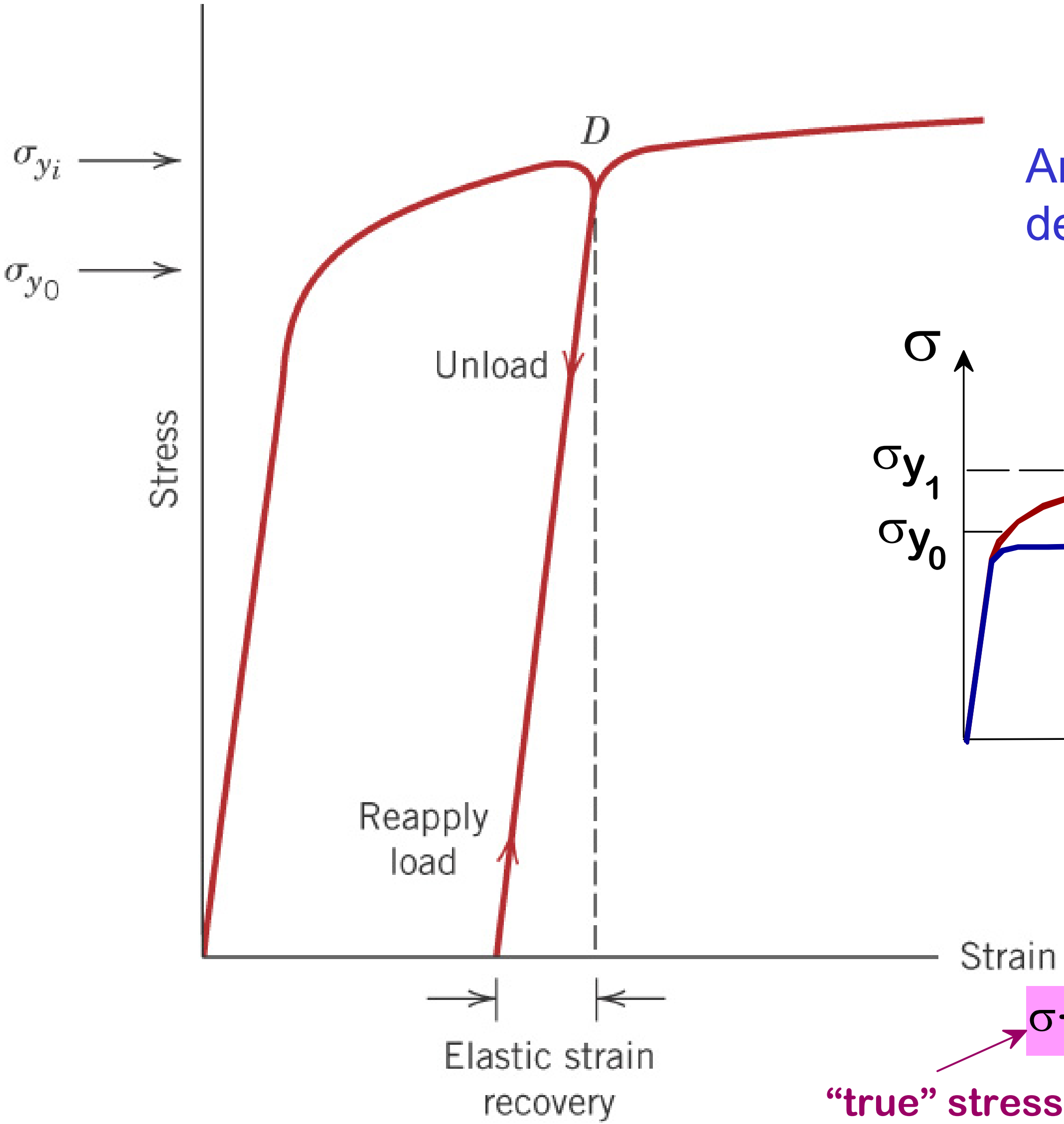
$$\text{Engineering stress} = \frac{F}{A_0} = \frac{8000 \text{ lb}}{(\pi/4)(0.505 \text{ in.})^2} = 40{,}000 \text{ psi}$$

$$\text{True stress} = \frac{F}{A} = \frac{8000}{(\pi/4)(0.497)^2} = 41{,}237 \text{ psi}$$

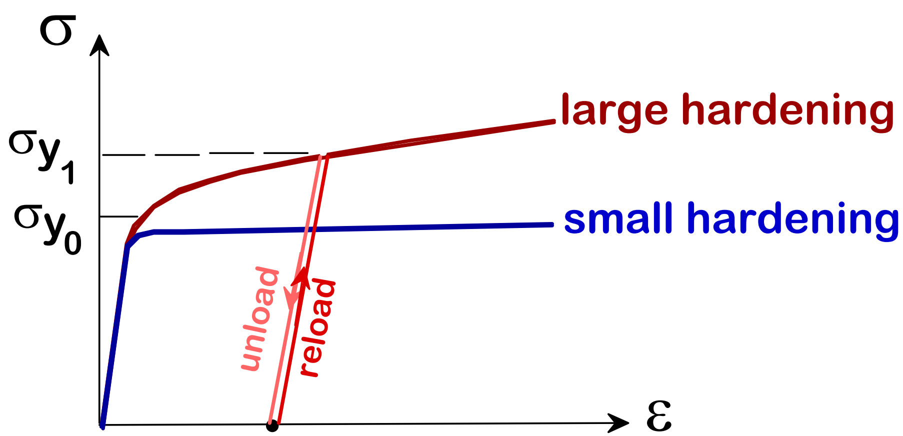
$$\text{Engineering strain} = \frac{l - l_0}{l_0} = \frac{2.120 - 2.000}{2.000} = 0.060 \text{ in./in.}$$

$$\text{True strain} = \ln\left(\frac{l}{l_0}\right) = \ln\left(\frac{2.120}{2.000}\right) = 0.058 \text{ in./in.}$$

Strain Hardening



An increase in σy due to plastic deformation.



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

"true" stress (F/A)

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

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

Strain Hardening (n, K or C values)

Table 7.4 **Tabulation of *n* and *K* Values (Equation 7.19) for Several Alloys**

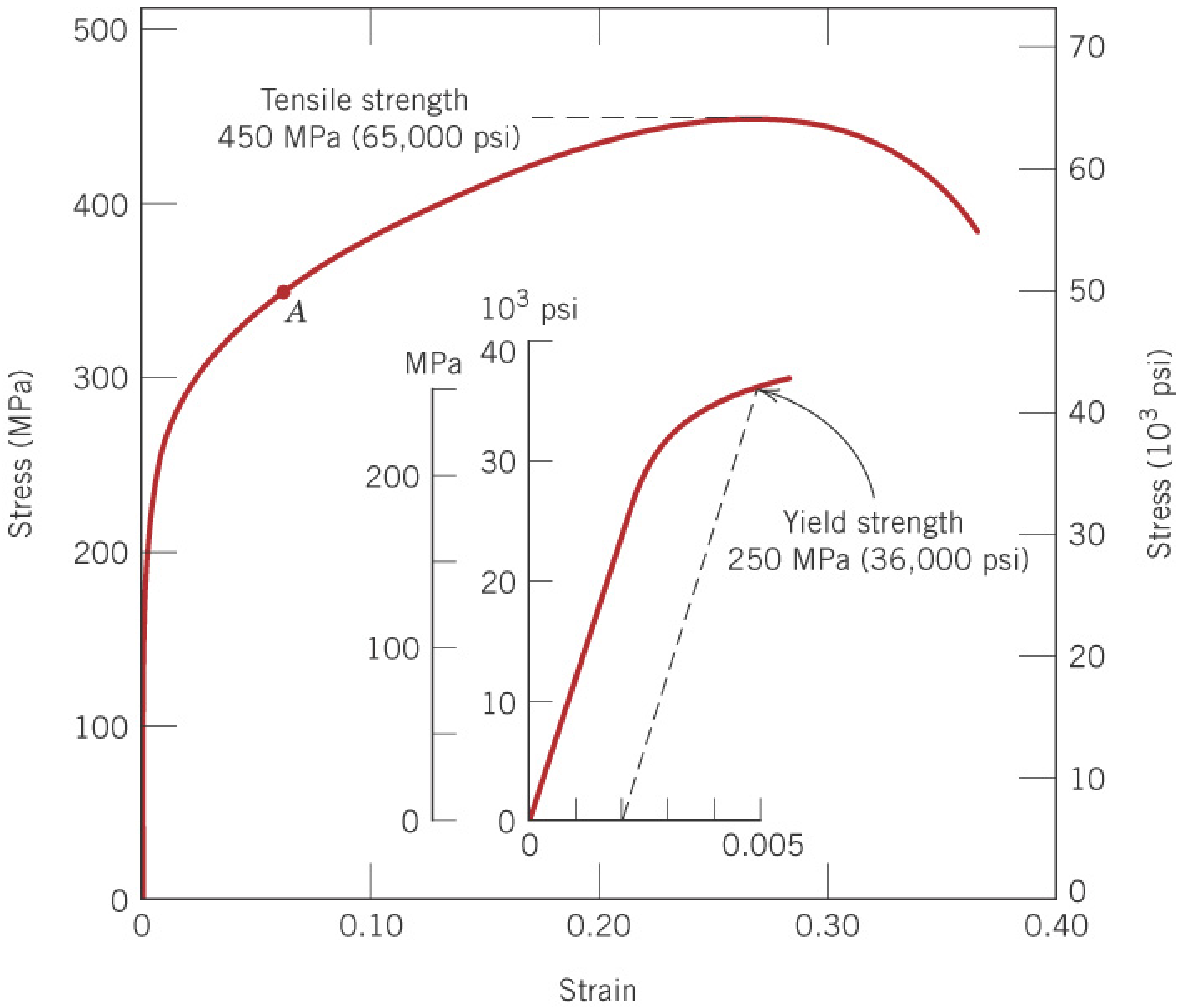
		K	
Material	***n***	***MPa***	***psi***
Low-carbon steel (annealed)	0.21	600	87,000
4340 steel alloy (tempered @ 315°C)	0.12	2650	385,000
304 stainless steel (annealed)	0.44	1400	205,000
Copper (annealed)	0.44	530	76,500
Naval brass (annealed)	0.21	585	85,000
2024 aluminum alloy (heat treated—T3)	0.17	780	113,000
AZ-31B magnesium alloy (annealed)	0.16	450	66,000

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

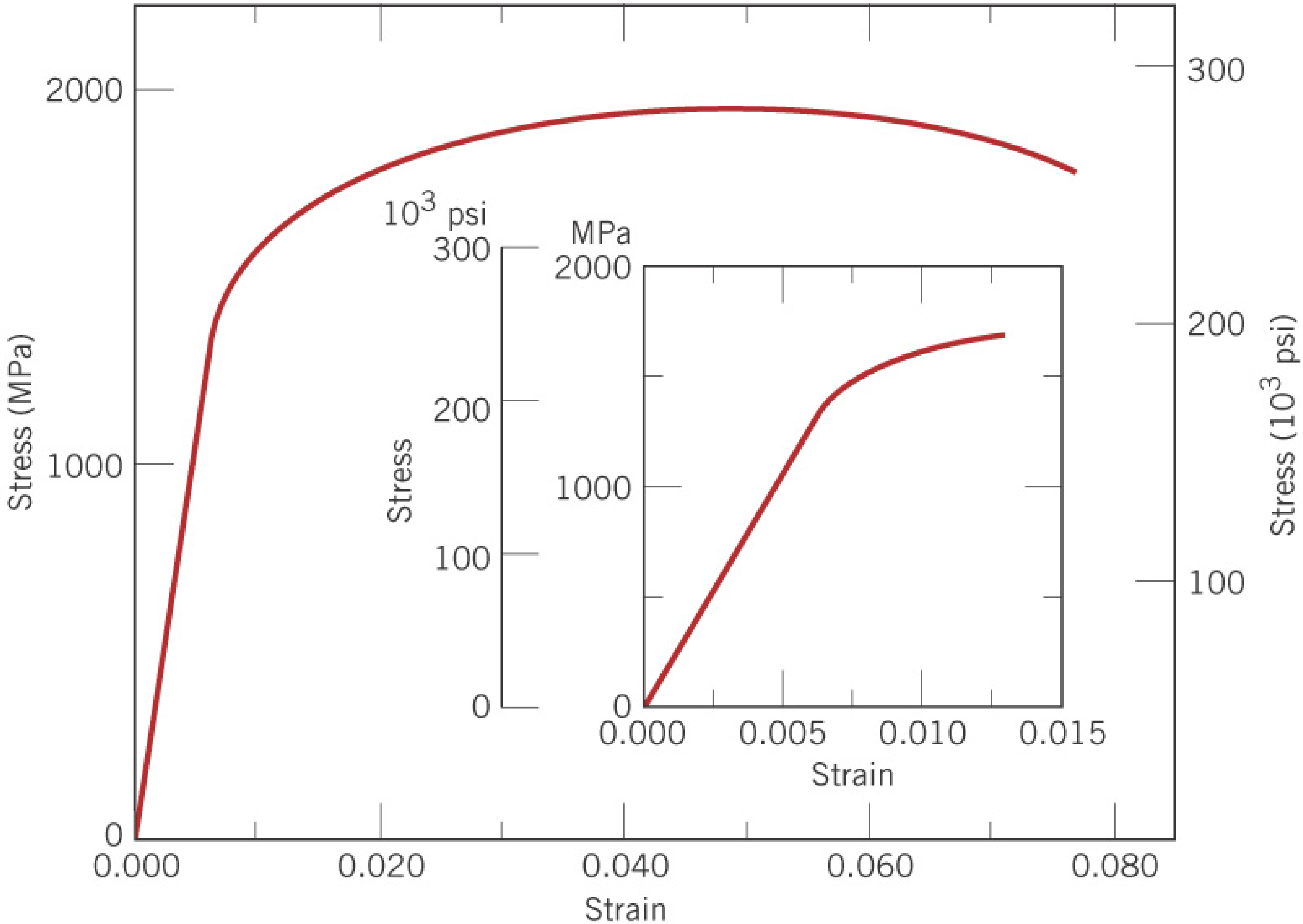
hardening exponent:
n=0.15 (some steels)
to n=0.5 (some copper)

"true" stress (F/A)

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



Tensile strength
450 MPa (65,000 psi)
A
Yield strength
250 MPa (36,000 psi)
Stress (MPa)
Stress (10^3 psi)
Strain
MPa
10^3 psi
0
100
200
300
400
500
0.10
0.20
0.30
0.40
10
20
30
40
50
60
70
0.005



Stress (MPa)
2000
1000
0
0.000
0.020
0.040
0.060
0.080
Strain
Stress (10^3 psi)
300
200
100
10^3 psi
MPa
300
2000
200
1000
100
0
0
Stress
0.000
0.005
0.010
0.015
Strain

02. Benkelman Beam

- Reference:
  - **ASTM D 4695 – 03**
  - **AASHTO T 256-01**
  - **SNI 2416: 2011**
- **Introduction: History of Benkelman Beam**
- **Concept on Pavement Measurement**
- **Equipment and Field Procedure**
- **Data Analysis**

History of Benkelman Beam

Alvin Carlton Benkelman, Sr.

- A.C.Benkelman devised the simple deflection beam in 1953 for measurement of pavement surface deflection.
- It is widely used all over the world evaluation of the requirements of strengthening of flexible pavements.
- This method is done to lay down a uniform procedure for the design of flexible overlays or per I R C:81-1981 here a tentative guideline was published by the Indian road congress under the title “Tentative Guidelines for strengthening of flexible road pavements using Benkelman beam Deflection technique” .

Theoretical Concept of BB

- Due to traffic or repetition of load wearing course of the pavement surface gets deteriorated.
- In order to overcome this problem performance analysis of the pavements surface is chosen for assessing the pavement quality.
- Performance of flexible pavements is closely related to the elastic deformation of pavement under the wheel loads.
- The deformation or elastic deflection of pavement under a given load depends upon sub grade soil type, its moisture content and compaction, the thickness and quality of the pavement course, drainage conditions pavement surface temperature etc.

BB Field Measurement

BB Field Measurement