AC 2007-2340: ELASTIC MODULUS OF BONE USING ULTRASONIC TESTING

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I. Background

In 2003, a slow loop assessment of the mechanical engineering curriculum at the United States Military Academy at West Point was conducted to determine whether the objectives of the mechanical engineering program conformed to the ABET Accreditation standards of "keeping abreast with current technology." As a result of this slow loop assessment, the Dean of the Academic Board approved a comprehensive change to the mechanical engineering program, incorporating additional disciplines in the biological sciences, mechatronics, energy systems, and systems engineering. Furthermore, in order to continually teach the recent technological advances in society, a slow loop assessment was also conducted in each of the courses taught in the mechanical engineering program. As a result, the Engineering Materials course at West Point incorporated the study of newer classes of materials such as biomaterials, nanotechnology (nanoelectromechanical systems – NEMS), and smart materials (piezoelectric materials, shape memory alloys, and electrorheological fluids). In the biomaterials block of instruction, a new laboratory exercise was devised and incorporated to provide the students exposure to contemporary methods in measuring mechanical properties of biological tissue. Thus, this exercise tasked the students to measure the elastic modulus of a cow femur using ultrasound technology.

The primary learning objectives of this laboratory exercise were (1) to determine the elastic constants of a biologic composite material using an ultrasonic method. (2) To gain an appreciation for why natural materials are nearly always composite, and (3) to discuss how medical devices may influence the material due to load sharing considerations.

II. Conduct of the Laboratory

In order to prepare for the laboratory exercise, two samples of cow femurs were purchased along with approximately one gallon of acetic acid (distilled vinegar). Three cross-sectional disks 1 cm thick were cut from the cow femur (Disk 1) at the proximal end of the diaphysis (just inferior of the metaphysis towards the head of the femur), (Disk 2) the middle of the diaphysis, and (Disk 3) at the distal end of the diaphysis (just superior to the metaphysis towards the knee joint) (Figures 1 and 2). Each cross-sectional specimen was cut with a low-speed, diamond-tipped wafering saw (Buehler, Isomet 1000, Lake Bluff, IL) to ensure that the specimens were not damaged. The cross-sectional specimens were then cut in the cortical region (compact bone) to form one cubic centimeter specimens. It is important to mark the sections that are cut in order to maintain the proper coordinate system, which is a standard SAE system (long axis is z, front is x).   This could be done by dye or chamfering edges. Bone also varies in mechanical properties with each anatomic region. It can be instructive to students to keep track of where each bone block came from and have different groups compare results statistically. Each cross-sectional specimen yielded four (4) one cubic centimeter specimens positioned anteriorly, posteriorly, medially, and laterally. This same procedure was performed to the two other cross-sectional specimens to produce a total of twelve (12) one cubic centimeter specimens.

The discarded portions of the cow femur were then immersed into a bucket of acetic acid to decalcify the periosteum of the remaining diaphysis. This remaining diaphysis was immersed in the acetic acid for approximately 14 days.

During the laboratory exercise, each lab group of three students was provided a one cubic centimeter sample of the cortical layer of the cow femur. The students calculated the density of the cortical bone specimen by measuring the volume and weighing each specimen. Next, they ultrasonically measured (Panametrics-NDT EPOCH 4Plus, Olympus NDT, Waltham MA) the velocity of wave propagation through the specimen using a 2.25 MHz transducer. The laboratory groups measured the wave velocity in both the longitudinal and lateral directions of their specimens (Figure 2). Once the groups measured the ultrasonic wave velocity (micrometers/second) and density of their bone specimens, they used the following equation [1] to determine the elastic constants of the cow femur:
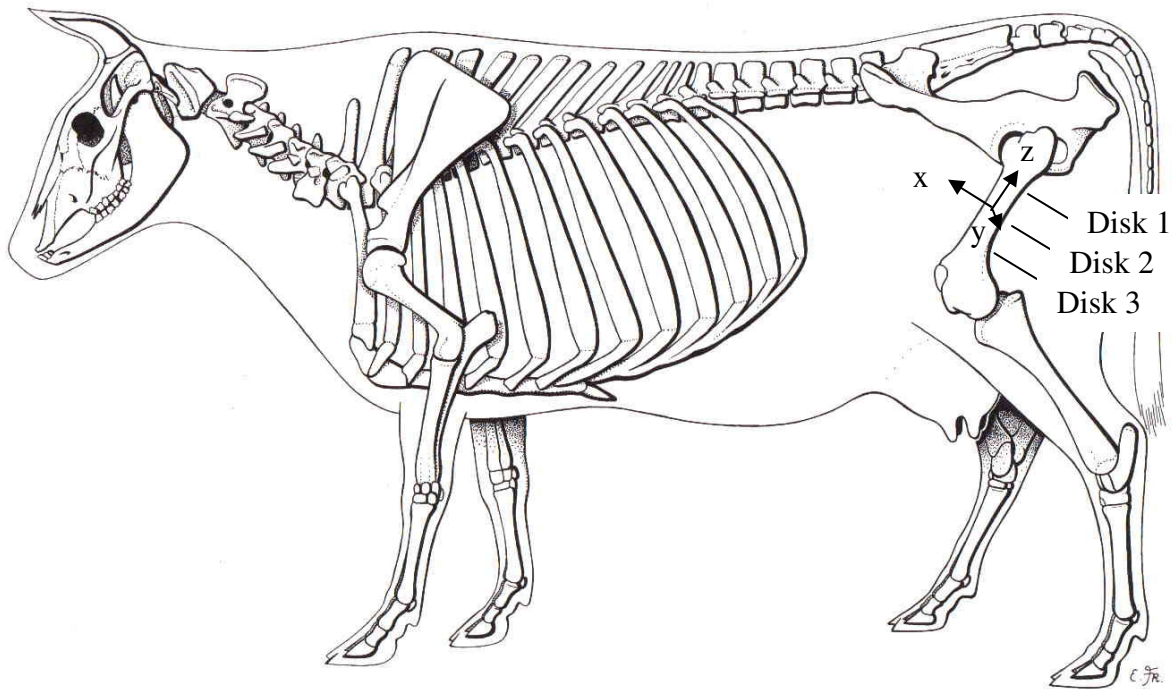
$$C_{ii} = \rho(V_{ii})^2 \tag{1}$$

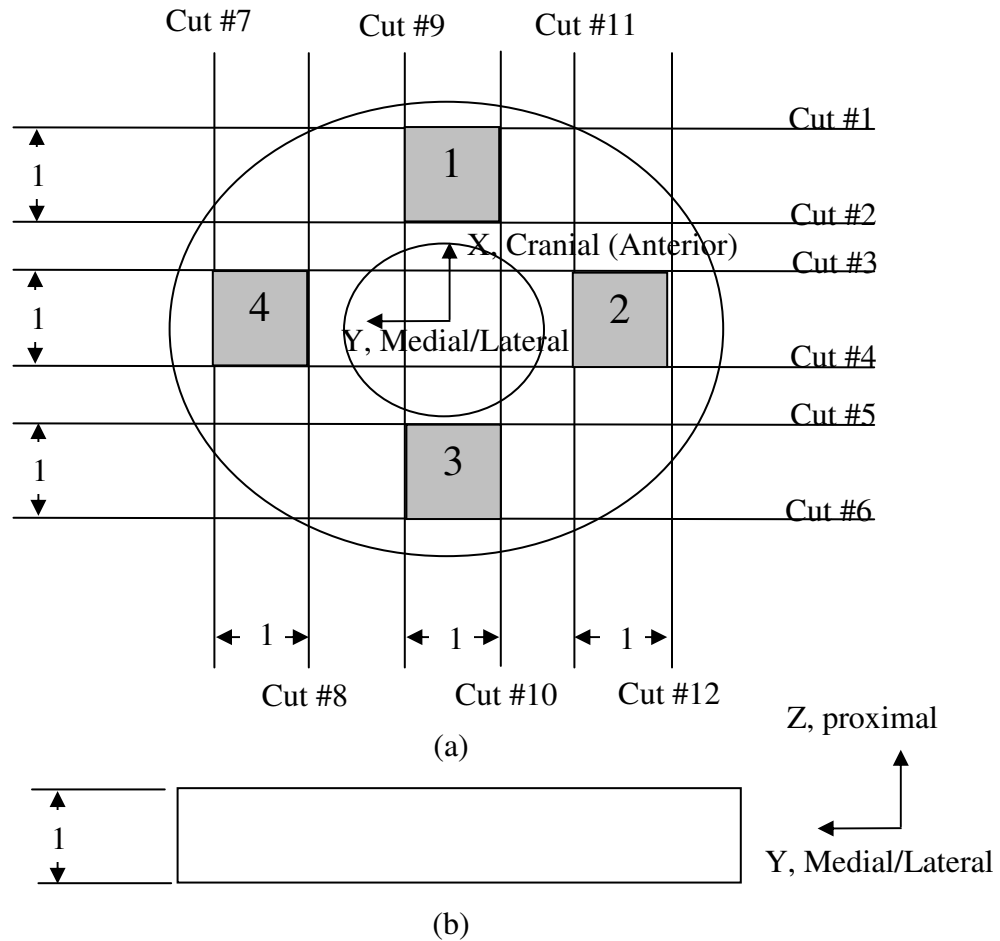**Figure 1:** Local coordinate system for the femur [2].

Figure 2: (a) Cutting sequence for creating 4 cubes of bone material. (b) Cross-section of one of the disks. Many one cm^3 disks could be created from one femur or tibia.

The elastic constants were calculated rather than Young's modulus because the material is anisotropic. Reference values for the elastic constants are readily available in the open literature and are well known for bovine cortical bone. Young's modulus and Poisson's ratio could be calculated; however, it would require that shear-wave velocity be measured in order to calculate all nine stiffness coefficients for an orthotropic material. This can be used as a teaching point to reinforce their understanding of composites and their appreciation of the complexity of biologic materials.
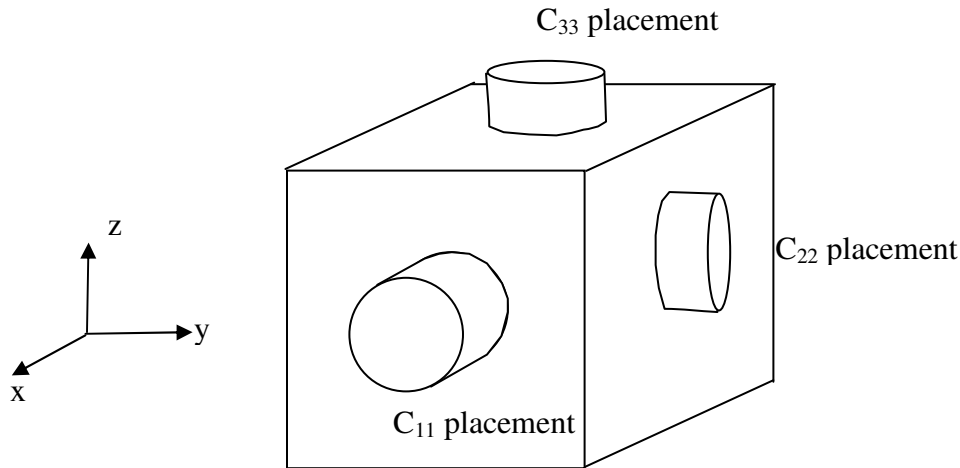
Figure 2: Placement of transducers for measurement of three elastic constants.

The next portion of the laboratory exercise required the students to analyze and palpate the remaining portion of the diaphysis which had been immersed in acetic acid for approximately 14 days. The composite nature of bone is demonstrated by removing the mineral phase and leaving the collagen.

III. Results

The measurement of the dynamic modulus of elasticity using ultrasound techniques correlated well with the reported values for the elastic modulus of a bovine femur. In most cases, only slight discrepancies were noted and the percent discrepancies between reported and the experimental values ranged from 5-10%. The large difference in elastic constants between the longitudinal and the lateral directions clearly demonstrated the anisotropic behavior of bone. The lateral direction's dynamic modulus of elasticity was nearly half of that of the longitudinal direction. This large disparity demonstrated that the bone has to be exhibit a larger modulus of elasticity in the direction of loading to withstand the compressive, shear and torsional stresses which are applied mainly along the axis of the diaphysis. The low modulus of elasticity in the lateral direction also demonstrated that the long bones in the body are not as rigid/stiff and are prone to break or fracture transversely through the cross-section of the bone. This is basically along the grain of the bone. This also explains the clever modeling of the bone in that it is thinner along the medial portion of the diaphysis since bones are usually not exposed to forces applied laterally to the long axis; this allows the body to not fabricate an "inefficient" bone of constant cross-sectional area which would be characterized by an excessive amount of weight and an excessive amount of strength/rigidity in a direction where loads are usually not applied (i.e. transverse direction). Therefore, the long bones in the body are ideally engineered to support compressive loads along the axis of the bone since the strength/rigidity in the
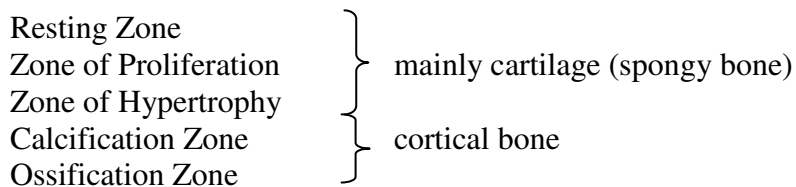
longitudinal direction is optimized. This was the most vital learning objective that the students learned from the laboratory exercise.

By examining the mineralized bone, students essentially expose the collagen and its properties are much like tendon. This easy accessibility to the composite structure helps students understand how a brittle material can serve as a primary structural member of the body and generally not break over the course of ones life. Osteogenesis imperfecta (commonly known as brittle bone disease) is a collagen defect and this portion of the lab exercise can be used to illustrate the role of collagen serves in enhancing fracture toughness bone.

This laboratory exercise also enabled the students to learn about the different regions of a long bone – the compact bone (cortical bone) and the spongy bone (cancellous or trabecular bone). They were able to easily identify these portions due to the distinct boundary observable from samples of cross-sectional specimens which had not been further cut to produce cubic centimeter cortical specimens.

IV. Reflections

After teaching the course and conducting the first iteration of the bone laboratory exercise, one of the primary faculty completed the 1st semester of medical school, and felt some additional changes could be made to the format of the biomaterials block by incorporating the study of cartilage and bone as a lead into the bone lab. If the students were able to learn about cartilage and the formation of cartilage from chondroblasts through appositional or interstitial growth, then they would be able to more clearly understand the development of bone from cartilage (via endochondral growth) or intramembranous growth (from connective tissue). The students would be able to then understand the the femur (a long bone) develops solely from endochondral growth and can see why trabecular and cortical regions develop from:

> Resting Zone
> Zone of Proliferation   } mainly cartilage (spongy bone)
> Zone of Hypertrophy
> Calcification Zone   } cortical bone
> Ossification Zone

In addition, we believe that the students could also be exposed to the different regions of the bone (diaphysis, metaphysis, epiphysis) and internal structures such as the epiphyseal plate (junction between epiphysis and metaphysis). The importance of this would be to illustrate that if the bone is broken at the epiphyseal plate in a patient at an early age, then the bone loses its ability to continue to grow via endochondral bone growth; the long bone will be noticeably shorter than its corresponding long bone located on the opposite side of the sagittal plane.

The focus of the biomaterials block seems to be focused in orthopedic applications and this makes sense since the majority of synthetically engineered biological structures pertain to this field (i.e. hip joint replacement, knee joint replacement, etc.). However, during the third class of the biological sciences block of instruction, it was felt that other aspects of biomaterials

should be emphasized such as the use of shape memory alloys (nickel-titanium alloys) in fabricating stents for implantation into the cardiovascular system.

The first class of the biomaterials block provided the students with a broad coverage of biomaterials such as the definition of a biomaterial, requirements for a biomaterial (such as biocompatibility), and a broad problem which enabled the students to apply their knowledge of fluid mechanics to model the turbulent flow of blood through an artery/vein by solving for the shear wall stress and normal stress. The students were thus able to relate engineering principles to biological systems. We believe that this class provided the students with a good introduction to biomaterials.

The second class taught at a very superficial level the body's immune system and how the immune system causes rejection of an implanted structure (excessive neutrophilic reactions which necrotize the surrounding tissue, thus loosening the implanted material, etc.). We believe that this is also vital for the students to learn during the biological systems block.

Because the laboratory objectives deal with experimental determination of mechanical properties and anisotropy, the techniques could easily be transferred to other composite structural materials, such as wood. In this case, blocks of wood could be created and the basic procedure of measuring the density and finding the velocity using ultrasonic transmission could be easily performed and Equation 1 would be valid. However, by not using bone, it would be more difficult to separate the basic structural components of the composite by function as it was with bone. If, for more advanced students, one wanted to calculate all nine orthotropic coefficients, it would be necessary to have shear wave transducers in addition to the standard axial wave transducers. The elastic modulus and major Poisson's ratio could be calculated from the elastic constants and might be a nice exercise for students. Adding that portion of the lab could help students appreciate the differences between isotropic materials and more complicated materials.

V. References

1. Rho, J.Y. (1996) An ultrasonic method for measuring the elastic properties of human tibial cortical and cancellous bone. *Ultrasonics*. **34**:777-783.

2. http://www.magnussa.com/cowscele.jpg