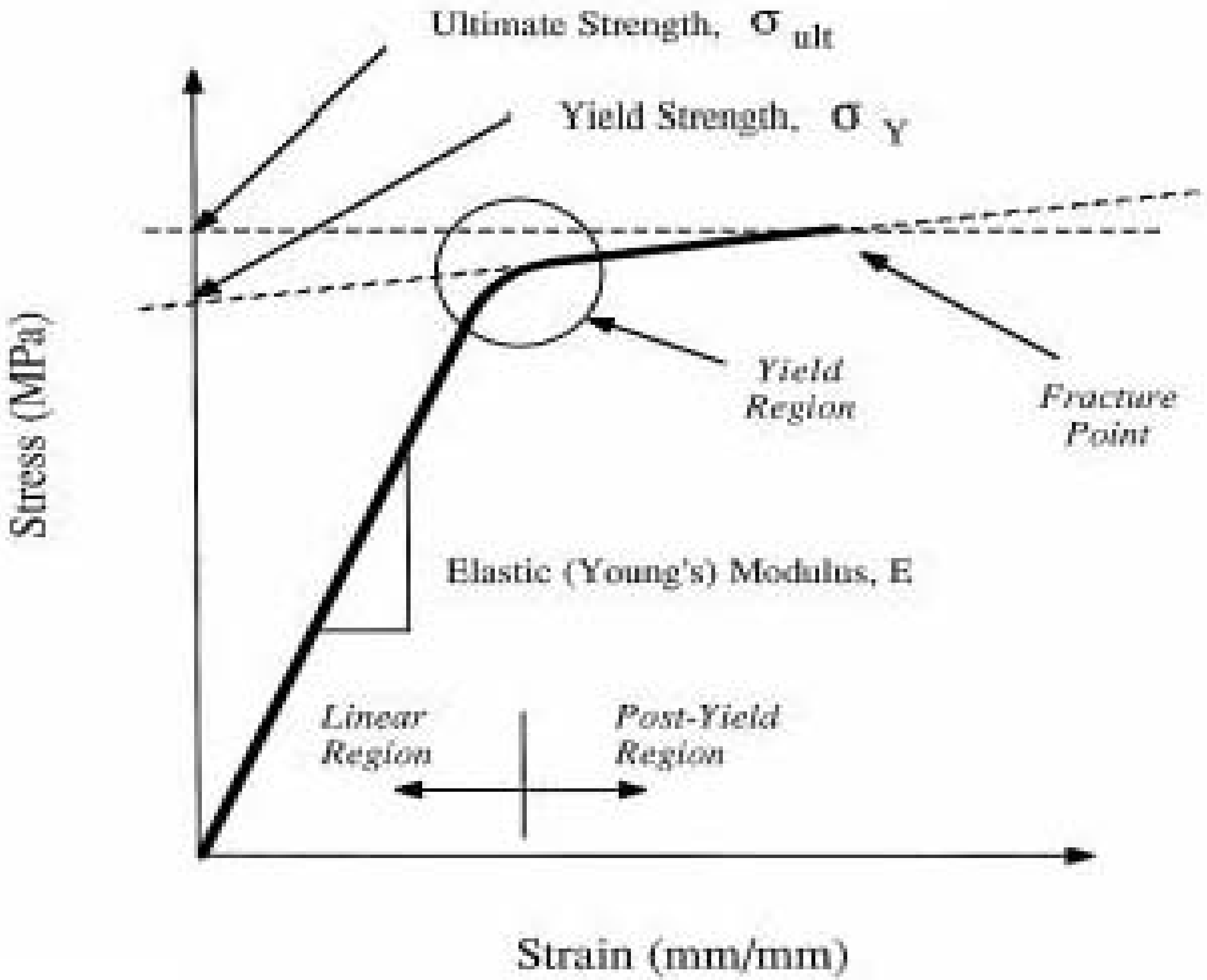
Mechanical Behavior of the Skeleton
&
Measuring Strains in Bones

Definitions

- **Strength**
  - Load at the failure point
- **Stiffness or rigidity**
  - Load required to deform the bone by a given amount
  - Slope of the load-deformation curve

Definitions

- **Toughness**
  - Work or energy required to yield or fracture the structure
- **Poisson’s ratio**
  - How much a material bulges when compressed
  - Or how much a material contracts when stretched



Stress Strain Curve

Stress Strain Curve

- 3 region
  - Initial linear region
  - Yield region
  - Post-yield region
- The modulus is the slope of the linear region
- Strength properties are obtained from the yield and post-yield regions

Stress Strain Curve (cont'd)

- Yielding
  - Onset of permanent deformation
  - At the junction of the linear and post-yield regions
  - Yield strength $ó_y$
    - Microstructural damage starts to occur
- Fracture occurs when the ultimate strength $ó_{ult}$ is reached.

Mechanical Properties

- Elastic Behavior
- Strength
- Energy Absorption, Ductility and Brittleness
- Viscoelastic Behavior
- Strain Rate Sensitivity
- Creep Behavior

Energy Absorption, Ductility and Brittleness

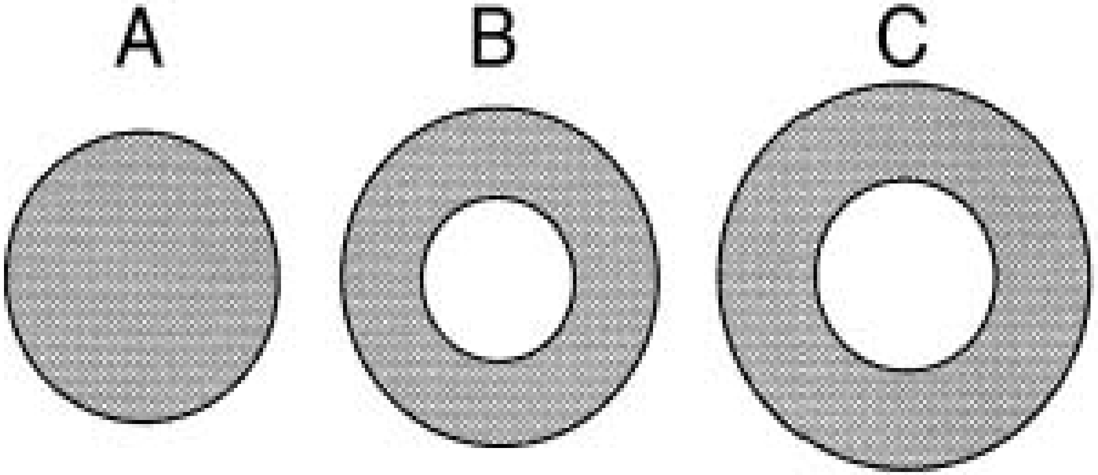
- If energy delivered to the bone is greater than the energy the bone can absorb
  - Fracture occurs
- For both tensile and compressive loading in the longitudinal direction
  - Ultimate strains >>> yield strains
  - Substantial energy before fracture

Energy Absorption, Ductility and Brittleness (cont’d)

- For longitudinal loading
  - Ultimate strain strength is larger than yield strain
  - Relatively ductile
- For transverse loading
  - Lowest resistance
  - Ultimate strain is close to the yield strain
  - Relatively brittle

Mechanical properties (contd)

- Tensile strengths in primary bone
  - Longitudinal (X3)
  - Circumferential (X1)
  - Radial directions (0.4)



Area (cm^2)	2.77	2.85	3.09
Relative axial strength	1.00	1.03	1.11
Moment of inertia (cm^4)	0.61	1.06	1.67
Relative bending strength	1.00	1.49	2.05

Rate of Deformation

- Cortical bone
  - Viscoelastic material
  - Stronger, stiffer and more brittle as strain rate increases
- Hypothesis
  - Viscoelastic nature of the bone helps in damping out muscle contracture

Mineralization

- The amount of mineral per unit volume of whole bone
- It is a function
  - Porosity
  - Mineralization of the organic matrix
- Specific Mineralization
  - The amount per volume of bone matrix, exclusive of the volume of the void spaces in the structure

Mineralization (cont'd)

- Volumetric and a specific mineralization deficit
  - Increased rate of bone turnover
  - Increased sigma period
- Reduced mineralization
  - Lengthening of the Osteonal refilling period
  - Metabolic bone diseases like rickets or osteomalacia.

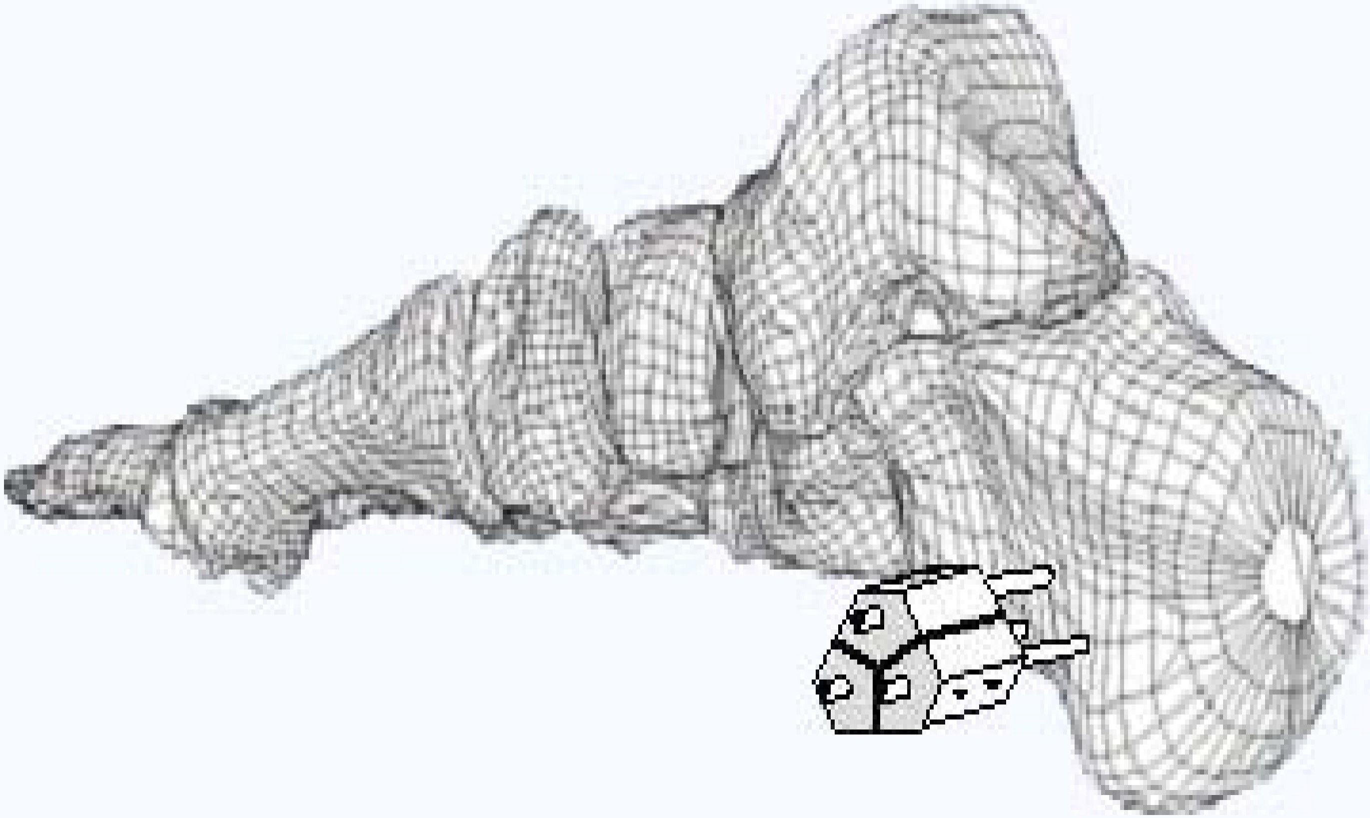
Factors important in mechanical adaptation

- Strain mode
  - Tension, compression or shear
- Strain Direction
  - The principal directions of strain relative to the bone surface
- Strain rate
  - The rate at which bone is deformed
- Strain frequency
  - The number of deformation cycles/second

Factors important in mechanical adaptation (cont'd)

- Stimulus duration
  - The period over which deformation cycles are applied
- Strain distribution
  - The pattern of strain magnitude across the bone section
- Strain energy
  - The elastic energy stored in bone during deformation

Measuring Strains In Vivo



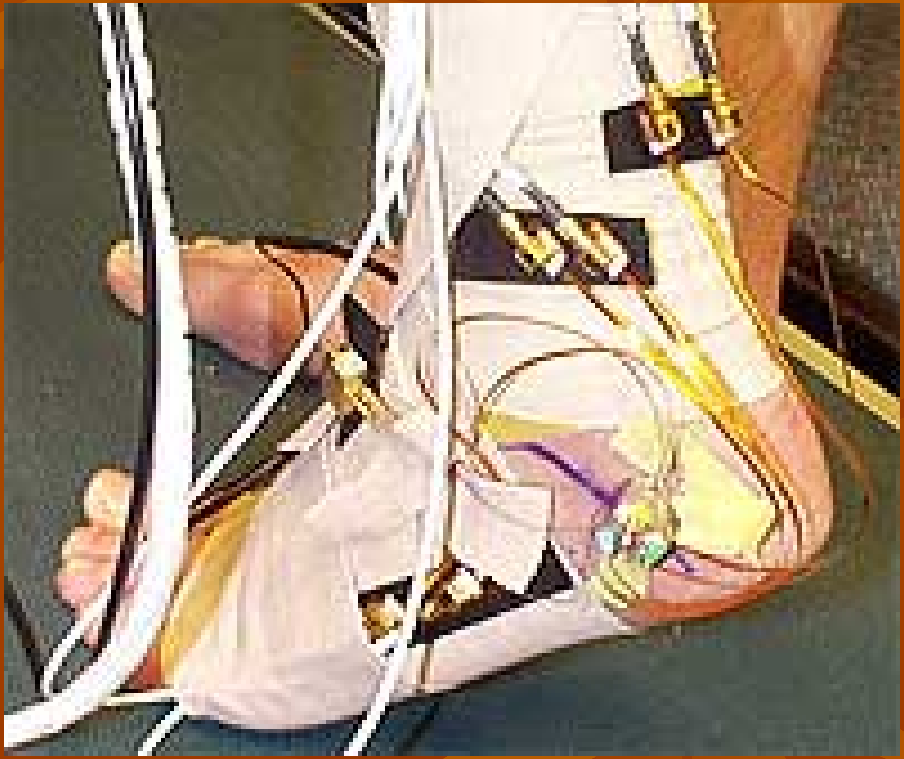
Multi-Axial Bone Extensometer (Lerner Research Institute)

Measuring Strains In Vivo

- Strains experienced during normal daily activities directly relate to
  - Study of age related bone loss
  - Post-menopausol osteoporosis
  - Fracture healing
  - Disuse osteoporosis

Measuring Strains In Vivo (cont'd)

- **Purpose**
  - Measure
    - physiological bone strain magnitudes (4000 με and above)
    - Strain rates (30,000 με /sec or more)



Measuring Strains In Vivo (cont'd)

Measuring Strains In Vivo (cont'd)

Method :

- Three stainless steel pins
  - 1.57-mm diameter
  - Implanted approximately halfway through the lateral side of the left calcaneus
- Acrylic bodies with capacitive sensors and target surfaces were attached to the protruding end of the intracortical pins

Measuring Strains In Vivo (cont'd)

- Data was collected and processed
  - LabVIEW data acquisition program (National Instruments, Austin, TX)
- Activities ranging from standing to running on a treadmill
- Recording the displacement changes from the initial position of the endpoints (three total displacements) of the protruding rods to their positions in periods of stress. This data yielded three strains

Measuring Strains In Vivo (cont'd)

Results :

- For standing with weight on both feet
  - Principal compressive strain angle at the surface of the lateral aspect of the calcaneus = 141.6 +/-0.8° from the horizontal X-axis
- Walking trial (at 5 km/hr)
  - Range of angles from 142° to 149°

Measuring Strains In Vitro

- Differential Variable Reluctance Transducer ("half bridge LVDT")
  - www.microstrain.com

The End

Strain Mode

- Frost’s Three Way Rule
  - To determine where bone formation and bone resorption will occur
  - Based on the magnitude of strain and the strain mode.
- Minimizing tensile strains produced by bending
  - Reduces the need for Osteonal remodeling within the tensile cortices
- Compressed cortices remodeling
  - Greater rate than tensile cortices

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Strain Direction

- Beneficial for osteons to be aligned with the principal loading direction
- Alter interlamellar shear forces
- Alter forces between the osteon and the interstitial matrix
- Planes of minimum shear strain
    - Aligned with the principal directions of strain

Strain Direction (cont’d)

- Plane of maximum shear strain
  - Aligned at 45^{o} to the principal direction of strain
- Reduces the shear strain
  - In the cement line
- Reduces fatigue damage

Strain Rate

- Haversian remodeling
  - Not related to strain rate associated variables
  - Adaptations to strain rate cannot occur by additional filling of Haversian canals to decrease porosity.
  - Accomplished by expansion of cortex

Strain Frequency

- Repetitive strains
  - Promote net bone formation
- Fatigue life increases significantly as the strain frequency increases over 15 Hz

Stimulus Duration

- Vigor of bone response
  - Not enhanced by additional loading cycles
  - Magnitude is not dependent on stimulus duration
- First few cycles of the load
  - Provide the stimulus to initiate bone adaptation
- Some other factor may control the magnitude or rate of the response

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Strain Distribution

- Strain required to elicit an adaptive response may be lower if the manner of loading is different from the usual pattern of loading.
- Bone is adapted to a range of strain situations
- Adaptive responses are more easily generated
  - Variety of different loading conditions
  - Not by increased repetitions of the normal pattern of loading

Strain Energy

- Scalar rather than a tensor
- Always positive regardless of whether loads are tensile or compressive
- These characteristics implies that strain energy is a simpler variable than strain and so a more tractable signal. Hence not much information is known about it
- Hypothesized that it is the controlling variable for bone density

8mm Stroke Subminiature DVRT
www.microstrain.com

Differential Variable Reluctance Transducer

Description

- Features:
  - Outside body diameter of 4.76mm
  - Smaller body length to stroke ratios
  - Hermetic packaging
  - High temperature options (up to 175 deg. C)
  - Resolution of 0.16 microns (-3dB @ 1KHz

Differential Variable Reluctance Transducer (cont’d)

- Two coils
  - Measure the linear movement of a ferrite core
- Core position is detected
  - By measuring the coils' differential reluctance
    - Using a sine wave excitation
    - Synchronous demodulator
    - Cancels out temperature effects
- Coils and flex circuit leads
  - Sealed in vacuum pumped epoxy
  - Within the stainless steel case
  - The flex circuit is covered by a polyurethane sheath for strain relief

Elastic Behavior

- Anisotropic material
  - Deformation is dependant on the loading direction
- Elastic properties of cortical bone
  - Cortical bone has a longitudinal symmetry
    - osteonal microstructure
- Loads applied perpendicular to the longitudinal axis
  - Approximately isotropic
  - Substantially different from loads in the longitudinal direction
    - Parallel to the axis of the osteons

Elastic Behavior (cont'd)

- Human cortical bone usually is considered to be a transversely isotropic material
- Transverse isotropy is a subset of anisotropy
- Elastic properties of an isotropic material
  - Young's modulus
  - Poisson's ratio

Elastic Behavior (cont'd)

- The modulus of cortical bone in the longitudinal direction
  - Approx. 1.5 times its modulus in the transverse direction
  - Over 5 times its shear modulus
- Relatively high Poisson's ratios (0.6)
  - Indicate that cortical bone bulges more than metals when subjected to uniaxial compression

Strength

- Depend on the loading direction
  - Transversely isotropic
- Depends on type of loading
  - Tension
  - Compression
  - Torsion
- Hence asymmetry in the strength properties

Strength (cont'd)

- Typical stress-strain curves
  - For uniaxial, monotonic tension
  - Compression loading of cortical bone
  - Both in the longitudinal and transverse directions
  - Bone is stronger in compression than in tension

Strength (cont’d)

- Longitudinal loading
  - Tensile strength is ~ 130 MPa
  - Compressive strength is ~190 MPa
- Transverse loading
  - Tensile strength is ~ 50 MPa
  - Compressive strength is ~ 130 MPa
- Tensile and compressive yield strengths are approximately equal to the respective ultimate strengths
- Maximum stresses that bone can sustain are close to its yield strength

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Viscoelastic Behavior

- Cortical bone displays viscoelastic behavior
- Mechanical properties are sensitive to both
  - Strain rate
  - Duration of the applied loads

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Strain Rate Sensitivity

- Strain rate increases as activity becomes more strenuous
- The increase in the initial slope of the stress strain plot
  - Higher modulus at higher strain rates
- Yield and ultimate strengths increase as the strain rate increases
  - Stronger and stiffer for more strenuous activity

Strain Rate Sensitivity (cont'd)

- At high strain rates
  - Greater than 0.1 per second
  - High-impact trauma
  - More brittle as ultimate strain decreases for loading in the longitudinal direction
- Ductile to brittle transition as the strain rate increases

Strain Rate Sensitivity (cont'd)

- For the range of strain rates typical of more normal activity
  - Less than 0.1 per second
  - Ductility increases as ultimate strain increases as the strain rate increases
- Optimal range of strain rates for maximum energy absorption
  - 0.01 to 0.1 per second

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Creep Behavior

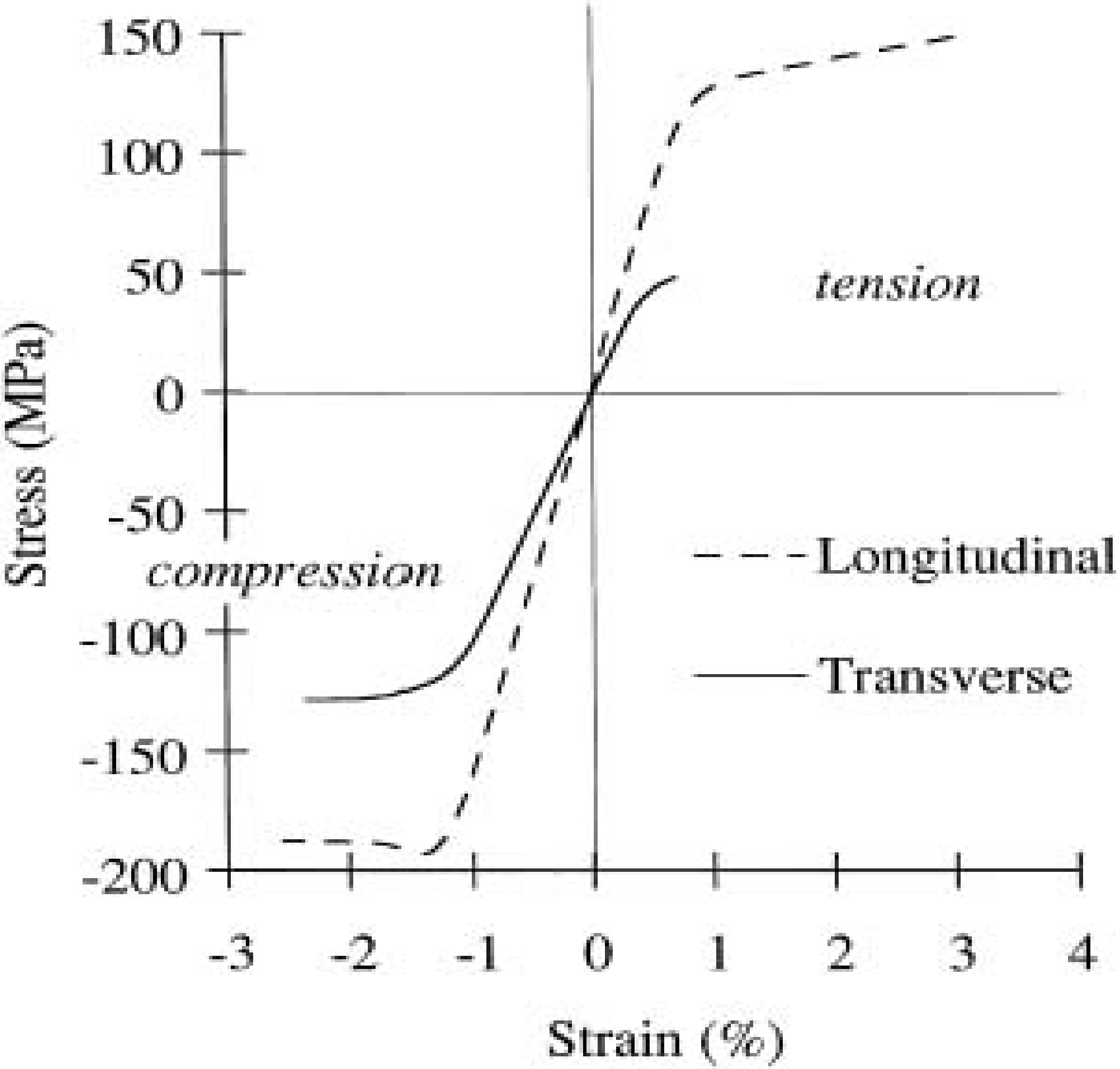
- Deformation that occurs due to a constant load for a period of time
  - Bone will continue to deform
- Creep curve for tensile loading
  - Strain as a function of time for a constant stress level

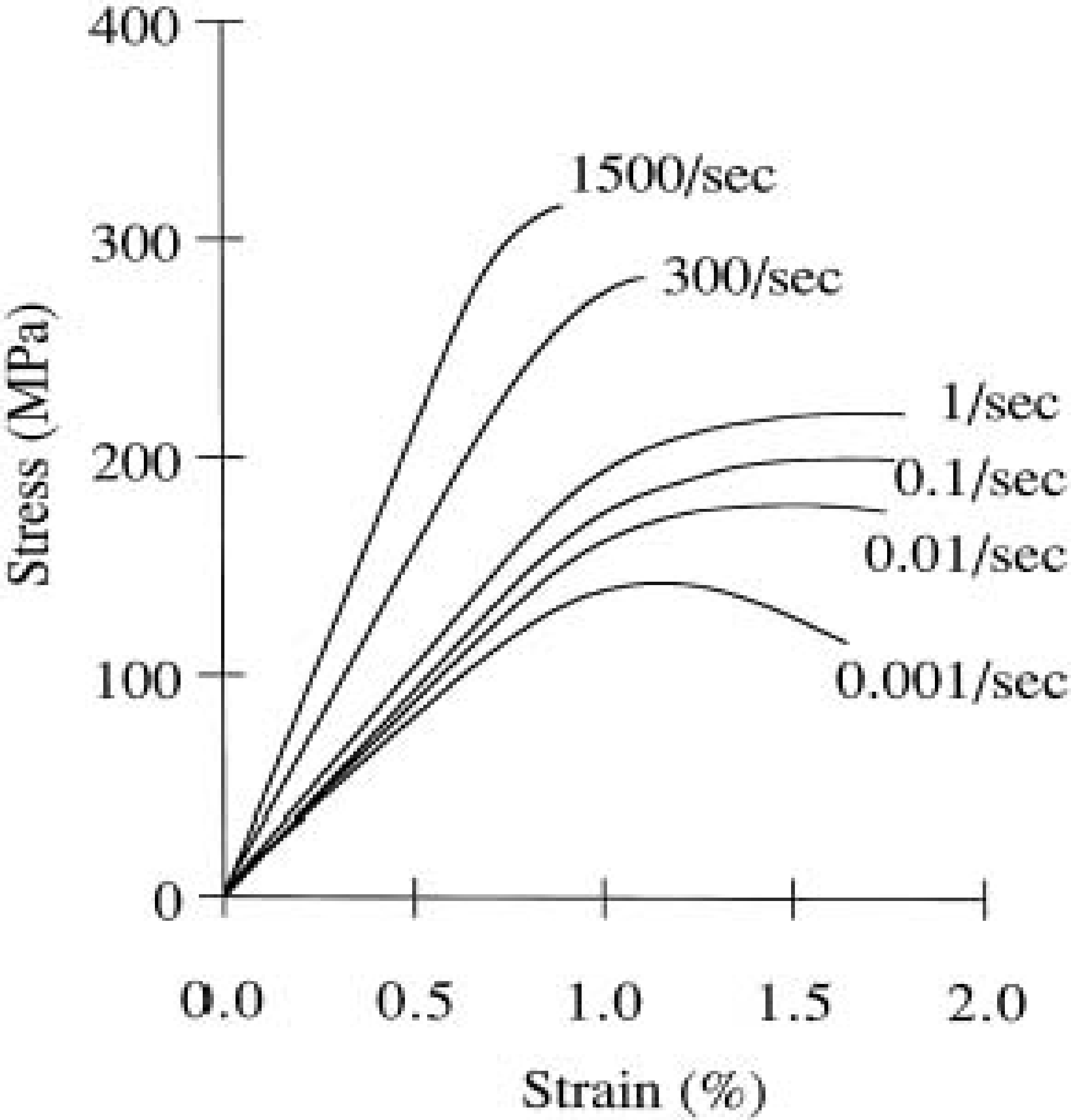
Creep Behavior (cont'd)

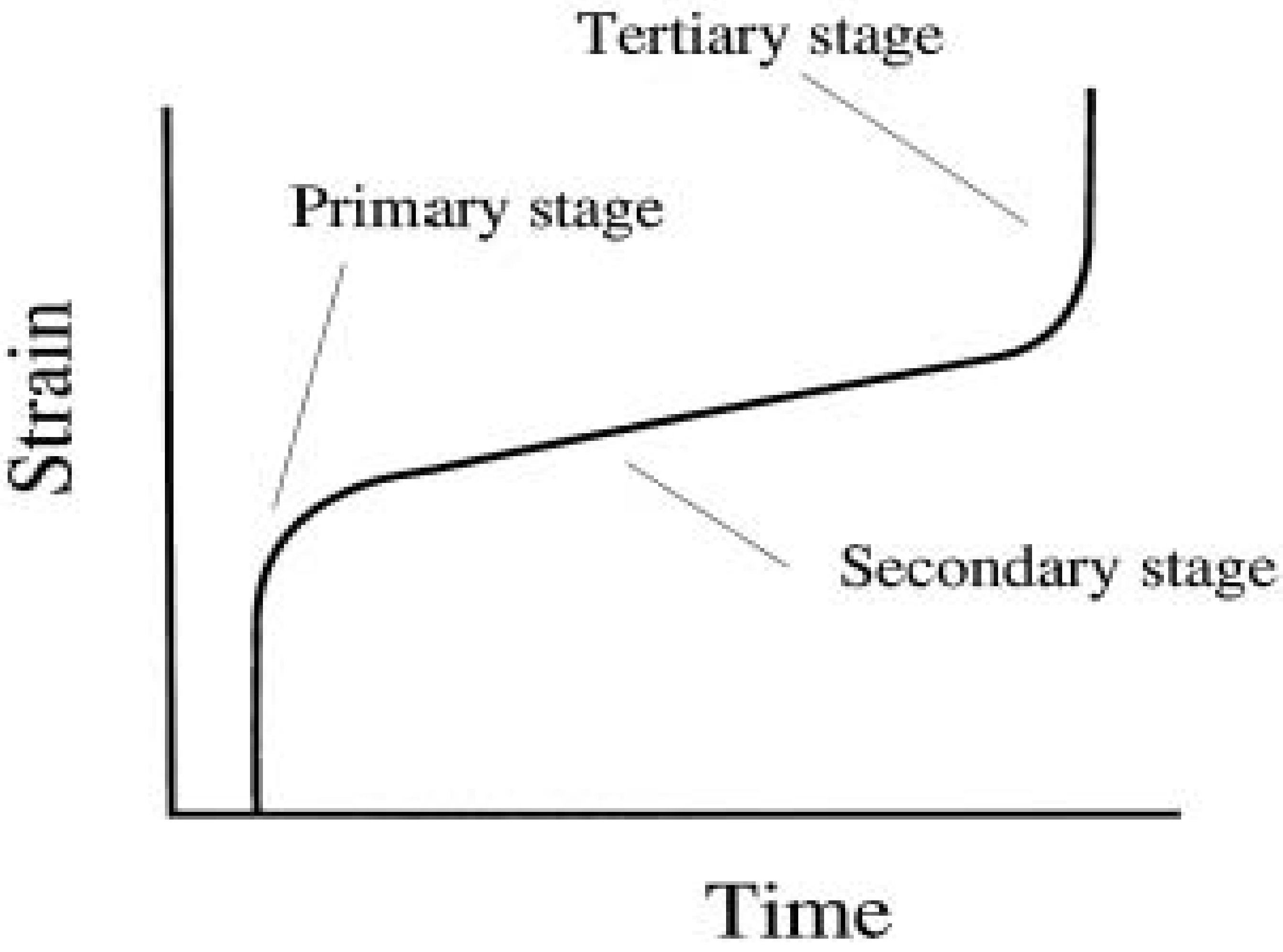
- Primary stage
  - Specimen strain continues after loading
  - Creep rate gradually decreases
- Secondary stage
  - Lower, usually constant creep rate
- Tertiary stage
  - Increase in the creep rate just before creep fracture

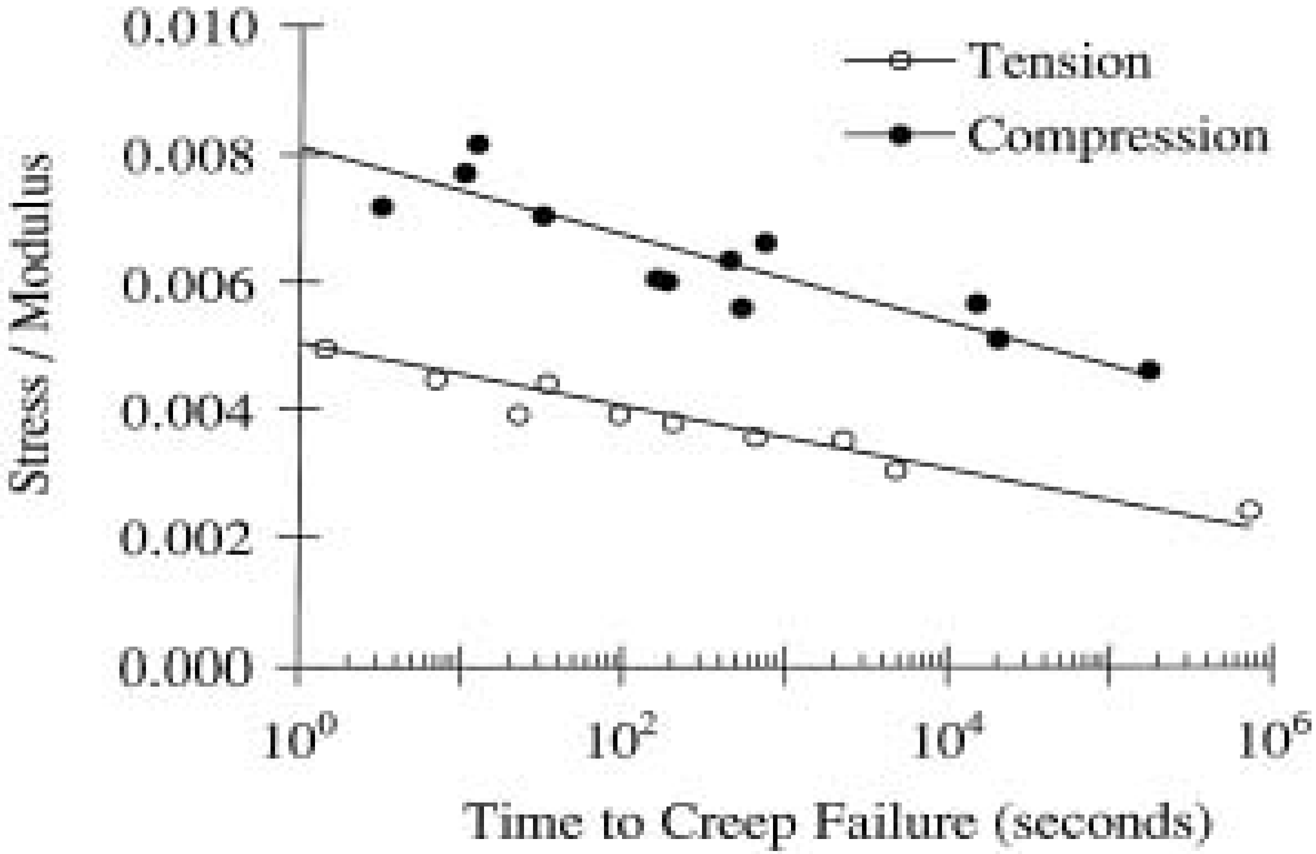
Creep Behavior (cont'd)

- Sometimes creep fracture will occur
  - Loaded at certain levels for enough time
  - Although the stress level is well below the yield and ultimate strengths
- Resistance is greater for compressive than for tensile loading
- Viscoplastic behavior
  - ***Visco*** from the creep behavior during loading
  - ***Plastic*** from the permanent deformation after unloading


150
100
50
0
-50
-100
-150
-200
Stress (MPa)
-3
-2
-1
0
1
2
3
4
Strain (%)
tension
compression
Longitudinal
Transverse


400
300
200
100
0
Stress (MPa)
1500/sec
300/sec
1/sec
0.1/sec
0.01/sec
0.001/sec
0.0
0.5
1.0
1.5
2.0
Strain (%)


Tertiary stage
Primary stage
Secondary stage
Strain
Time


0.010
0.008
0.006
0.004
0.002
0.000
Stress / Modulus
Tension
Compression
10^0
10^2
10^4
10^6
Time to Creep Failure (seconds)