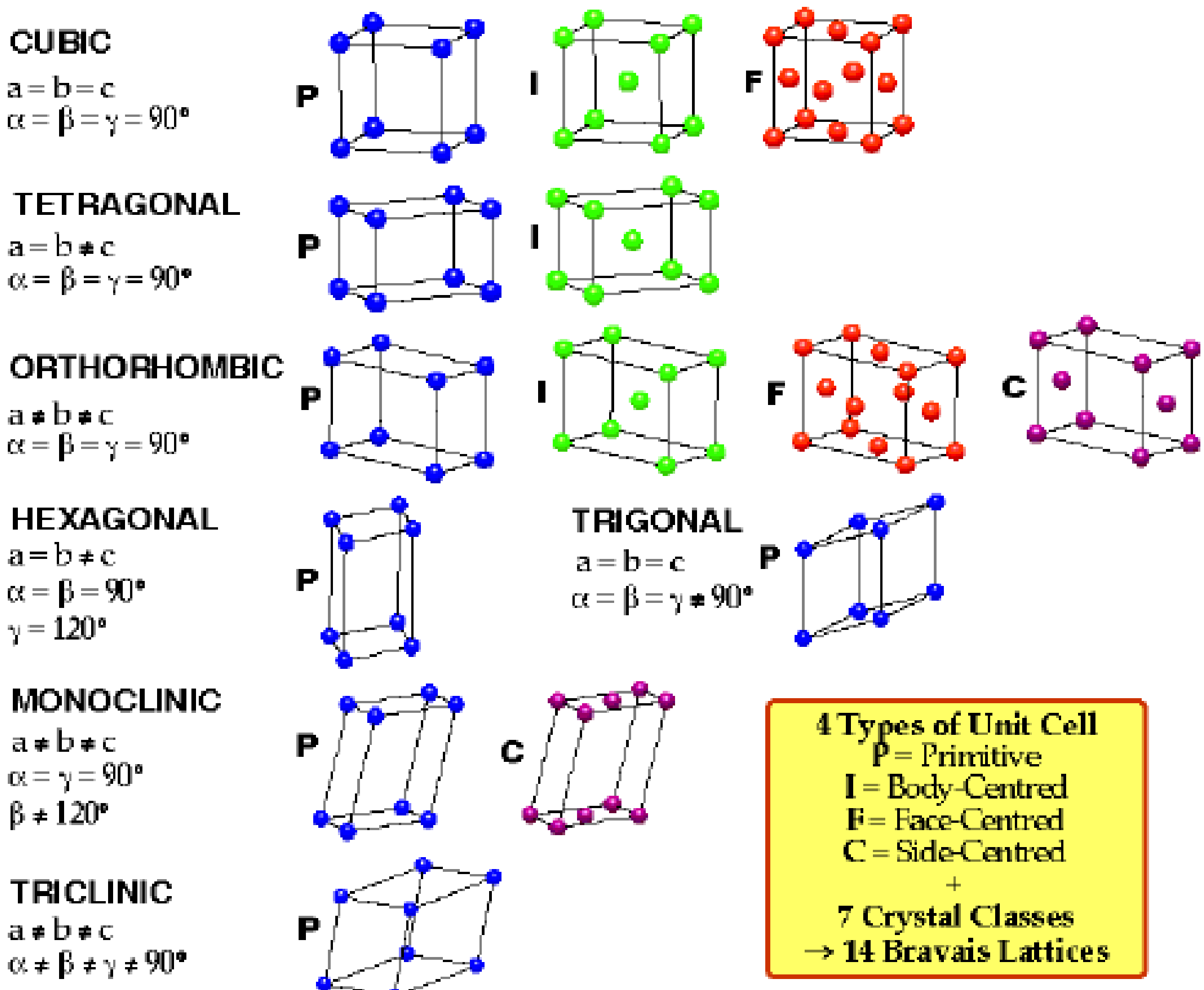
Structure and Mechanical Properties of Materials

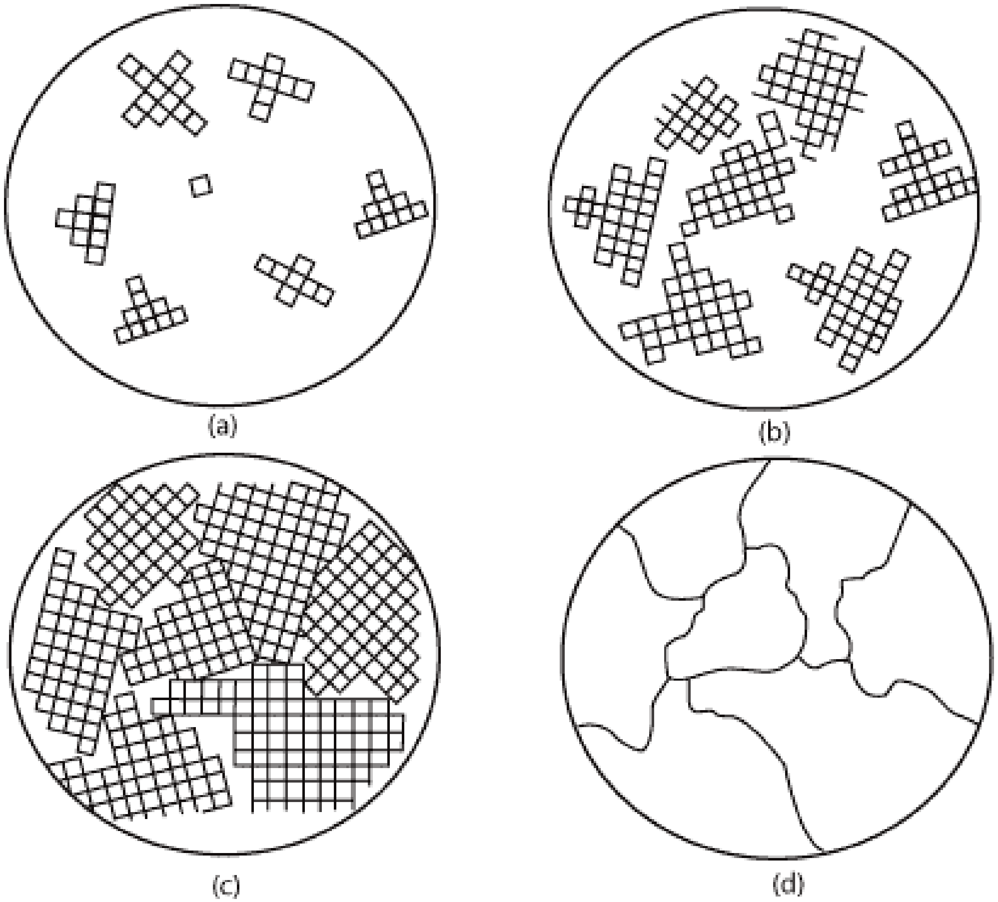
Introduction to Material Properties

- New Focus on:
  - Fundamental information on the bulk properties of biomaterials
  - Basic level to enable understanding of metallic, polymeric, and ceramic substrates
- In the next few classes we will cover:
  - Crystal structure
  - Stress-strain behavior
  - Creep, fracture, fatigue, and wear of materials

The 14 Bravais Lattices



Solidification of a Polycrystalline Material



a) *Nucleation of crystals,* ***b)*** *crystal growth,* ***c)*** *irregular grains form as crystals grow together,* ***d)*** *grain boundaries as seen in a microscope.*

Grain Boundaries

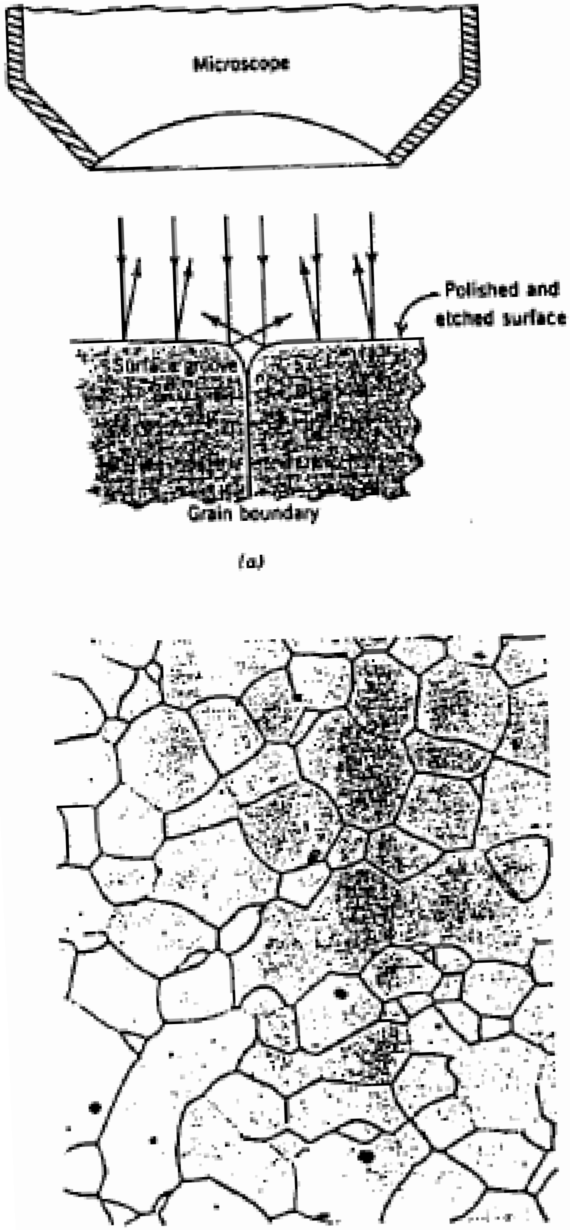


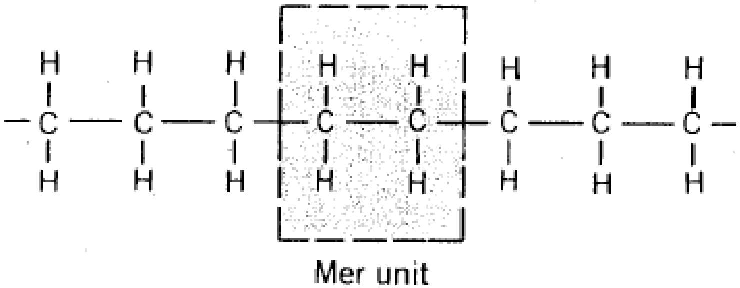
Figure 4.12 (*a*) Section of a grain boundary and its surface groove produced by etching; the light reflection characteristics in the vicinity of the groove are also shown. (*b*) Photomicrograph of the surface of a polished and etched polycrystalline specimen of an iron–chromium alloy in which the grain boundaries appear dark. 100×. (Photomicrograph courtesy of L. C. Smith and C. Brady, the National Bureau of Standards, Washington, DC.)

The Three Common Types of Materials

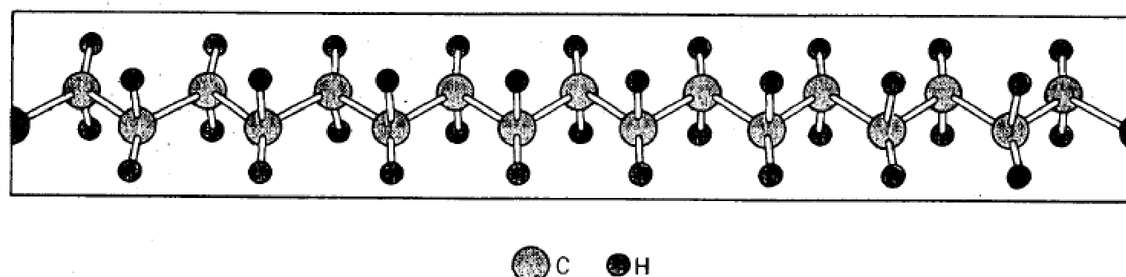
- The three common types of materials are - metals, ceramics and polymers
- These have different types of interatomic bonding
- Metals are atoms with free outer electrons (metallic bonding)
- Ceramics are generally solid inorganic compound (ionically and/or covalently bonded)
- Polymers are chain structures that are based on covalent carbon-carbon bonds and dipolar attractions

  - linear polymers (thermoplastics)
  - three-dimensional polymers (thermosets)

Introduction to Carbon Polymers

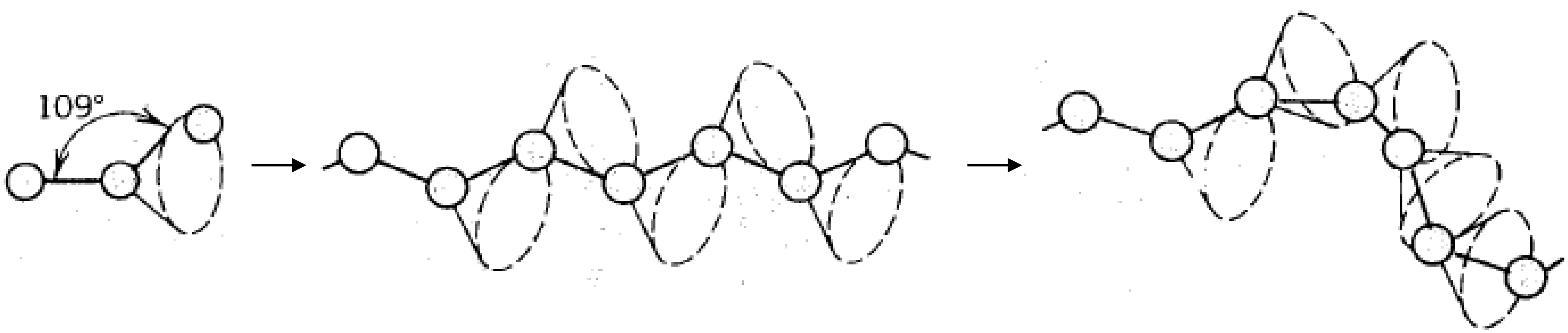


The unit at the base of Carbon Chains

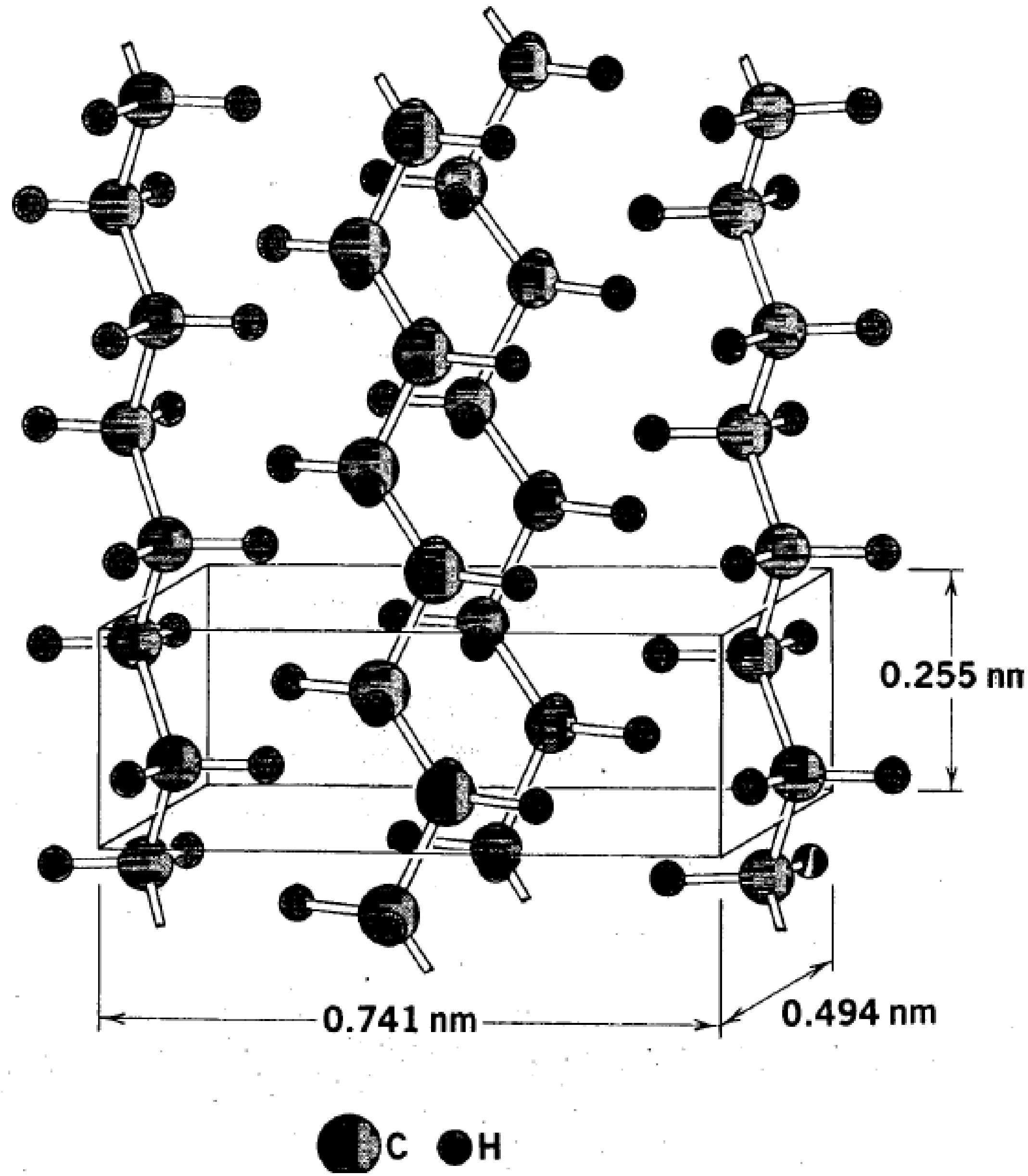


3-D Representation of a chain of single bonded carbons

Carbon chains can only rotates in specific ways



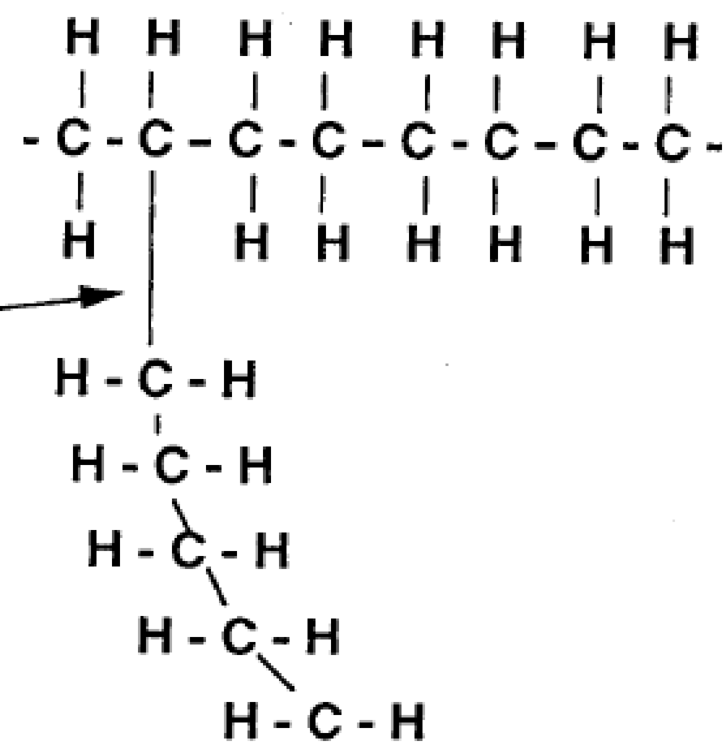
Introduction to Carbon Polymers



Branching in Polymers

An extension of the concept of adding large side groups is for the group to itself be a large polymeric molecule. This is termed *branching*.

Branching can be encouraged by adding an agent that strips away hydrogen, opening the way for another bond with carbon.

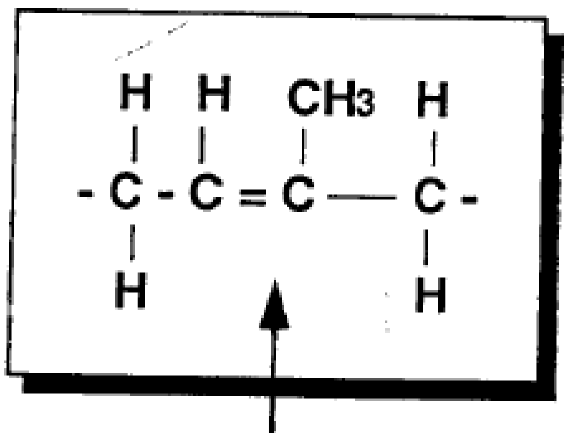


Branching in polyethylene can reduce crystallinity from 90% to 40%. The increased structural complexity retards the formation of regular, ordered arrangements of molecules

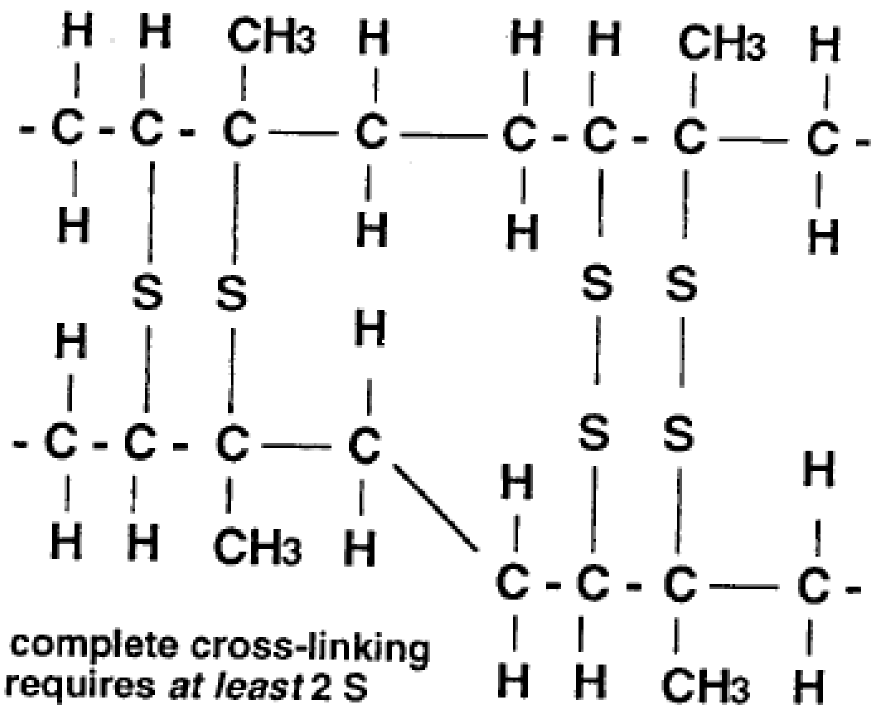
Cross-Linking in Polymers

The complete transition from linear polymer to network polymer can be caused by extensive branching, called *cross-linking*.

The most common examples are rubber molecules cross-linked by sulfur: *vulcanization*.

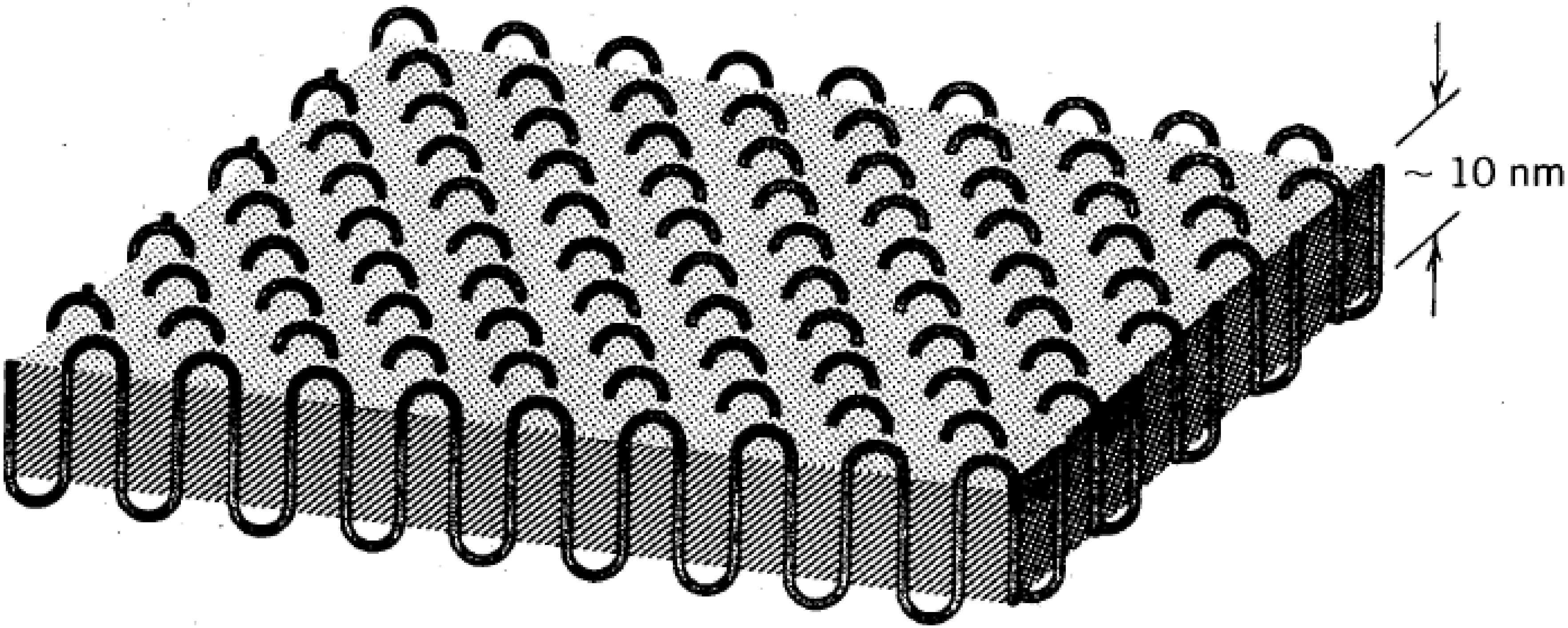


Isoprene mer is bifunctional *and* contains a double bond.

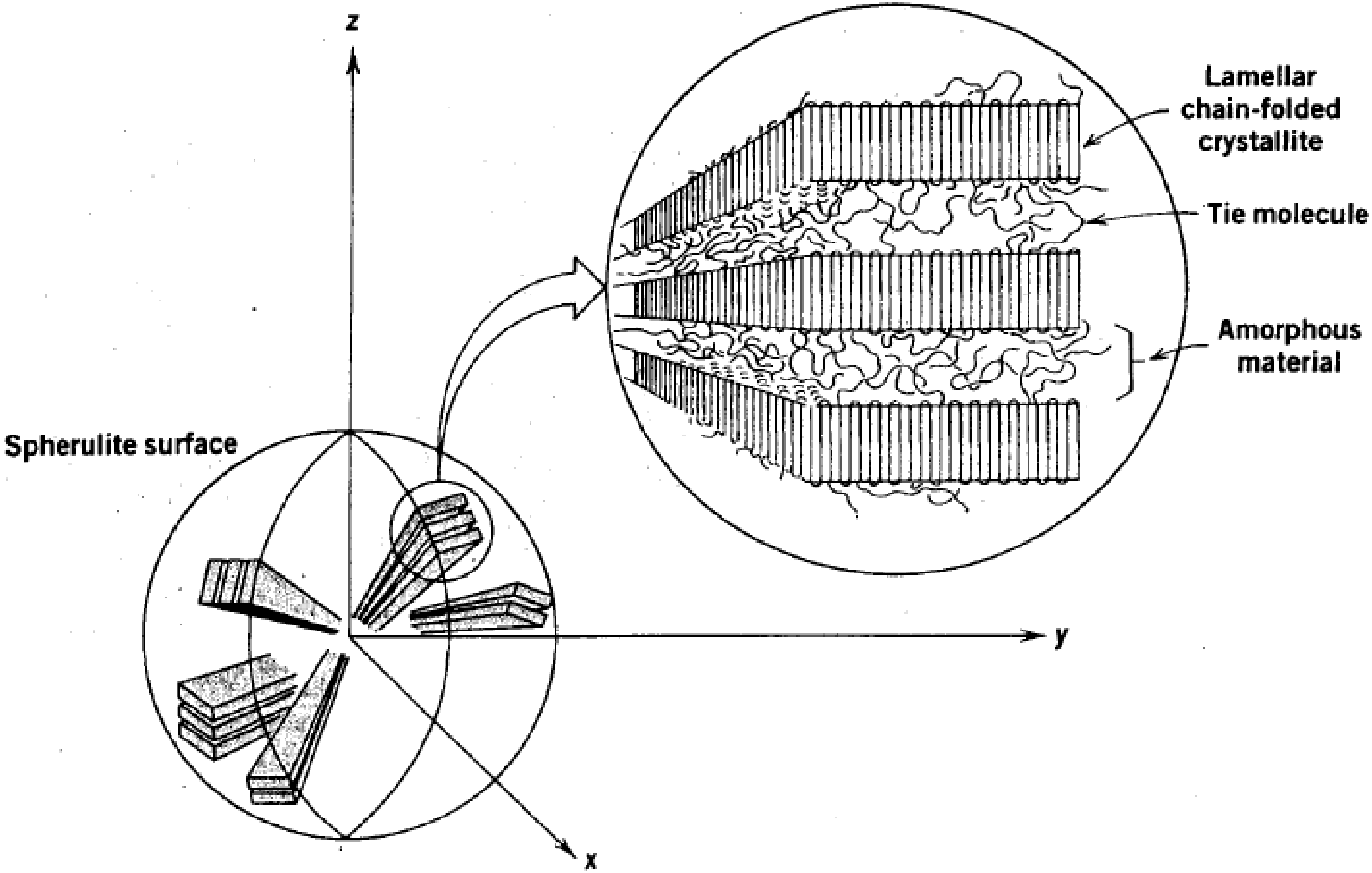


n.b. complete cross-linking requires *at least* 2 S atoms per mer.

Multy-Component Polymers



Multi-Component Polymers



Mechanical Properties of Materials

- The application of biomaterials requires a good understanding of their mechanical properties

- Mechanical properties may be described as the response of materials to mechanical loads

- The mechanical properties of materials are strongly influenced by their structure/microstructure

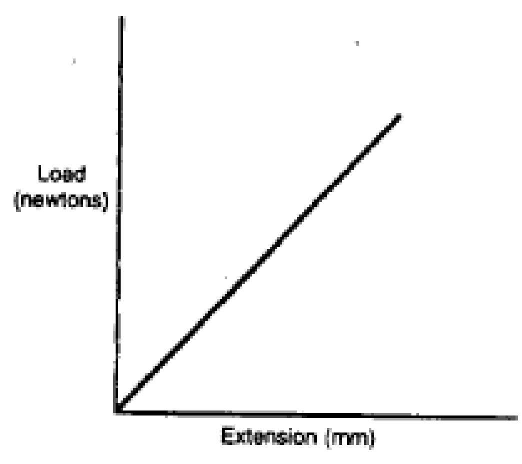
- Basic mechanical properties will be described along with experimental methods for their measurement

  - elastic-plastic behavior
  - creep and viscous flow
  - fracture and fatigue
  - wear of materials

Fundamentals of Elastic Behavior

- In 1678 Robert Hooke showed that a solid material subjected to a tensile (distraction) force would extend in the direction of traction by an amount that was proportional to load
- The above is known as Hooke's law which expresses the fact that most solids behave like springs under relatively small loads
- Elastic behavior is associated with chemical bonding & force-separation curves

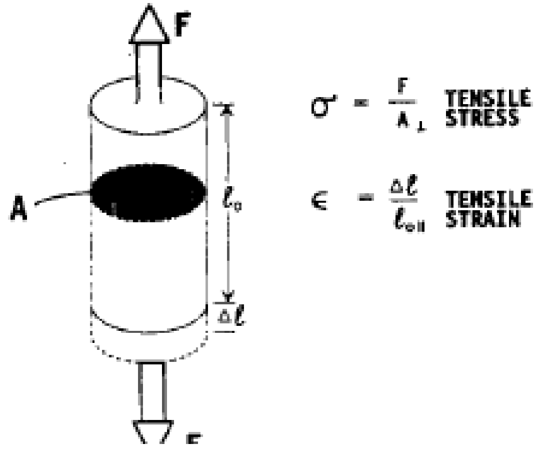
Schematic Illustration of Hooke's Law



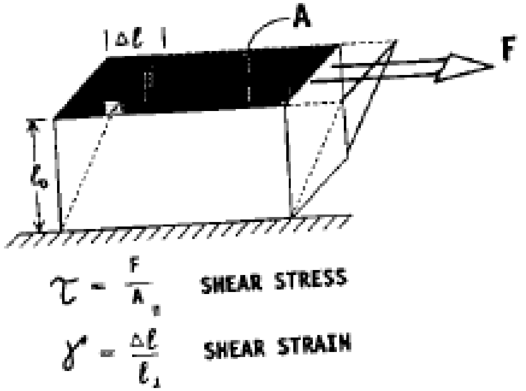
Basic Types of Loading and Deformations

- The deformation depends not only on load but also on geometry and material structure/composition
- The effects of geometry can be considered by normalizing loads with respect to area or deformation with respect to length
- This may be done for tensile or shear deformation
- Constitutive behavior provides relationship between stress and strain ($\sigma = f(\varepsilon)$ or $\tau = f(\gamma)$)

Tensile Deformation

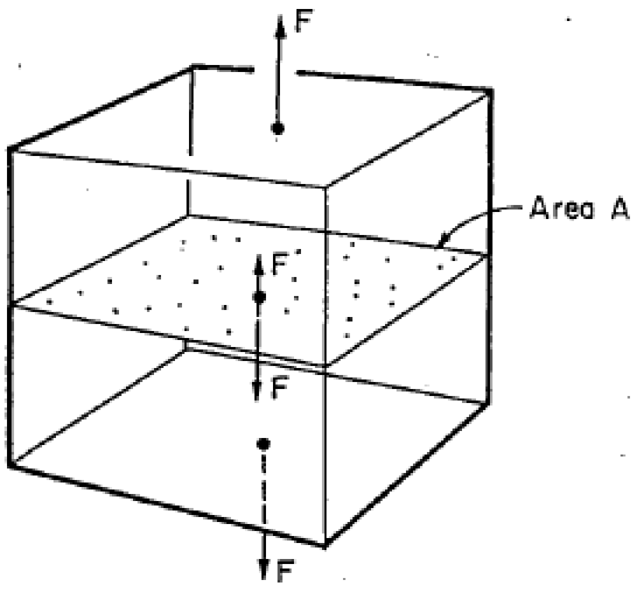


Shear Deformation

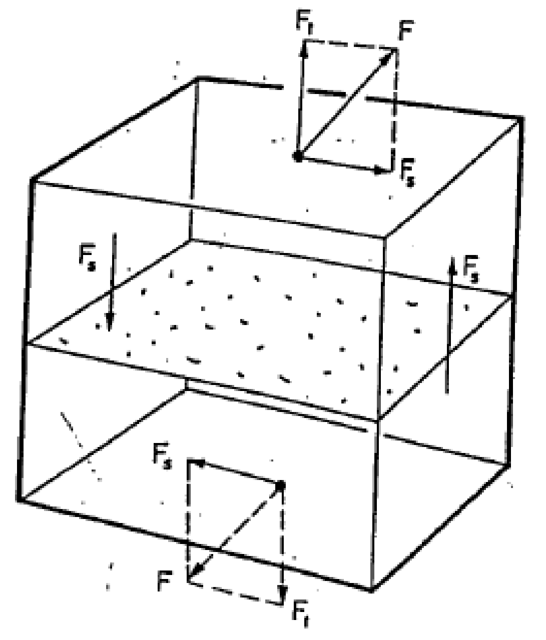


Definition of Stress

Tensile Stress

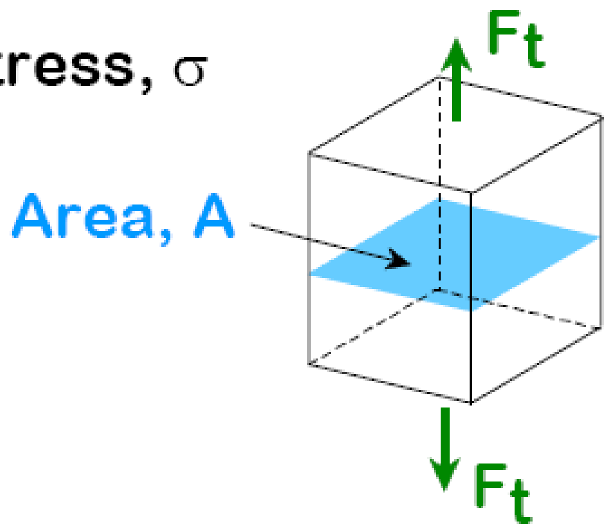


Shear Stress



Definition of Stress

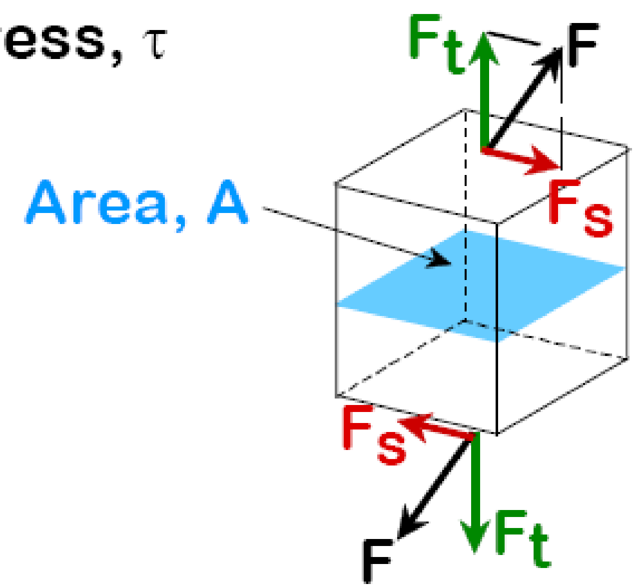
Tensile Stress, σ



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

original area before loading

Shear Stress, τ



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

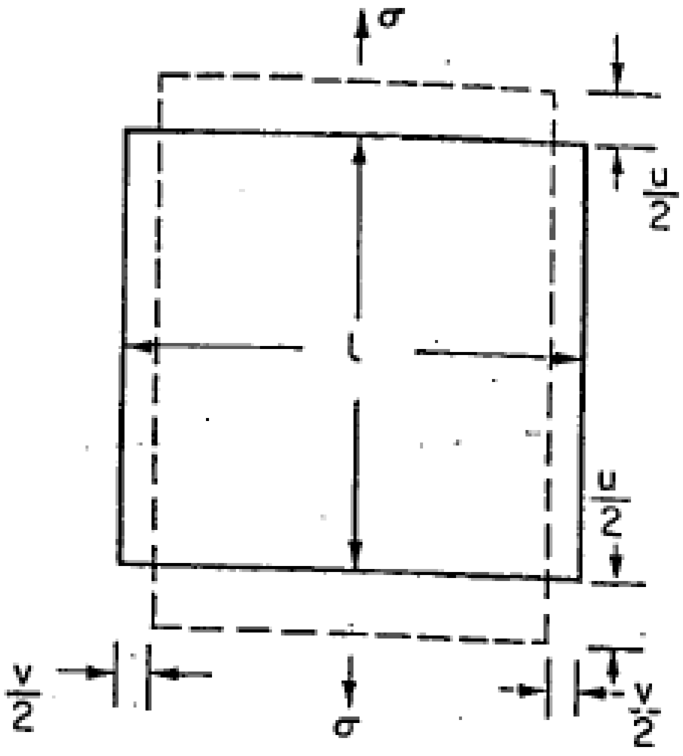
stress has units:

N/m^2 or lb/in^2

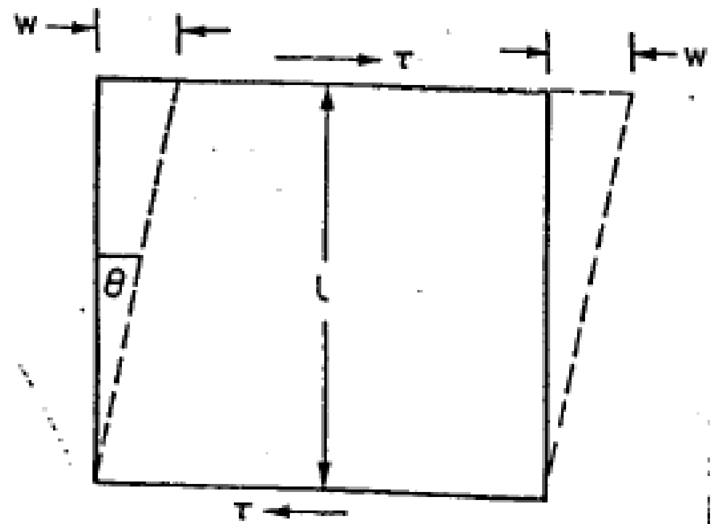
Anderson 205-6-4

Definition of Strain

Tensile Strain
Lateral Strain



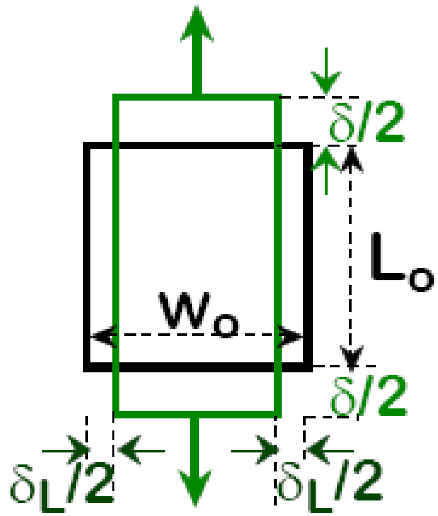
Shear Strain



Definition of Strain

Tensile Strain, ε

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

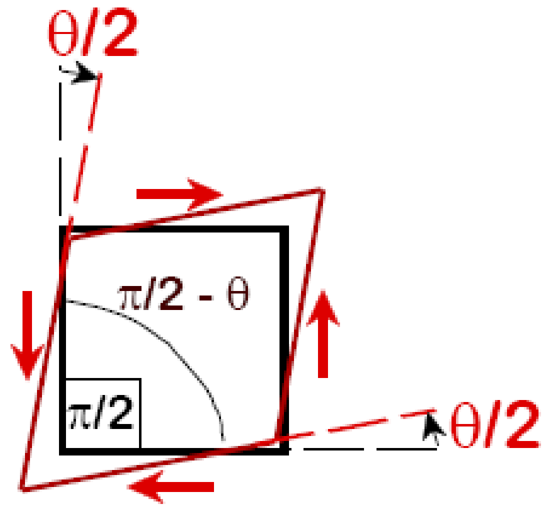


Lateral Strain, ε_L

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

Shear Strain, γ

$$\gamma = \tan\theta$$

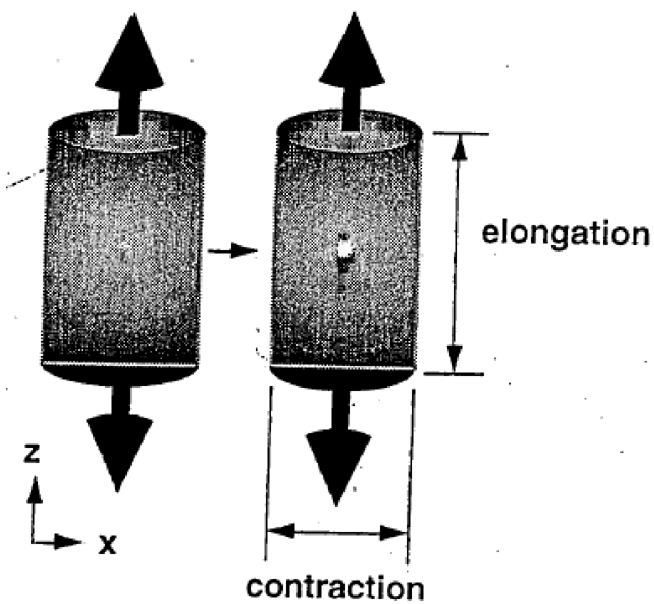


strain is always dimensionless!

Poisson’s Ratio

The stress-strain curve does not show an important feature of plastic deformation:

-A contraction perpendicular to the extension caused by a tensile stress



The effect is characterized by *Poisson's Ratio*:

$$\nu = -\frac{\varepsilon_x}{\varepsilon_z}$$

$\nu = 0.29$ for ductile iron
$\nu = 0.35$ for magnesium

Definitions of Elastic Constants

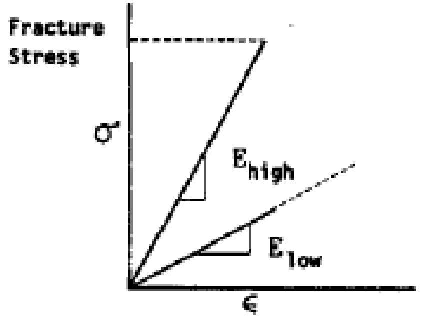
- From Hooke's law - we have the following relationships between stress and strain

  $\alpha = E\varepsilon$ (tension or compression)
  $\tau = G\gamma$ (shear)

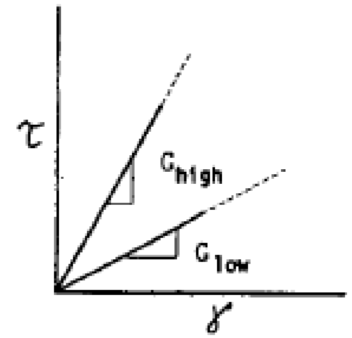
  where E is the Young's modulus and G is the shear modulus

- For isotropic solids $E = 2G(1+\nu)$

Tensile Deformation



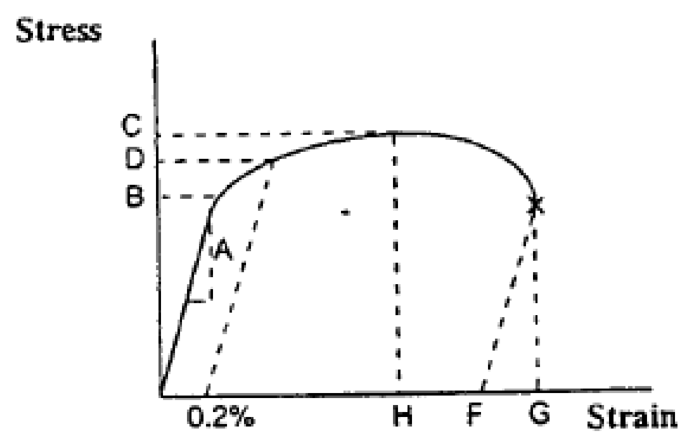
Shear Deformation



Basic Definition of Tensile Properties

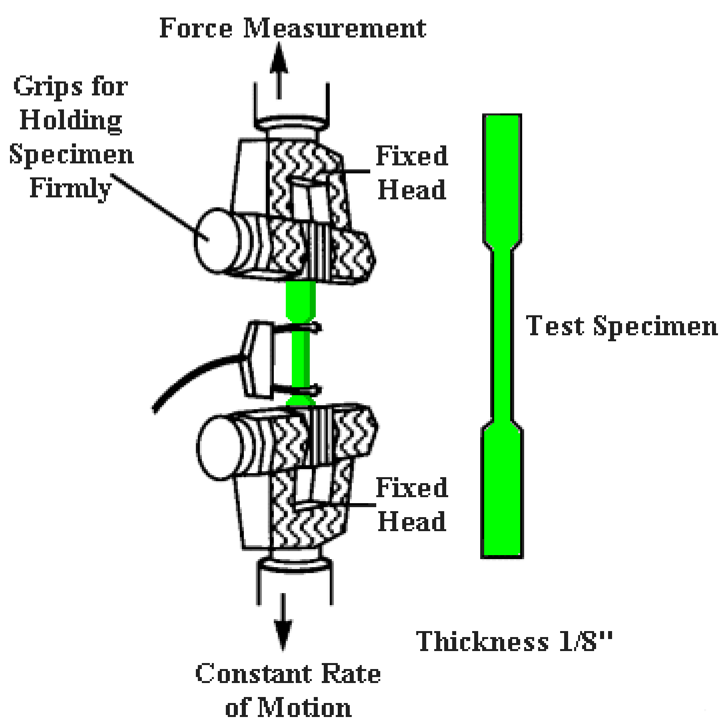
- The basic definitions of strength, elongation and modulus are provided in the schematic below
- Yield strength often defined with a 0.2% strain offset
- Ultimate tensile strength corresponds to peak load/stress
- May define percent elongation to failure or plastic strain to failure

Schematic Illustration of Tensile Properties



Tensile Properties and Their Measurement

- Most tensile tests are conducted on servo-hydraulic or electro-mechanical testing machines
- Load is monitored in series with a load cell attached to the specimen
- Displacement is monitored with a displacement gage within a narrower section of the specimen

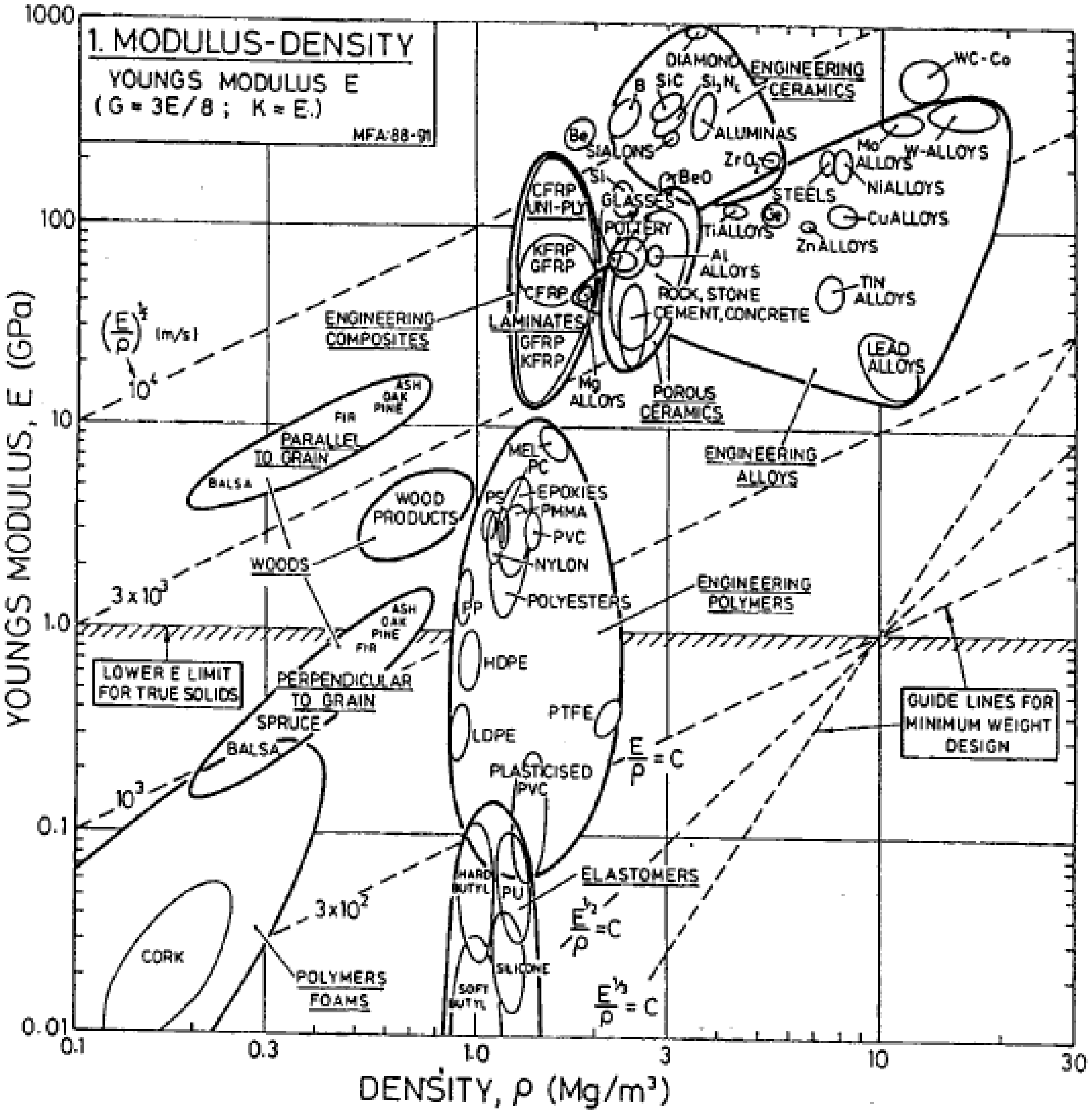


Tensile Properties of Biomaterials

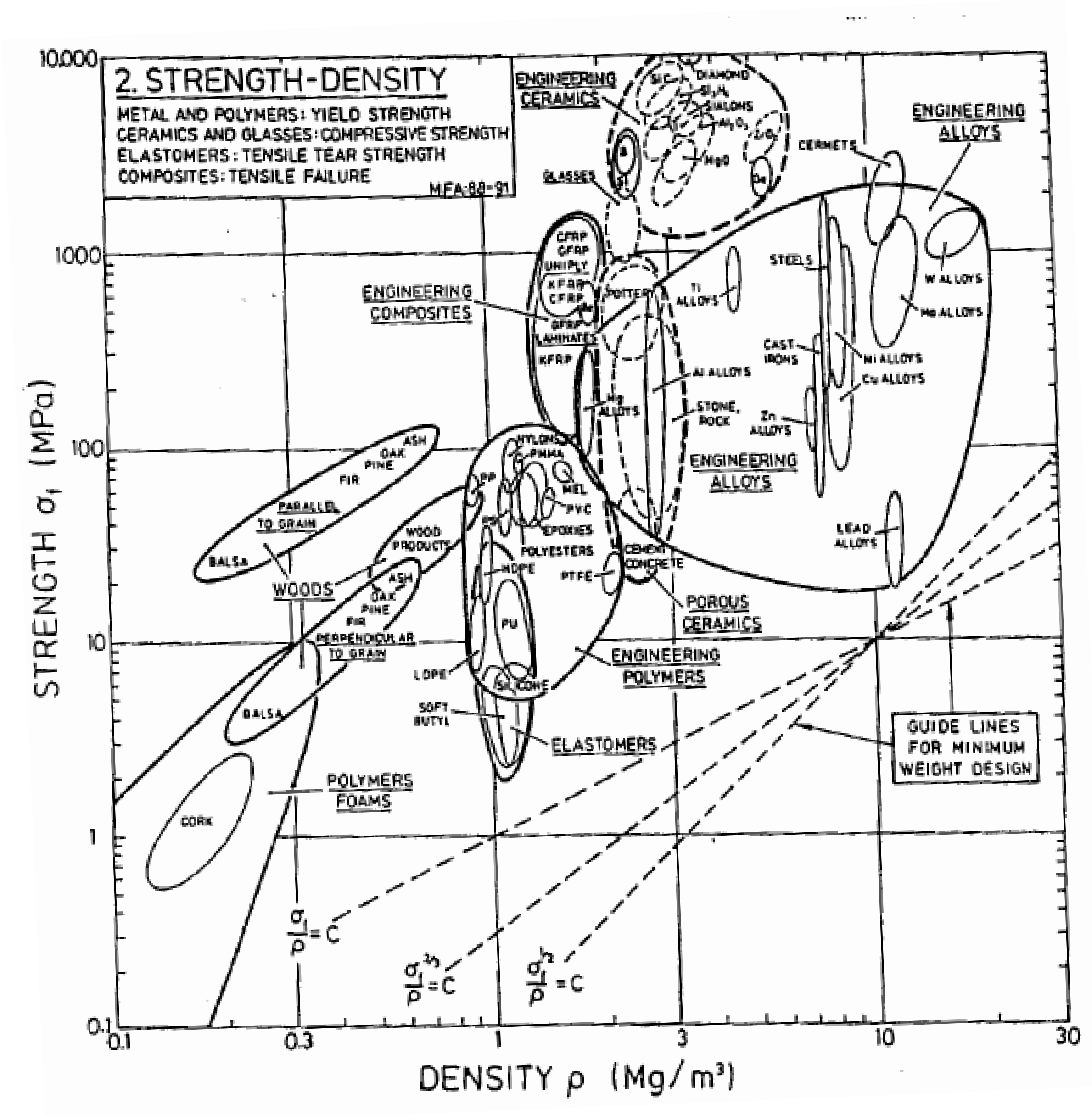
	Elastic modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Elongation to failure (%)
Al_2O_3	350	—	1,000 to 10,000	0
CoCr Alloy[a]	225	525	735	10
316 S.S.[b]	210	240 (800)[c]	600 (1000)[c]	55 (20)[c]
Ti 6Al–4V	120	830	900	18
Bone (cortical)	15 to 30	30 to 70	70 to 150	0–8
PMMA	3.0	—	35 to 50	0.5
Polyethylene	0.4	—	30	15–100
Cartilage	[d]	—	7 to 15	20

[a]28% Cr, 2% Ni, 7% Mo, 0.3% C (max.), Co balance.
[b]Stainless steel, 18% Cr, 14% Ni, 2 to 4% Mo, 0.03 C (max), Fe balance.
[c]Values in parenthesis are for the cold-worked state.
[d]Strongly viscoelastic.

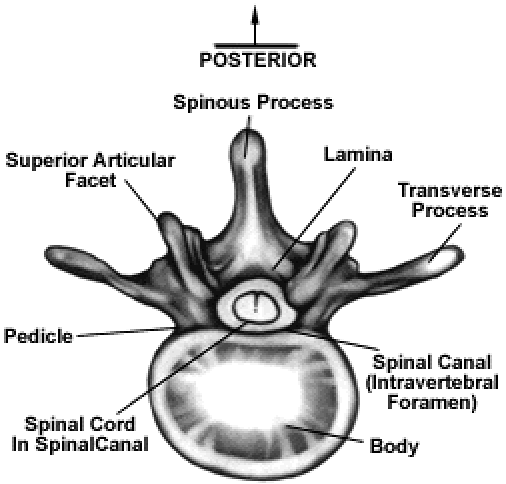
Young's Modulus over Density

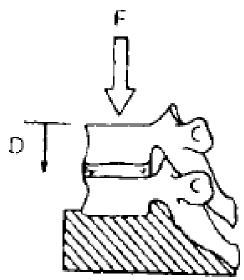


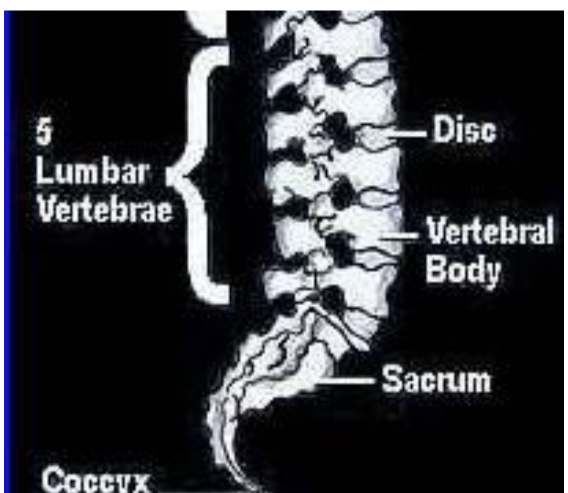
Strength over Density

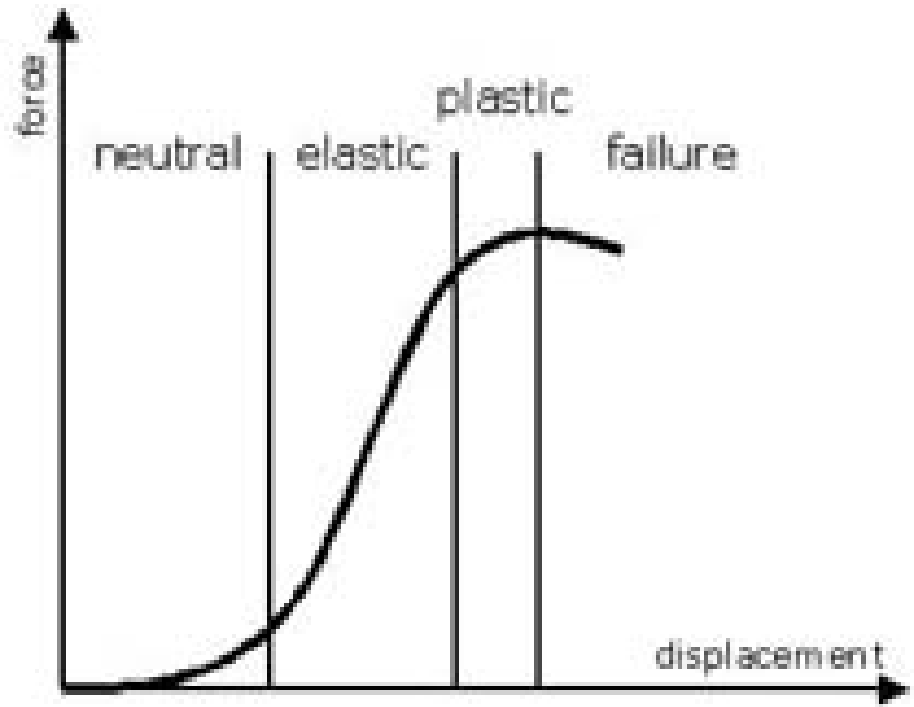


Non-Linear Deformation of Lumbar Vertebra



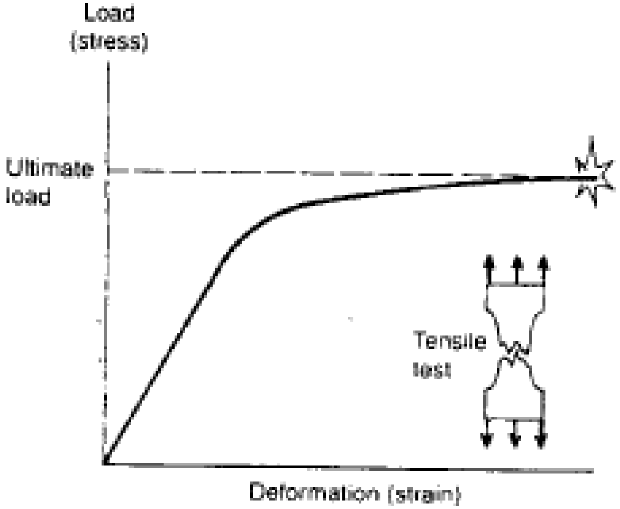


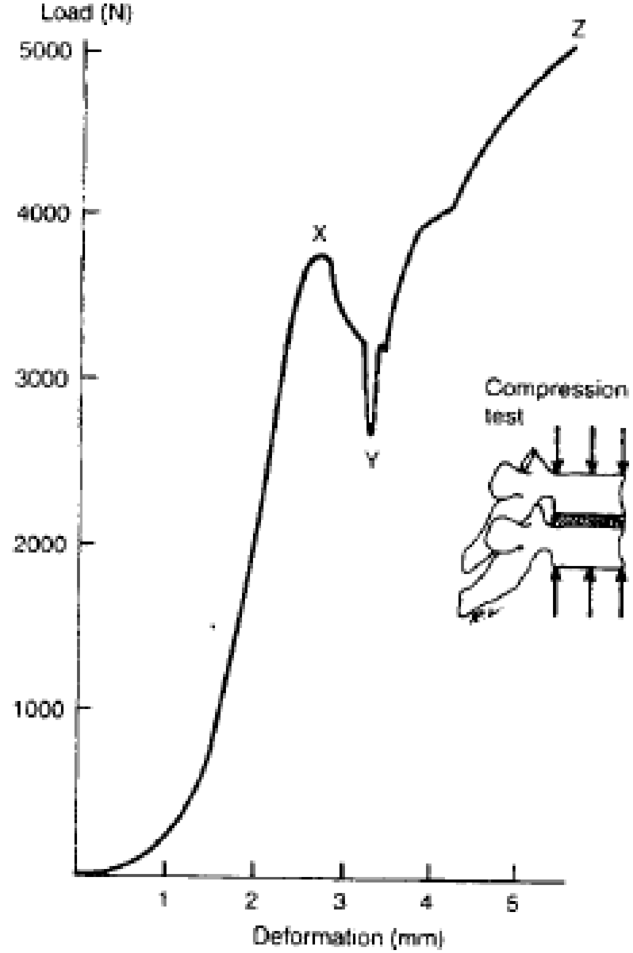




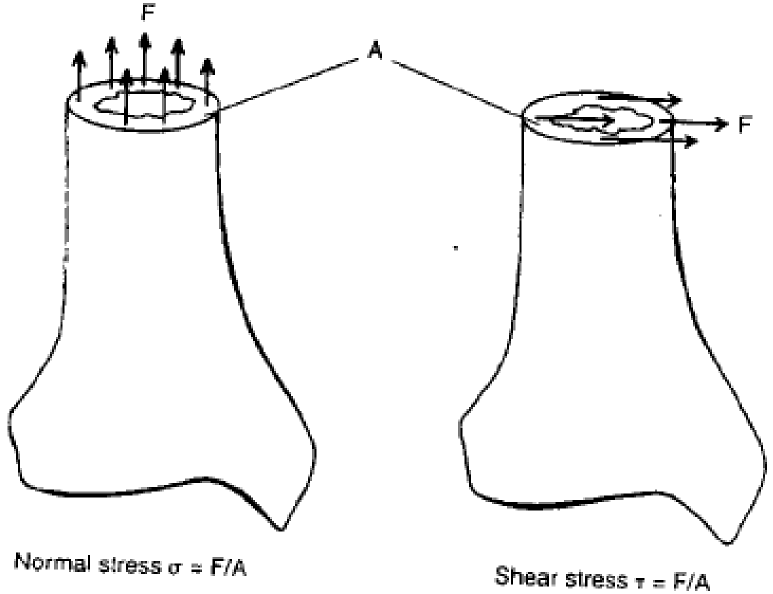
Non-Linear Deformation of Lumbar Vertebra

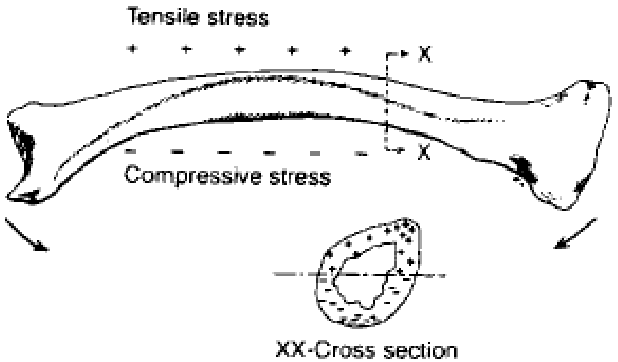
Ultimate load under Tension/Compression

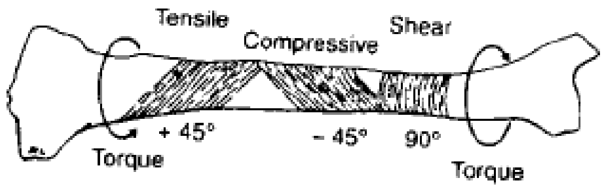




Stresses on Bone Under Different Types of Loading

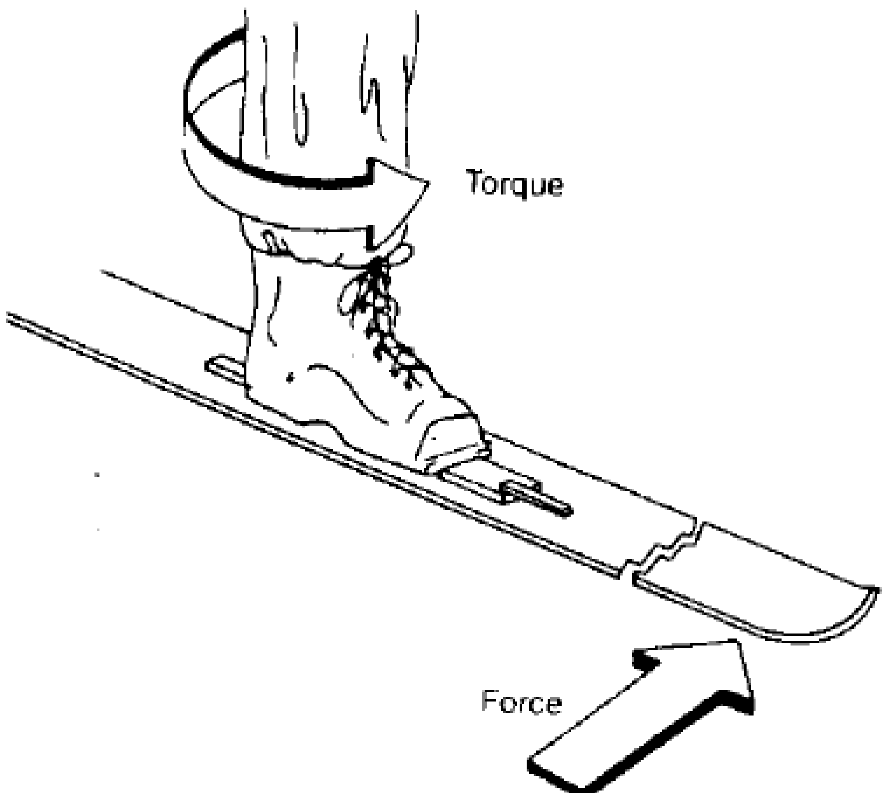


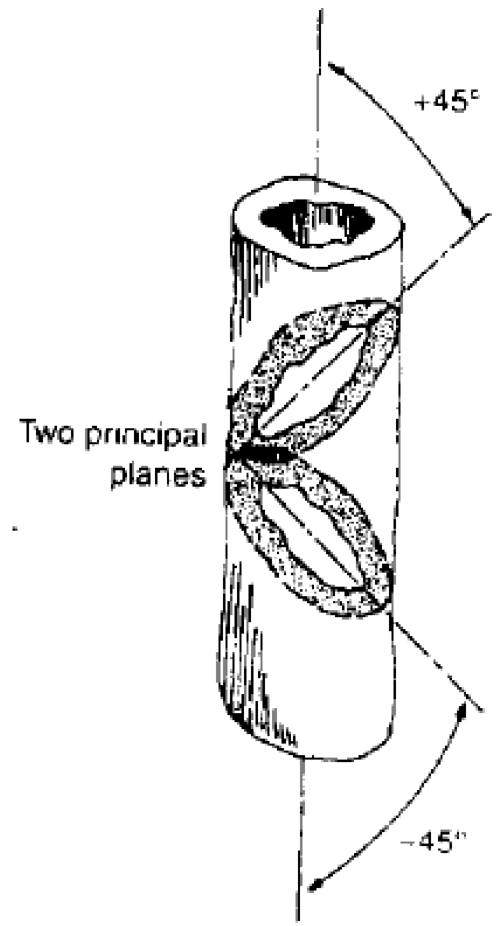




Stresses on Bone Under Different Types of Loading

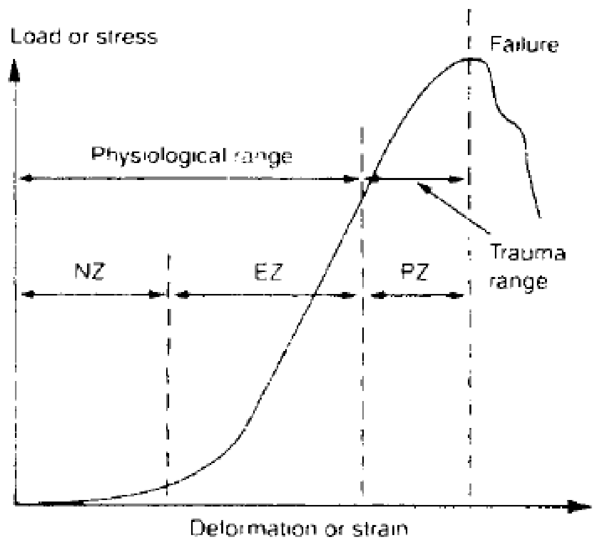
Principal Stresses and Ski Injury in Tibia due to Torque





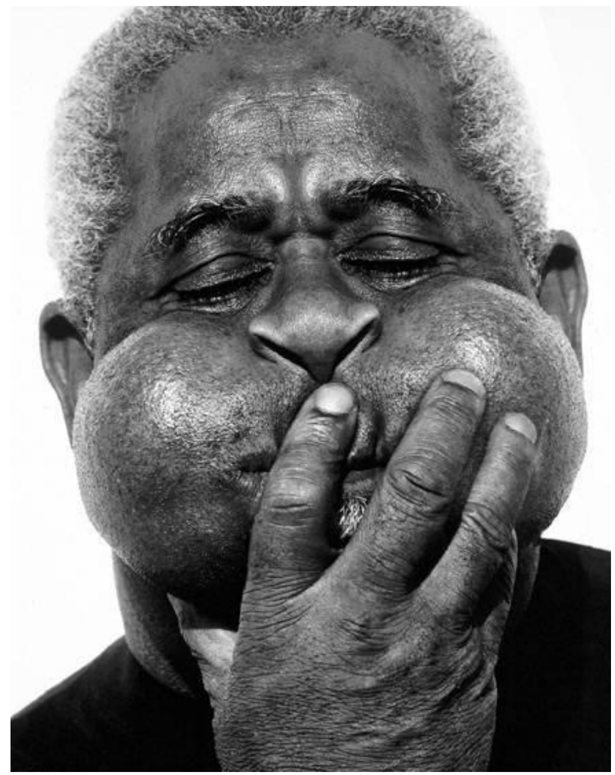
Mechanical Properties of Tissue

- The deformation behavior of tissue can be divided into biomechanically and clinically relevant regions
- For example, the deformation behavior of a ligament may be divided into physiologic and traumatic ranges
- Little effort is needed to deform ligamant into neutral zone (NZ), more needed to deform into the elastic zone (EZ), and micro-trauma occurs in plastic zone (PZ)



Plasticity of Tissue

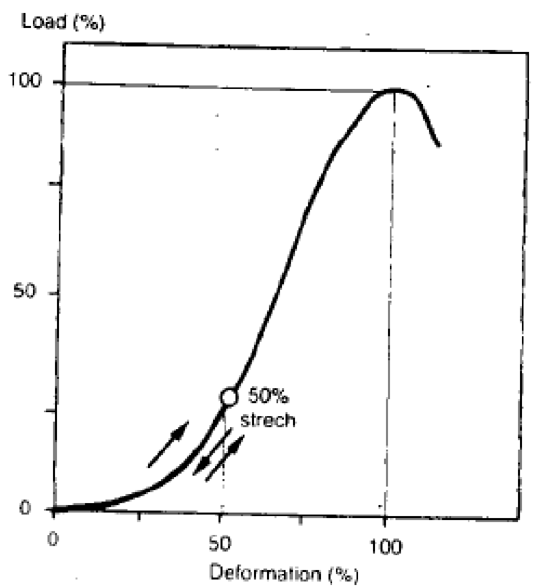
- **Plasticity occurs in the range where loads or deformations result in permanent shape changes**
- **Example of Dizzie Gillespie – legendary trumpet player**
- **Difference between cheeks as a young or old man**

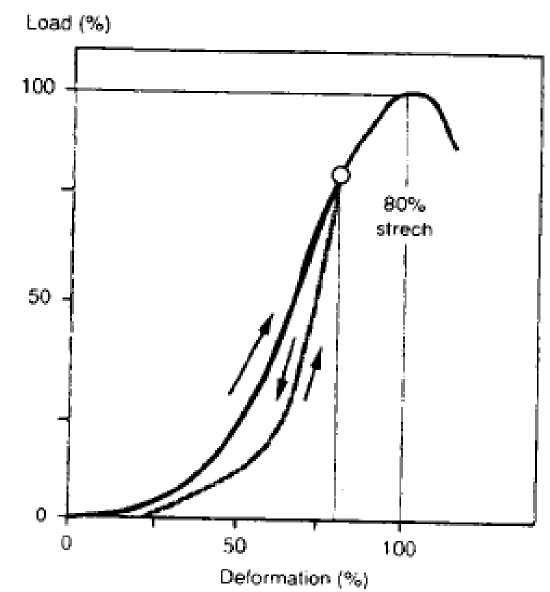


Sub-Failure Injury

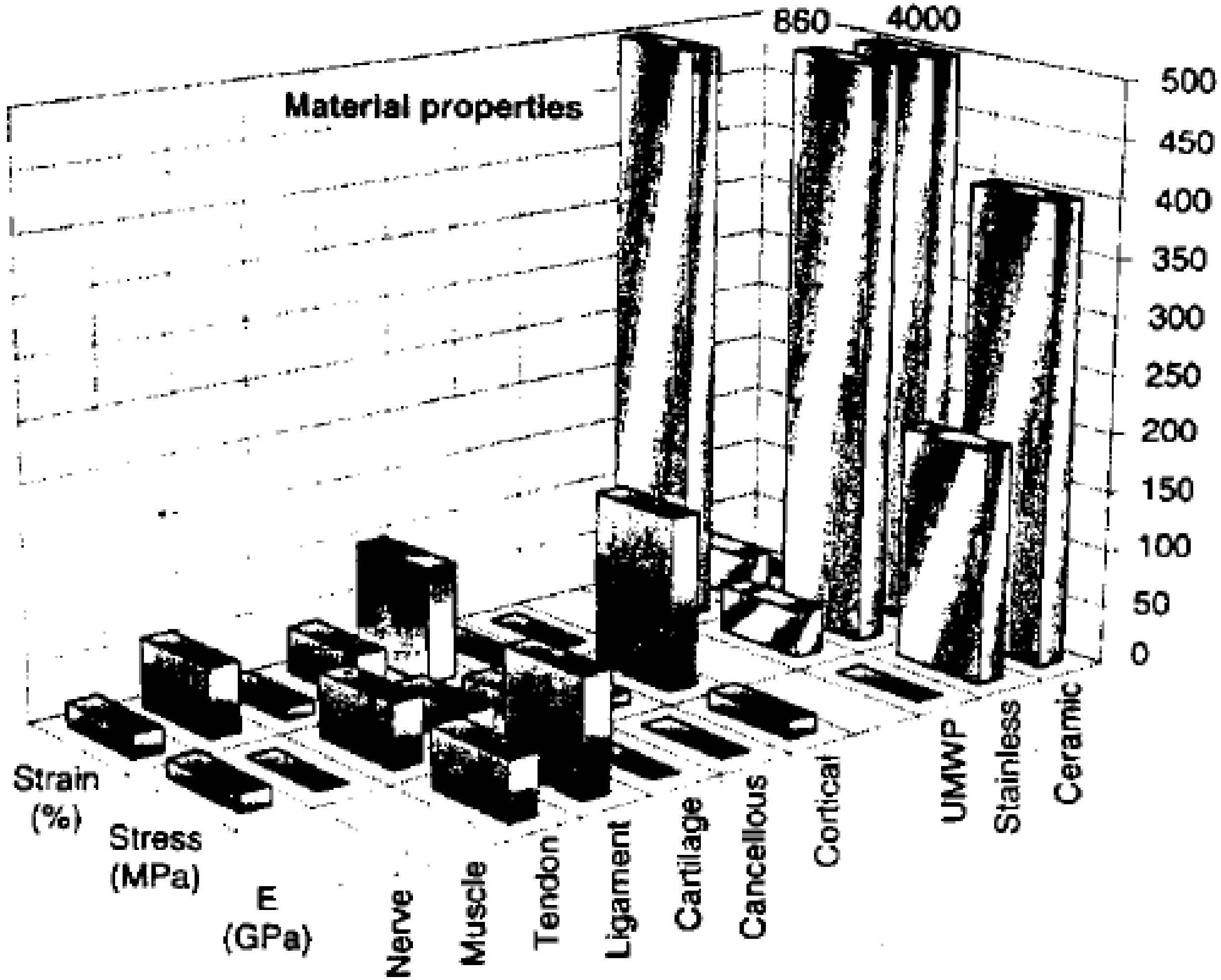
- This is associated with stretching of soft tissue

- Stretching results in incomplete failure of tissue
- Failure is 100% of stretch
- Consider failure of rabbit anterior crucial ligament
- 80% stretch causes permanent deformation/injury
- Failure load upon unloading is unchanged
- May cause joint instability or clinical problems



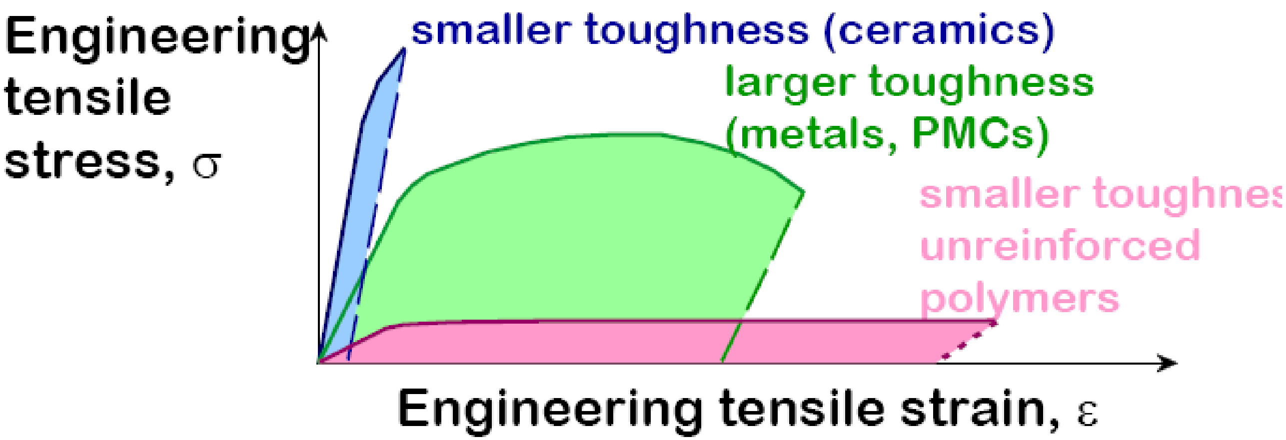


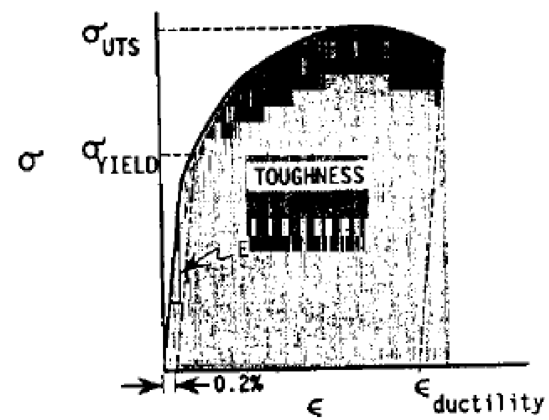
Material Properties of Biological/Implant Materials



Basic Definition of Toughness

- The area under the stress-strain curve corresponds to the energy (work) required per unit volume for the deformation of a material until failure
- This work corresponds to the toughness of the material
- Toughness must be distinguished from fracture toughness which is a measure of the resistance to crack growth





Summary and Concluding Remarks

- This class presents an introduction to the structure and properties of materials
- A simple introduction to amorphous and crystalline structure was presented
- This was followed by some basic definitions of stress, strain & mechanical properties
- The mechanical properties of soft and hard tissue were then introduced
- Balance of mechanical properties is key for design