Chapter

Mechanical Properties and Elasticity Model for Bovine Hard Tissue

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Abstract

This chapter aims at establishing engineering material properties of bovine hard tissue cut out of long bone. The study and design of implants, medical devices, and their bone material necessitate the knowledge of mechanical properties of bone to be evaluated. Braces or steel plates are used as fixation devices in animals who are treated for the fracture to bone or cracked bone. Braces or steel plates are fixed to the bone by rods and screws. For checking the stability of these inserted metallic parts, they have to be compatible with bone. The metal and bone form composite action for the load transfer mechanism. To ensure proper biomechanics and design of these inserts and accessories, we need to know the elastic properties of bone. This chapter establishes the modulus of elasticity, poisons ratio of Bovine femur bone. The experimental study establishes the orthotropic behavior of Bovidae femur bone. This experimental research provides comprehensive mechanical properties of Bovidae femur bone, through series of mechanical tests. By performing compression tests on a bone specimen, stress, strain, elastic modulus, poison's ratio, and yielding point of bone are established. The bovine long bone exhibits orthotropic or transversely isotropic nature of femur bone as expected. The data presented here is for samples derived from goat and water buffalo. The solid mechanics approach using stiffness matrix is adopted to establish elastic constants. The data of elastic constants, compliance, and stiffness coefficients obtained can be used for finite element analysis to simulate stability of composite, femur bone, and metallic fixation. The values of compression strength, Young's modulus, Poisson's ratio, and shear modulus are higher for water buffalo male than that of female showing gender difference. This may be attributed to lower bone density in females due to hormone secretion.

Keywords: elastic constants, compressive strength, femur bone, transversely isotropic, orthotropic, poisons ratio

1. Introduction

The ruminant mammals which include sheep, goats, antelopes, bison, African buffalo, water buffalo, wildebeest, impala, and domestic cattle are the members of the biological family Bovidae. Water buffalo species are particularly used for dairy products such as milk, butter, and cheese on large scale. After age, they are also useful for meat. Hence this is an economically important species. Similarly, goats are widely used for meat. In rural India, goats are useful for milk also. In the case of water buffalo, Femoral fractures are observed after falling during mounting or on slippery flooring. Due to high body weight and an inability to reduce the fracture, Femoral fractures in mature water buffalo have a grave prognosis.

2. Transversely isotropic or orthotropic material properties

In bone, like wood and many other biological structures, there is a "grain" or preferred direction associated with the structure. The mechanical behavior of bone and other directional composites is dependent upon the direction of the applied load. Bone material is assumed as anisotropic, and as many as twenty-one independent elastic constants are required to completely characterize their mechanical behavior. Most materials have planes of symmetry that reduce the number of material constants [1, 2]. For example, materials having properties that differ in each of two mutually perpendicular directions are termed orthotropic. Nine elastic constants are required to fully characterize their mechanical behavior. To determine the nine independent elastic coefficients of an orthotropic material the following mechanical tests are required. Compressive tests in each of three mutually perpendicular material directions; three lateral deformation tests to obtain Poisson ratios. Standards from the ASTM C469, D1621 [3, 4] have been adapted for mechanical testing procedures on biological tissue [5]. Bone is assumed to be highly anisotropic. This anisotropy in different issues may vary. In the long bone appetite needles, collagen fibers, lamellae, blood vassal, etc. show a clear tendency to be oriented along the length of the bone. In general most of the loads in bone are likely to be acting along its length.

3. Composition of bone

Bone matrix is material having both fluid and solid phases. Two main solid phases; the organic and the inorganic (mineral) substance, give bones their hard calcified structure.

3.1 Organic material

Organic matrix consist of type I collagen fibrils and non-collagenous components.

1. Collagen fibrils: The most important factor determining bone tissue quality in terms of its elasticity is collagen arrangement and structure in the bone. Collagen fibrils form 90% of the whole matrix of the bone. Extracellular collagenous matrix is impregnated with inorganic materials, mainly hydroxyapatite Ca10(PO4)6(OH)

2. Non-collagenous components: Non-collagenous components surrounding the mineralized collagen fibers. It is a ground substance, forms the remaining 10% of the organic matrix. It is consisting of protein, Phospholipids, polysaccharides, or glycosaminoglycans (GAGs), chiefly in the form of complex macromolecules called proteoglycans to cement together the layers of mineralized collagen fibers. More information is given by various workers.

3.2 Inorganic material (minerals)

The term mineralized and calcified arises from the fact that the major component of bone is calcium phosphate in the form of crystalline carbonate apatite.

The mineral substance of bone is calcium phosphate hydroxyapatite. On the other hand, they may vary according to the type of bone and may change during the calcification process. In reality, the organic–inorganic relationships in bone are still completely known. Unlike collagen, apatite crystals (Ap) are very stiff and strong. However, bone strength is higher than that of either collagen or apatite, it is because of similar to concrete, the softer component prevents the brittle cracking of stiff one from, while the soft one prevents the stiff component from yielding. The organic material provides bone its flexibility, while the inorganic material provides bone its resilience.

The bone composition depends on many factors, such as the species, type of bone, sample location from which it is taken, and the sex, age, and bone tissue, for example, woven, cortical, cancellous. However, the overall composition roughly estimated by volume is 1\3 rd Ap, 1\3 rd collagen, other organic contents, and 1\3 rd H2O. A roughly amount of Calcium and phosphate is about 65–70% dry weight of a bone. Collagen fibers compile approximately 95% of the extracellular matrix and it is about 25–30% of the bone's dry weight. The amount of water is up to 25% of the total wt. of bone, while 85% of the water to be found in the organic matrix surrounding the ground substance and collagen fibers. The 15% is located in cavities and canals that residence the bone cells.

4. Structure of bone

As described by K. Endo et al. [6], bone is recognized as cancellous, also known as spongy or trabecular and cortical also known as compact. In any long bone, Cortical bone is about four times the accumulation of cancellous bone. The basic material of cancellous and compact bone is identical; thus, the difference between the two is the amount of porosity and the organization. The porosity of cancellous bone ranges from 30 to 90%, while the porosity of cortical bone ranges from 5 to 30%. Bone porosity is not permanent and can alter in response to disease, transformed loading, and the aging process. The periosteum is the fibrous outer covering present in all bones except the joint regions, which are enclosed with articular cartilage. There are various terms used to explain the complex design of bone at a higher resolution. Both cancellous and cortical bone may contain two types of vital architecture, lamellar and woven. Bone can also be termed as primary or secondary bone. The term either haversian or laminar is used for regions within cortical bone. The relative proportion between the compacta and the diverse medulla with the skeletal segments and their role, but the higher strength-to-weight ratio maintains its validity. The calcified volume of thick compacta of cortical bone at the diaphysis of long bones is about 90% and an eccentric cylinder medulla, which containing hemopoietic, red bone marrow in youth, and fatdepleted, yellow, non-hemopoietic marrow in adults. At the flared metaphyseal region the thickness of the compacta is negligible. The short and flat bones, as well as the metaphysis and epiphysis of the long bones, are lined with thin compacta. The medulla consists of interlacing laminar termed, osseous trabeculae.

5. Literature review

Experimental verification of size effects in loaded bovine cortical bone has been carried out by Kieser et al. [7] They represented 2 and 3-dimensional finite element–based numerical models of loaded bovine cortical bone which incorporate the dominant microstructural feature: the vascular channel or Haversian canal system.

The numerical results for the virtual material samples when loaded in bending showed that they revealed size effects not forecast by either classical (Cauchy) or more generalized elasticity theories. The comparison between the values of flexural modulus and characteristic length in bending, for the specimens with axial and transversely orientated voids derived from experimentally measured size effects and those computed with a void fraction of 0.145, SX of 0.5 mm, SY of 0.433 mm, and matrix modulus of 20 GPa was given. They noted the value of axial Young's modulus as17.9GPa and transverse Young's modulus 8.6 GPa. The finite element method showed the value of axial Young's modulus 16.4 GPa and transverse Young's modulus 8.4 GPa.

Wei Sheng et al. [8] and T Attia [9] assessed femur biomechanics of different material assignments. Based on the validity of the assignment using the Finite element method they suggested how to choose the most simple and economic material assignment method. Kaori Endo et al. [6] In this paper they studied the influence of volume of cancellous bone and baseline structure on the variation in cancellous bone strength when subjected to cyclic loading. Two 2-year-old bovines were used to prepare fifteen cubic cancellous bone specimens. They were divided into three groups: femoral head, neck, and proximal metaphysis. Micro-computed tomography was used to determine structural indices of each 5-mm cubic specimen. First samples were subjected to uniaxial compressive loading at 0.05 mm/min with initial 20 N loading, 0.3 mm displacement for five cycles, and then unloading to 0.2 mm with 0.1 mm displacement for five successive cycles. During five loading cycles, elastic modulus and yield stress of cancellous bone decreased exponentially. They correlated the decrease ratio of yield stress clearly with bone volume fraction (BV/TV, $r = 0.96$, $p < 0.01$) and structural model index (SMI, $r = 0.81$, $p < 0.01$). The linking of bone strength after yield stress with structural deterioration of cancellous bone was indicated from data. Finally, they proposed that estimated baseline cancellous bone structure from non-fractured bone contributes to the cancellous bone strength during the collapse. During five loading cycles, elastic modulus and yield stress of cancellous bone decreased exponentially. Yield stress in the bovine femur was Metaphysis, neck and head are 16.8 MPa, 16Mpa, and 30Mpa respectively. Elastic properties were ranging from 428 to 625 MPa.

David C. Kieser et al. [7], Havaldar [10] and Kottha [11] considered cortical and medullary diaphyseal diameters, cortical cross-sectional area, bone length, cortical thickness, and bone density for morphological comparison. The four-point flexure tests for bending stiffness, Young's modulus of bending, and ultimate strength in bending tests was conducted as Biomechanical tests. Mid-diaphyseal cortical compressive elastic modulus and strength for torsional stiffness (Nm/degree) were also studied. Three samples of every bone type

a. rear deer femur;

b. rear pig femur, and

c. rear sheep femur were used for tests.

Young's modulus and ultimate strength in bending for whole bone samples were determined by a four-point bend test of the whole femora. The load was applied through the top rollers, with the lower supporting rollers being self-aligning. The previously reported ultimate strength for deer femora was 174 MPa but they observed a lower value of 98 MPa. For sheep femur, it was 44 MPa.

Mohamed S. Gaith and Imad Al-Hayek [12] compared elastic stiffness and the degree of anisotropy for the femur human and bovine bones is presented.

Orthotropic symmetry is used to model Bovine and human femurs. The mechanical elastic stiffness can be described by nine independent elastic stiffness coefficients which are a function of elastic material parameters, namely, Young's modulus, shear modulus, and Poisson's ratio. The largest value (72 GPa) was noted for bovine plexiform while the human tibia bone has the smallest. The bulk modulus and the overall elastic stiffness have the same behavior for all bones except phalanx. Elastic moduli are an important parameter to expose internal anisotropy and its effect on bonding strength. In conclusion, they stated that the largest overall elastic stiffness observed for bovine femur plexiform and has the most isotropic (least anisotropic) symmetry also seen in bovine [13, 14].

6. Mechanical testing of hard tissue

6.1 Selection of bone sample

The femur bone is selected for the study of its elastic properties. The head of the femur.

articulates with the acetabulum in the pelvic bone forming the hip joint, while the distal part of the femur articulates with the tibia shown in **Figure 1**. By measures, the femur is the strongest bone in the body.

Selection of bovine species:

1. Goat Male (Capra aegagrushircus)

2. Water Buffalo Female (Bubalusbubalis)

3. Water buffalo Male (Bubalusbubalis)

Basic specimen preparation as per standards of materials testing code given by, American Society for Testing and Materials (ASTM). Designations for compressive testing (ASTM C469, D1621) [3, 4].

6.2 Sample collection and preservation

Freshly cut Femur bone samples from Goat Male were collected. All muscles and soft tissue of bone should be removed. Samples to be washed with water and kept in hydrated condition. The weight of the Goat male femur bone was 125gm and length was 18 cm, While the weight of one buffalo male or female femur bone was 1100 gm and the length was 35–40 cm. The diameter of the long bone middle section of female buffalo femur bone was seen to be greater than male buffalo femur bone. But the length of male buffalo femur was found greater than female buffalo femur.

Figure 1.
Test specimen, fresh femur bone of goat male (Capra aegagrushircus).

The sample was preserved in distill water at 24 degrees Celsius. Samples were tested within 5 days.

6.3 Sample cutting and preparation

Yuri 4 inch Cutting Wheel Diamond cutter was used for cutting sample as shown in **Figure 2**. At the time of cutting of sample with a diamond cutter, bone sample reduces its strength and minerals because of high heat formation due to friction at the cut. It finally causes error in results. For good results samples were prepared by using saline water as a lubricant to release heat at the interface of diamond cutter and bone.

6.4 Compression testing of samples

The specimens for compression test are rough-cut cubes out of bone with the orientation of specimens maintained along the axis of the long bone. During the test, bone is kept at room temperature (∼24°C) in wet conditions. During testing, care is taken to ensure that the test specimens are kept hydrated. Three cubic samples were obtained from one femur bone. Out of three cubic samples, one sample was kept along the direction of fibers i.e. along the longitudinal axis of bone for compression test as shown in **Figure 3**. The other two samples were used to measure the compression strength of femur bone in the transverse direction shown in **Figure 3**.

6.5 Calculation of properties

To find elastic constants of bone, fundamental elasticity equations were used assuming transverse isotropy of bone. Measurement of longitudinal and lateral

Figure 2.
Test sample, cubes of water Buffalo female (Bubalusbubalis), cut out of test specimen.

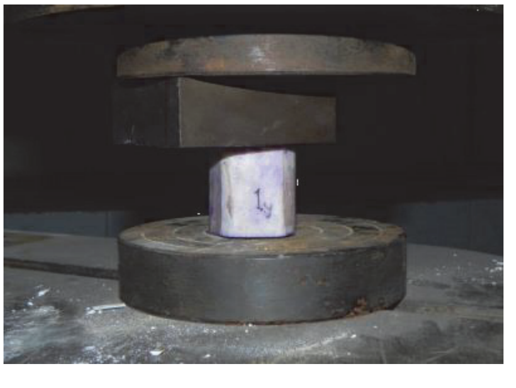

Figure 3.
Testing of the bone sample for compression load, tested under UTM, with controlled rate of loading.

deformations facilitates the calculation of strains in respective directions. Stresses are evaluated from loads applied.

Sample calculation of Goat Male

1. Compression strength (σ) = P/A, where P is the compressive load at failure, A is cross sectional area.

2. Linear strain (εL) = δL/L

3. Lateral strain (εT) = δT/L

4. Young's moduli (E) = σ/εL

5. Passion's ratio (ν) = εT/εL

6. Shear Modulus = E/2(1+ν)

Orthotropic material stiffness matrix constant of Goat Male (*Capra aegagrushircus*)

$$C_{ijkl} = \begin{Bmatrix} 9.08 & 1.81 & 1.85 & 0 & 0 & 0 \\ 1.81 & 9.08 & 1.85 & 0 & 0 & 0 \\ 1.85 & 1.85 & 13.4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.57 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3.57 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3.6 \end{Bmatrix} \tag{1}$$

Orthotropic material stiffness matrix constant of Water Buffalo Female (*Bubalusbubalis*) (**Table 1**)

Property	Goat male (*Capra aegagrushircus*)	Water buffalo female (*Bubalusbubalis*)	Water buffalo male (*Bubalusbubalis*)
σ_1	45 MPa	23.9 MPa	25 MPa
σ_2	46 MPa	24.5 MPa	26 MPa
σ_3	91 MPa	54 MPa	63 MPa
E_1	7923 MPa	5060 MPa	5790 MPa
E_2	8512 MPa	4860 MPa	5660 MPa
E_3	12600 MPa	11080 MPa	11780 MPa
ν_{12}	0.17	0.193	0.205
ν_{23}	0.18	0.211	0.216
ν_{31}	0.19	0.222	0.233
G_{12}	3385 MPa	2126 MPa	2402 MPa
G_{23}	3606 MPa	2008 MPa	2319 MPa
G_{31}	5042 MPa	4540 MPa	4788 MPa

Table 1.
Mechanical properties derived from testing.

$$C_{ijkl} = \begin{Bmatrix} 5.19 & 1.12 & 1.2 & 0 & 0 & 0 \\ 1.12 & 5.19 & 1.2 & 0 & 0 & 0 \\ 1.2 & 1.2 & 8.28 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1.09 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.09 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 \end{Bmatrix} \tag{2}$$

Orthotropic material stiffness matrix constant of Water buffalo Male (*Bubalusbubalis*)

$$C_{ijkl} = \begin{Bmatrix} 6.06 & 1.27 & 1.49 & 0 & 0 & 0 \\ 1.27 & 6.06 & 1.49 & 0 & 0 & 0 \\ 1.49 & 1.49 & 12.56 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.33 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.33 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.4 \end{Bmatrix} \tag{3}$$

7. Discussion

This experimental study shows that Young's Modulus and Poisson's Ratio can be determined from load–displacement relation. When tested using UTM, All bone samples show much higher modulus in the axial direction (E_y) than the other two transverse directions, this is due to the transversely isotropic behavior of bone. This is attributed to the parallel orientation of grains along the longitudinal direction. In the other two transverse directions, Modulus was nearly the same. This is consistent with the values obtained by other researchers, Reilly and Burstein [15], Kulkarni and Sathe [16], R. Shahar [17]. Hence orthotropic nature of the material is exhibited by long bone. It is seen that the values of compression strain, Young's modulus, Poisson's ratio, and shear modulus are higher for Water Buffalo Male (Bubalusbubalis) than that of female showing gender difference. This may be attributed to lower bone density in females due to hormone secretion.

The results obtained here for Poisson's ratios of femur bone fall within a narrow range. The values found on our experiments for goat male 0.17 to 0.19, for Water Buffalo Female (Bubalusbubalis) 0.19 to 0.22, and for Water Buffalo Male (Bubalusbubalis) 0.22 to 0.23. These values are in good agreement with 0.20 to 0.22 reported by Kulkarni and Sathe [16], however, the range is different than 0.12 to0.63 reported by Pithioux et al. [18].

The values of compression strength of femur bones tested in this study show variation in three groups of samples. The compressive strength of the Goat male (Capra aegagrushircus) femur bone ranges from 92 MPa to 100 MPa in the longitudinal direction. The compression strength of the Goat Male (Capra aegagrushircus) femur bone reported in this work is 97 MPa. A previous study reported a similar value of compressive strength of femur bone in Ovis (sheep) 90 Mpa, Erickson et al. [19]. The compressive strength of Goat male (Capra aegagrushircus) femur bone ranges from 40 MPa - 52 MPa in the transverse direction.

Considering the above results following conclusions may be drawn:

1. Diameter of the diaphysis of Water Buffalo Female (Bubalusbubalis) femur bone was seen to be greater than Water Buffalo Male (Bubalusbubalis) femur

bone but the stiffness constant shows the higher valves in Water Buffalo Male (Bubalusbubalis) than Water Buffalo Female (Bubalusbubalis) because in Water Buffalo Male (Bubalusbubalis) femur bone grains are closely spaced that is more compact cortical bone and less spongy but in Water Buffalo Female (Bubalusbubalis) femur bone grains are relatively sparsely spaced i.e. It also exhibits more cancellous bone and more spongy nature as compared to male bone sample, this difference is attributed may be due to hormonal effect.

2. In Goat male (Capra aegagrushircus) femur bone compression strength in the longitudinal direction (91 MPa) is higher than that of transverse direction (46 MPa) and the same thing observed in Water buffalo (Bubalusbubalis) species. The higher values in the longitudinal direction than transverse direction is attributed to the orientation of laminas is parallel to the longitudinal direction and hence bone takes more load in the longitudinal direction.

3. For Goat male (Capra aegagrushircus) femur bone Young's Modulus in two transverse directions (E1, E2) is 7.8 GPa and 8.5 GPa respectively which is nearly the same but it has a higher Youngs Modulus value in the longitudinal direction (E3, 12.6 GPa) which indicates that bone is transversely isotropic. While for water buffalo the modulus of elasticity values are observed to be, female in transverse direction 5060Mpa, In longitudinal direction 11080 Mpa. For Male buffalo in transverse direction 5790 Mpa, Longitudinal 11780 Mpa

4. For Goat male femur (Capra aegagrushircus) bone Poisson's ratio varies from 0.17 to 0.19, for Water buffalo (Bubalusbubalis) they are from 0.19 to 0.23.

5. Water buffalo (Bubalusbubalis) has a larger bone cross-sectional area than Goat male and thus stress is comparable to bone cross-section. (Capra aegagrushircus) The magnitude of shear modulus is seen as a higher value in Goat male (3.6 GPa. (Capra aegagrushircus) than Water buffalo (2.0 for Female, 2.4 GPa for Male) (Bubalusbubalis). This is in line with the fact that Goat bone is subjected to more torque due to jumping and twisting and hence exhibits more torsional strength than buffalo, by natural cell development.

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Conflict of interest

The authors declare no conflict of interest.

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