Chapter 3 Physics of the Skeleton

Functions of bone

1- Support: the muscles are attached through tendons and ligaments (bones + tendons and ligaments + muscles).
2- Locomotion: bone joints (hinges or articulations).
3- Protection of various organs: skull, ribs, spinal column.
4- Storage of chemicals: control of calcium in blood.
5- Nourishment: deciduous (baby) teeth and permanent teeth.
6-Sound transmission: ossicles in the middle ear impedance matching between sound in air and sound in the fluid in the cochlea.

Bone remodeling : is the replacement of old tissue by new bone tissue ,this mainly accurse in the adult skeleton to maintain mass.
Bone remodeling depends on age and sex.
Bone as a living tissue that has Blood supply as well as nerve.
Bone forming cells .
Osteoblasts build the bone by about 0.5 g of calcium each day
Osteoclasts destroy the bone by about 0.5 g of calcium each day
. Bones have about 1000 g of calcium to build the new skeleton in every seven years equivalently
. Osteoblasts dominate until 35 to 40 years old
. Osteoporosis: porous bones in older women.

Bone components:(collagen+ bone mineral +water).
1-Collagen:major organic fraction 40% of the weight of solid bone and 60% of its volume.
2- bone mineral: is the inorganic part of the bone ,it amount to 60% of the bones weight and 40% of its volume ,it contains many elements at different percents (H,C,N,O,Mg,P,S,Ca, and others).
Large percentage of calcium (22.2%)with heavy nucleus (z=40)high X-ray absorption much better than soft tissue.

Shapes of bones
. Flat, plate-like bones: shoulder blade (scapula), some bones of the skull, etc.

. Long hollow bones: bones in the arms, legs, and fingers
. Cylindrical bones: bones from the spine (vertebrae)
. Irregular bones: bones from the wrist and ankle
. Other bones: ribs, etc.

Types of bones
. Solid or compact bones: Found in the central shaft of bones
. Spongy or cancellous bones (trabecular bones): Found at the ends of long bones, Weaker than compact bones.

Mechanical properties of bone.

Density: **The density of compact bones is constant = 1.9 gm/cm3 (or 1.9 times as dense as water). It is independent of age.**

What can happen to a material body (solid) when we apply forces / constraints to the outside of the body?
Types of Deformation.
we can have two types of deformation.

- **Elastic Deformation →** ***in which body recovers its original shape after removal of 'force'***
  - **E.g. a compression of a spring → the spring comes back to its original shape after load/force is released**
- **Plastic Deformation →** ***permanent deformation (body does not recover its shape after forces are removed***
  - **E.g. bending a rod to a new shape → the rod does not come back to its original shape after being bent**

Stress and Strain

- **Stress is a quantity that is proportional to the force causing a deformation.**

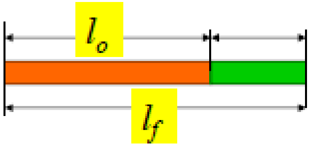
Stress is the external force acting on an object per unit cross-sectional Area.

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

F : Force applied in Newton
A : cross sectional area in m²
σ : stress in N/m2

· **Strain is the result of stress, which is the measure of the degree of deformation.**

$$\varepsilon = \frac{\Delta l}{l_o}$$



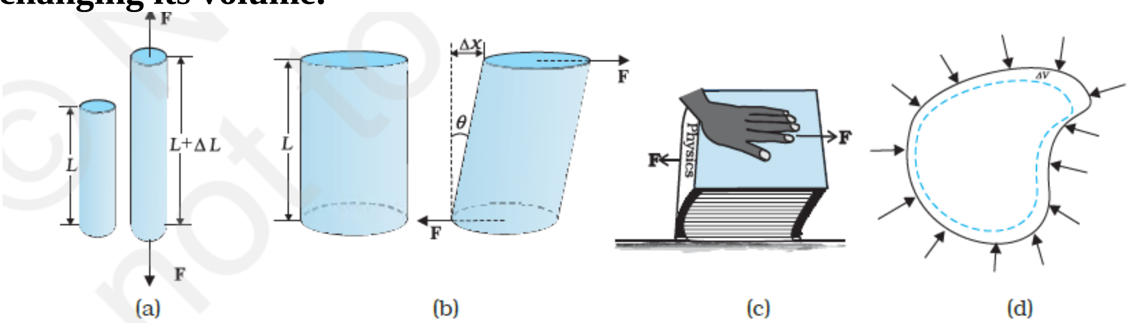
Δl : elongation (m)
lo : original length of a material (m)
ε : strain Dimensionless

Types of Stress

***Tension Stress*: is the force per unit area producing elongation of an object.**

***Compression Stress*: is the force per unit area producing compression of an object.**

Shear stress: is the opposite force "sliding forces " applied to parallel faces of the object. Producing change in shape of material without changing its volume.



Fig(1) A cylindrical body under tensile stress elongates by ΔL (b) Shearing stress on a cylinder deforming it by an angle θ (c) A body subjected to shearing stress (d) A solid body under a stress normal to the surface at every point (hydraulic stress). The volumetric strain is ΔV/V, but there is no change in shape.

HOOKE'S LAW

Stress and strain take different forms in the situations depicted in the Fig. (1). For small deformations the stress and strain are proportional to each other. This is known as Hooke's law.

Thus,

stress ∝ strain

stress = *k* × strain

where *k* is the proportionality constant and is known as modulus of elasticity.

Hooke's law is an empirical law and is found to be valid for most materials. However, there are some materials which do not exhibit this linear relationship.

STRESS-STRAIN CURVE

The relation between the stress and the strain for a given material under tensile stress can be found experimentally. In a standard test of tensile properties, a test cylinder or a wire is stretched by an applied force. The fractional change in length (the strain) and the applied force needed to cause the strain are recorded.

The applied force is gradually increased in steps and the change in length is noted. A graph is plotted between the stress (which is equal in magnitude to the applied force per unit area) and the strain produced. A typical graph for a metal is shown in Fig. 2. Analogous graphs for compression and shear stress may also be obtained. The stress-strain curves vary from material to material. These curves help us to understand how a given material deforms with increasing loads. From the graph, we can see that in the region between O to A, the curve is linear. In this region, Hooke's law is obeyed.

The body regains its original dimensions when the applied force is removed. In this region, the solid behaves as an elastic body.

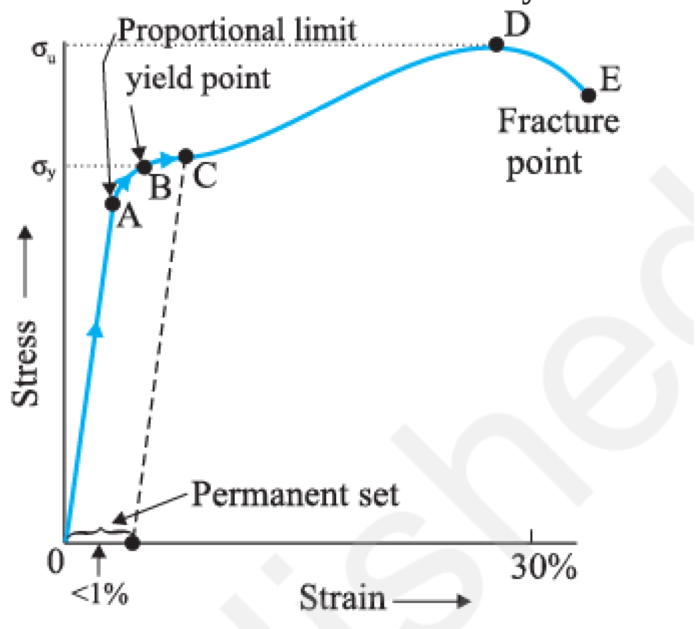


Fig. 2 A typical stress-strain curve for a metal.

In the region from A to B, stress and strain are not proportional. Nevertheless, the body still returns to its original dimension when the load is removed. The point B in the curve is known as yield point (also known as elastic limit) and the corresponding stress is known as yield strength (σ*y*) of the material.

If the load is increased further, the stress developed exceeds the yield strength and strain increases rapidly even for a small change in the

stress. The portion of the curve between B and D shows this. When the load is removed, say at some point C between B and D, the body does not regain its original dimension. In this case, even when the stress is zero, the strain is not zero. The material is said to have a permanent set. The deformation is said to be plastic deformation. The point D on the graph is the ultimate tensile strength (σu) of the material.
Beyond this point, additional strain is produced even by a reduced applied force and fracture occurs at point E. If the ultimate strength and fracture points D and E are close, the material is said to be brittle. If they are far apart, the material is said to be ductile.
As stated earlier, the stress-strain behavior varies from material to material. For example, rubber can be pulled to several times its original length and still returns to its original shape.
Fig. 3 shows stress-strain curve for the elastic tissue of aorta, present in the heart. Note that although elastic region is very large, the materialdoes not obey Hooke's law over most of the region. Secondly, there is no well defined plastic region. Substances like tissue of aorta, rubber etc. which can be stretched to cause large strains are called elastomers.

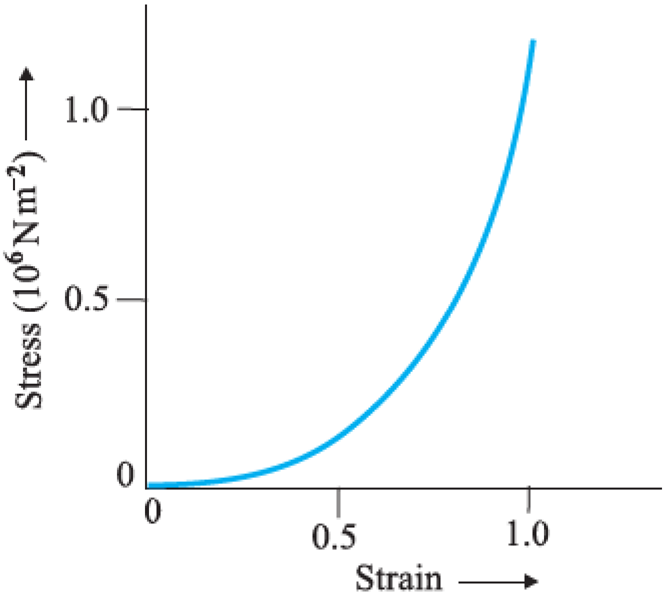


Fig. 9.4 Stress-strain curve for the elastic tissue of Aorta, the large tube (vessel) carrying blood from the heart.

ELASTIC MODULI

The proportional region within the elastic limit of the stress-strain curve (region OA in Fig. 2) is of great importance for structural and

manufacturing engineering designs. The ratio of stress and strain, called modulus of elasticity, is found to be a characteristic of the material.

$$\text{Elastic modulus} \equiv \frac{\text{stress}}{\text{strain}}$$

Deformation types and define an elastic modulus

1. **Young's modulus, which measures the resistance of a solid to a change in its length.**

$$Y = \frac{\sigma}{\varepsilon} = \frac{F/A}{\Delta L/L_0}$$

2. **Shear modulus, which measures the resistance to motion of the planes within a solid parallel to each other.**

$$Y = \frac{\sigma}{\varepsilon} = \frac{F/A}{\Delta x/h}$$

3. **Bulk modulus, which measures the resistance of solids or liquids to changes in their volume.**

$$Y = \frac{\sigma}{\varepsilon} = -\frac{\Delta F/A}{\Delta V/V_i} = -\frac{\Delta P}{\Delta V/V_i}$$

- **A negative sign is inserted in this defining equation so that Y is a positive number. This maneuver is necessary because an increase in pressure (positive ΔP) causes a decrease in volume (negative ΔV) and vice versa.**

Example1: Assume a leg has a 1.2m shaft of bone with an average cross sectional area of 3 cm^2. What is the amount of shortening when all of the body weight of 700 N is supported on this leg?

Solution: $\Delta L = LF/AY$ = (1.2 m)(7 × 10^2 N) / (3 × 10^{-4} m^2)(1.8 × 10^{10} N/m^2)

= 155.5 × 10^{-4} m = 15 mm.

***Example1*:If a compressive force of(3×10^4N) is exerted on the end of(20cm) bone ,of cross-section area (3.6cm^2),find if the bone will break and or the deformation in bone is(77×10^8N/m^2)** and Y0nug's modulus of bone =1.5×10^{10}N/m^2)?

Solution:

Stress developed in **bone is** $\sigma = \frac{F}{A} = \frac{3\times10^4}{3.6\times10^{-4}} = 8.33 \times 10^7 \frac{N}{m^2}$

σ < compressive strengthen of bone ‹it will not break

deformation in bone is Δl than we use :

$$y = \frac{stress}{strain} = \frac{\sigma}{\frac{\Delta l}{l}} =$$

$$\Delta l = \frac{\sigma l}{y} = \frac{8.77 \times 10^{7} \times 0.2}{1.5 \times 10^{10}} = 1.11 \times 10^{10} m = 1.11 mm$$

Measurement of Bone Mineral in the Body

The strength of bone depends to a large extent on the mass of bone mineral present. The most striking feature in osteoporosis is the lower than normal bone mineral mass which decreases very slowly, 1 to 2 % per year. Determination bone mineral mass by measuring such very slow rate of charge requires a very precise technique. The following methods of measurement are applied at present: Osteoporosis: lower bone mineral mass which **Decreases slowly, 1 to 2% per year**

1-X-ray film densitometry

2-Photon absorptiometry (Scintillation detector)
3-Mono energetic x-ray or gamma ray

Problems in measuring bone mineral mass using conventional x-ray
. X-ray beam has many different energies and x-ray absorption by calcium changes with x-ray energy
. X-ray scattering
.Film is a poor detector with nonlinear characteristics
: bone mineral mass (BM) = k $\log(I_0/I)$, g/cm2