

Bone Mechanics

Elastic Behavior

Bone as a Material

- ◆ What is the biggest difference between bone and other engineering materials?

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- ◆ What is the biggest difference between bone and other engineering materials?
 - Properties vary based on:
 - ◆ Anatomical function (location)
 - ◆ Age
 - ◆ Disease
 - ◆ Use!!!

Bone as a Material

- ◆ When discussing “bone properties,” what clarification should you make in terms of material type?

Mechanical Behavior of Cortical Bone

- ◆ What do you notice about Figure 3 in Natali and Miroi?

Mechanical Properties of Cortical Bone

- ◆ Are there differences in tensile and compressive Young’s modulus?
 - Dempster and Liddicoat (1952) - Yes
 - ◆ $E_T = 14.1 \text{ GPa}$
 - ◆ $E_C = 8.69 \text{ GPa}$
 - Reilley and Burstein (1975) - No
 - ◆ $E_T \text{ or } E_C = 17.1 \pm 3.1 \text{ GPa}$

Mechanical Properties of Cortical Bone

- ◆ Poisson's Ratio
 - 0.08 - 0.45 (Ko, 1953)

Anatomical Variation in Bone Properties

- ◆ Natali and Miroi
 - Tibia variations:
 - ◆ 1 = posterior
 - ◆ 3 and 4 = anterior
 - Femur
 - ◆ $E_{ML} > E_{AP}$
 - ◆ Why?

Elastic Models of Cortical Bone

- ◆ Assuming Orthotropy - Dempster and Liddicoat (1952)
 - Longitudinal: $E_C = 8.69$ GPa
 - Radial: $E_C = 3.76$ GPa
 - Circumferential: $E_C = 4.19$ GPa
- ◆ What simplification do these results indicate may be reasonable?

Orthotropic Models of Cortical Bone

◆ Nine constants (assume 3 = longitudinal direction)

- E_1, E_2, E_3
- G_{12}, G_{23}, G_{31}
- $\nu_{12} = \nu_{21}, \nu_{23} = \nu_{32}, \nu_{31} = \nu_{13}$

Orthotropic Model of Cortical Bone

$$[S_{ijkl}] = [C_{ijkl}]^{-1} = \begin{bmatrix} 1/E_1 & -\nu_{21}/E_1 & -\nu_{31}/E_1 & 0 & 0 & 0 \\ -\nu_{12}/E_2 & 1/E_2 & -\nu_{32}/E_2 & 0 & 0 & 0 \\ -\nu_{13}/E_3 & -\nu_{23}/E_3 & 1/E_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{31} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{bmatrix}$$

Transversely Isotropic Model of Cortical Bone

◆ 5 independent elastic constants:

- $E_1 = E_2$
- E_3
- $\nu_{31} = \nu_{32}$
- ν_{12}
- $G_{31} = G_{32}$
- $G_{12} = E_1/[2(1 + \nu_{12})]$

Elastic Models of Cortical Bone

◆ Data ranges from Natali and Miroi:

- E_1 : 6.91 - 18.1 GPa
- E_2 : 8.51 - 19.4 GPa
- E_3 : 17.0 - 26.5 GPa
- G_{12} : 2.41 - 7.22 GPa
- G_{13} : 3.28 - 8.65 GPa
- G_{23} : 3.28 - 8.67 GPa
- ν_{ij} : 0.12 - 0.62

Determination of Mechanical Properties

◆ The high standard deviations in property values seen in bone are not necessarily (although may possibly be) due to experimental error

- E: 15%
- ν : 30%
- G: 10%

Elastic Behavior of Trabecular Tissue

◆ What do you notice from Figure 1 of Linde?

Elastic Behavior of Trabecular Tissue

- ◆ What do you notice from Figure 2 of Linde?

- ◆ How do Figures 1 & 2 possibly change your interpretation of bone as an elastic material?

Mechanical Properties of Trabecular Tissue

- ◆ $E = 12 - 1080 \text{ MPa}$
 - How does this compare to cortical bone?
- ◆ $\nu = 0.01 - 0.64$
- ◆ Expect T-I or orthotropic behavior
 - Based on structural anisotropy
- ◆ Bone is extremely inhomogeneous
 - Up to 100% variation in apparent density (density of bone per overall unit volume) in adjacent iliac biopsies

Orthotropic Models of Trabecular Bone

- ◆ Elastic constants characterized analytically
- ◆ What can we see from Figures 15.4 and 15.5 in vanRietbergen and Huiskes?

Trabecular Properties and Bone Structure

- ◆ Why are trabecular tissue properties so dependent on bone structure?

Trabecular Tissue Properties and Bone Structure

- ◆ E and G vs. bone density
 - $R^2 = 0.70$ (E) and 0.80 (G)
- ◆ When structural assessment (MIL) is included, correlations improve significantly (Fig 15.7, vanRietbergen and Huiskes)

Mechanical Properties of Trabecular Material

- ◆ Determined using micromechanical tests and analytical methods
 - $E = 1 - 20$ Gpa
- ◆ Generally assumed to be isotropic -- why?
- ◆ Is variation due to:
 - 1) test method?
 - 2) normal biological variation?
 - 3) level of structural organization being tested?

Experimental Testing

- ◆ Why must we consider the effects of testing methods?

Experimental Testing

- ◆ Why must we consider the effects of testing methods?
 - No standards for testing
 - ASTM standards are often not applicable
 - ◆ Sample size
 - ◆ Sample preparation

Experimental Testing

- ◆ How do experimental conditions affect measured properties?

Experimental Testing - Storage

- ◆ Preferred methods:
 - Freezing
 - Ethanol + saline
- ◆ What are effects of formaline or drying?

Experimental Testing - Hydration

- ◆ Bone should be tested in fully hydrated condition
 - What is the effect of retaining bone marrow in trabecular specimens?
- Can soaking bone return its properties to *in vivo* levels?

Experimental Testing - Temperature

- ◆ Results at body temperature (37 C) show slightly lower E and than at room temperature (22 C).
 - 2 - 4% difference
 - Why?

Trabecular Stress

- ◆ How will trabecular stresses compare to apparent stresses?
- ◆ What errors will be induced by making this simple calculation of trabecular stress vs. a more complete analysis?

Experimental Testing

- ◆ To characterize a T-I material, need to conduct 2 axial tests (tension or compression) and 1 shear test
- ◆ Tests on multiple specimens may have issues with inhomogeneity of bone
- ◆ Can tests be done non-destructively on a single specimen of bone?
 - Do properties change after loading?
 - Can the same sample type and size be used?

Experimental Testing

- ◆ Ultrasonic tests can be done on a single specimen
 - Measure E's and G's, not ν 's
- ◆ What may be a problem in comparing ultrasonic test results to traditional test results?
