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MECHANICAL BEHAVIOUR OF BOVINE CORTICAL BONE USING RECTANGULAR MINATURE SPECIMENS

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Abstract— **Bone mechanical properties have been an important topic of study for many years. Thus, from a materials science perspective, understanding the mechanical properties of bone becomes a matter of paramount significance in order to develop a synthetic bone substitute with load bearing capability. Understanding mechanical properties of bone also enables developing more accurate models for analysis of implants and prospective bone-replacement materials. However, biological hard materials like bones are difficult to test mechanically in standard sizes because they come in small pieces and awkward shapes. These constraints may be overcome by employing miniature specimens for mechanical testing. The miniature specimen technique can be especially appealing in investigating the effect of non-uniformity of bone mechanical properties. The advantage of such miniature specimens includes the possibility of sampling very small volume of material within a heterogeneous structure such as cortical bone. This may also be used for studying biological materials that are not available in large enough volumes for conventional mechanical testing. Miniature specimen test technique has emerged to solve this practical problem. Therefore a study has been proposed for the characterization of bovine cortical bone using miniature specimen testing. This technique is especially useful in evaluating the properties in transverse direction of the bone as it is very difficult to extract specimens in the transverse direction because of the size and shape limitations.**

Keywords— **MINIATURE SPECIMEN, PROE, ANSYS**

I. INTRODUCTION

The design, development and application of a miniature specimen test technology for predicting the mechanical properties of cortical bone using rectangular miniature specimens. The miniature specimen technique can be especially appealing in investigating the effect of non-uniformity of bone mechanical properties. In order to find an appropriate bone substitute material, it is essential to have a thorough understanding of the mechanical behaviour of bone.

The structural integrity of mineralized tissues such as cortical bone is of great clinical importance, especially since bone forms the protective load-bearing skeletal framework of the body. Bone is the primary structural component of the human body. It protects vital internal organs and permits skeletal motions necessary for survival. Bone is unique when compared to structural engineering materials because of its well known capacity for self repair and adaptation to changes in mechanical usage patterns. For example, bone density alterations are commonly observed after periods of disuse or chronically increased activity. Bone is a relatively hard and lightweight composite material, formed mostly of calcium hydroxyapatite. It has relatively high compressive strength but poor tensile strength. While bone is essentially brittle, it does have a degree of significant elasticity contributed by its organic components.

Morphologically, there are two forms of bone: cortical (compact or dense) and cancellous (spongy or trabecular). Cortical or Compact bone represents nearly 80% of the skeletal mass and is found primarily in the diaphyses of long bones and forms a structural shell around trabecular bone at the end of long bones and the vertebrae (Carter et al. 1976, 1977). It is stiff with a longitudinal elastic modulus between 16-25 GPa and a low porosity of 5-30%(Cowin 1983). Cancellous or Trabecular bone, while only representing 20% of the skeletal mass represents 80% of the bone volume. It is less dense and has a porosity ranging from 30-90% (Melnis 1980). It forms low weight interior scaffolding, which helps bone maintain its shape by absorbing compressive forces. It is found in the epiphyseal and metaphyseal regions of long bones. In addition, short, flat and irregular bones are all made of trabecular bone covered with a thin layer of cortical bone.

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Bones can also be classified into one of four types based on their shape: long, short, flat and irregular. Long bones are tubular in structure (e.g. femur, tibia, humerus etc.). A typical long bone is shown in Figure1.1. The central shaft of a long bone is called the diaphysis, and has a hollow middle—the medullar cavity filled with bone marrow. Surrounding the medullar cavity is a thin layer of cancellous bone that also contains marrow. The extremities of the bone are called the epiphyses and are mostly cancellous bone covered by a relatively thin layer of compact bone. Short bones (e.g. finger bones) have a similar structure as long bones, except that they have no medullar cavity. Flat bones (e.g. the skull and ribs) consist of two layers of compact bone with a zone of cancellous bone sandwiched between them. Irregular bones are bones which do not conform to any of the previous forms (e.g. vertebrae).

LONG BONE:

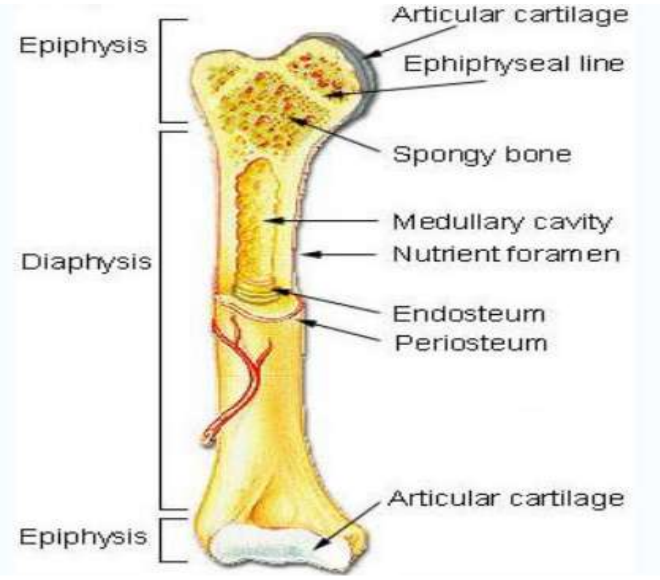

Figure 1.1

Factors affecting the mechanical properties of compact bone:

- Moisture Content and Mineralization
- Effect of Age
- Effect of Gender Rate of Deformation.

Miniature Specimen Test Technique

II. EXPERIMENTAL SETUP FOR SMALL SPECIMEN PUNCH TEST (SSPT)

Design Features of SSPT Apparatus

The essential elements of the miniature specimen test technique are punch and specimen holders known as dies (lower and upper dies), punch holder for load application and load v/s displacement measuring devices. The miniature specimen is supported by a rectangular slot of a lower die and the upper die with screws would keep the specimen in position. The load is applied by a punch which is attached to the punch holder. This assembly is gripped in universal testing machine. Appropriate load cells are chosen to accurately record the load applied through the punch on the specimen. The development of miniature specimen punch test setup involves the following steps:

- The design of small punch specimen
- The design of upper and lower dies for supporting the miniature specimen
- The design of punch holder and punch
- The design of versatile fixture (compression attachment) to accommodate the specimen holder and punch holder.

The Specimens:

A rectangular miniature specimen is designed as shown in Fig.2.1. The procedure for making this specimen is easier as compared to that of making conventional sub size tension test specimens. The preparation of specimen involves less number of machining operations. The selected geometry has additional advantage due to its convenience in finite element modeling and economy in computation time. The miniature specimen in the present investigation has been prepared in the following steps. Longitudinal and transverse miniature specimens of length 10mm, width 2mm and thickness 1mm were prepared as follows. The mid shaft of bovine tibia was cut with a hacksaw to a length of 80 mm perpendicular to the longitudinal axis of the bone. The 80 mm diaphyseal bone was cut into rectangular segments in longitudinal and circumferential directions of the bone. The rectangular segments were polished on a water cooled grinding table with 320 grit silicon carbide paper into straight beams with rectangular cross-section of width 10mm and thickness1 mm. At all stages in this procedure, the bone was either immersed in or kept moist with Ringer‘s solution. Finally, longitudinal and transverse miniature specimens of length 10mm and cross-section 2mmX1mm were cut on a Buehler Isomet 5000 low speed linear precision saw. The deviation in thickness was maintained within 1%.

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Figure2.1 Rectangular miniature specimen

The Design of Specimen Holder (Die):

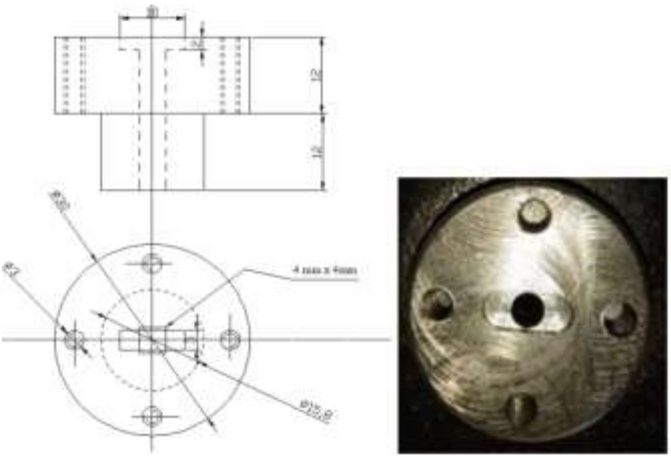

Figure 3.1Details of the miniature specimen holder lower die

The specimen used in the present case being very small could not be directly gripped in the testing machine. Therefore special specimen holder was designed for this purpose. The specimen holder consisted of upper and lower dies made of EN24 steel as shown in Figs 3.1 and 3.2 respectively. The two dies are joined by means of four clamping screws. The outer dimension of the specimen holder is taken in such a way that the holder fits smoothly on the fixture plates. Special attention was given to ensure that the rectangular slit in the lower die and rectangular protrusion in the upper die lie along the same line when both dies with the specimen are joined by means of clamping screws. So the upper and lower specimen holders were machined such that their dimensions matched to the maximum possible accuracy. The inner bore in the upper die is kept constant at 4 mm diameter to guide the punch. Lower die inner bore is provided with a 4mm X 4mm square pocket to allow the specimen to be displaced into the pocket when load is applied by the punch Miniature specimens of varying thicknesses can be accommodated by these specimen holders. These holders can accommodate rectangular specimens having dimensions ranging from 6 mm to 10mm in length and thickness from 0.5 mm to 2 mm.

Figure 3.2 The miniature specimen holder upper die

The Design of Punch holder and Punch:

The punch and punch holder are very important components of the setup because the load is applied through these components. In the present investigation, punch with a cylindrical headed tip along with punch holder are designed and developed. The punch holder is designed in such a way that it would accommodate the punch firmly. The punch holder possesses a 15mm deep cylindrical hole with 6.3mm diameter. The lower end of this hole is closed with an adjustable screw to support the punch. The outer diameter is 15.8mm with a shoulder of diameter 22.15mm. Details of the punch holder are shown in Fig. 3.3. The punch holder is made of EN24 steel. In this setup the load is applied through a rigid punch with a cylindrical tip. The cylindrical headed tip punch is made of EN24 steel. The lower portion of the punch is of 15mm length and 6.3mm diameter and this is precisely maintained to ensure correct fitting in the punch holder. The upper portion of the punch is also kept with a cylindrical tip of diameter=2mm and tip length=3.5mm. The detailed dimensions of the cylindrical headed punch are shown in Fig.3.5. Fig. 3.6 shows the punch in a punch holder.

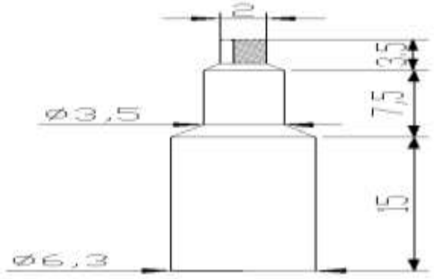

Figure 3.3 Cylindrical tip punch

Figure 3.4 Punch in a punch holder

The Design of Small Specimen Punch Testing Fixture:

The test on miniature specimens is generally performed on a modern universal testing machine at room temperature. The difficulties were noted in the alignment of punch, miniature specimen and specimen holder (die). The alignment of these components is critical during testing and accuracy of results is doubtful if proper alignment is not maintained. In this regard important requirements are as follows: (a) The punch axis of symmetry be coincident with die axis of symmetry (b) strict design tolerances for the punch and dies and (c) a specimen with uniform thickness at any point. In the present study, the eccentricity effects are minimized by proper alignment for example by using versatile precision alignment fixture and by accurate machining of the punch, dies and specimen. The fixture is designed in such a way that the punch holder with punch, specimen holder and the specimen are exactly aligned along a single center line during loading without any eccentricity.

The test fixture consists of two plates with center holes: the diameter of the hole is same as the outer diameter of the lower die i.e. 15.8 mm. These circular plates are attached to two cylindrical bars, so that the plates would come closer to each other when tensile force is applied on end blocks as in compression attachment. The movement of the plates is quite smooth in the axial direction. Each end block possesses a 12.5 mm diameter hole to attach a cylindrical rod with a guide pin; the other end of this rod is fixed in the crosshead jaw of the testing machine. The detailed geometry of the fixture and its components are shown in Fig. 3.5 in the assembled mode. The specimen holder with miniature specimen, the punch holder and the punch can be fitted or removed at any stage from the test fixture without any difficulty.

Figure 3.5 Small punch test fixture with specimen holder, punch holder, punch& connecting rods in an assembled mode.

Experiments on Miniature Specimens:

The experimental investigation was carried out on the miniature specimens as detailed above. In chapter 3, a special test fixture has been developed to conduct the test on the miniature specimen using the UTM. Firstly, the specimen is placed into the groove of the specially designed die. The groove in the die ensures proper alignment of die and the test specimen while fixing in the machine. The punch was used for applying the load to the specimen through the punch holder. All these were aligned and loaded in the machine, which was furnished with the load and displacement measuring devices. The complete assembly consisting of punch, punch holder and die with the miniature specimen. The complete assembly is installed in the UTM. The miniature specimen were tested at a very low crosshead speed. At least 5 specimens were tested in each direction. During the test the load - displacement diagrams were recorded. Typical experimental outputs of the miniature specimen test are reported in the form of load - displacement diagrams in the longitudinal and the transverse directions as shown in Figs. 4.6 and 4.7 respectively.

RESULTS OF MINIATURE SPECIMEN TEST: The results of miniature small punch test are reported in Table 4.1. The table also demonstrates the maximum load on the specimen and the corresponding displacement in both longitudinal and transverse directions. The average values based on the tests on five specimens are reported in

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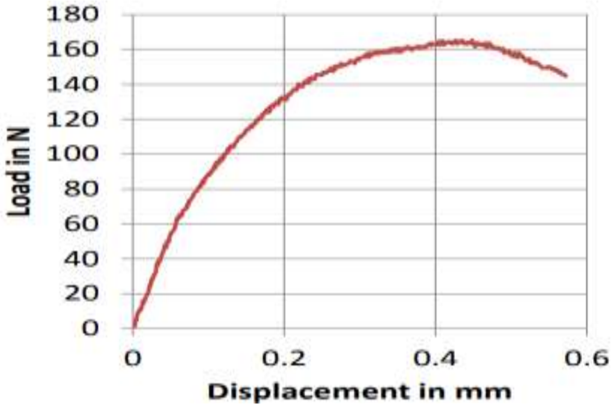


Fig.4.6 Typical Load-Displacement diagram of miniature specimen in longitudinal direction (experimental)

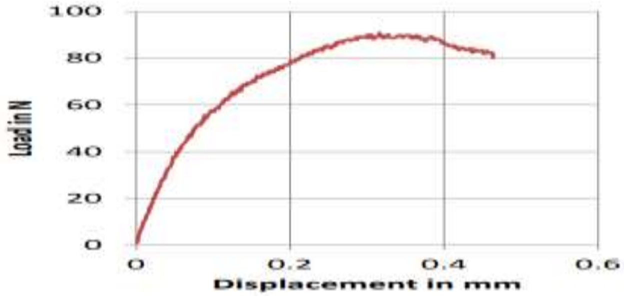


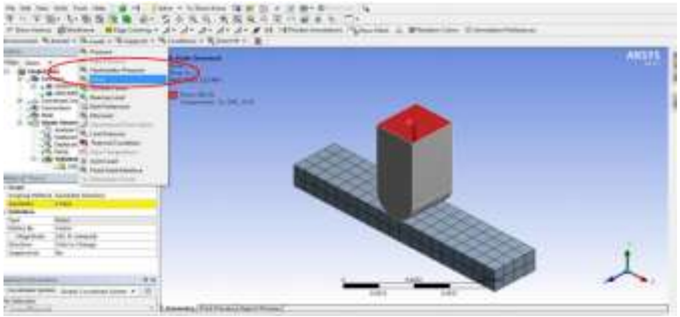
Fig.4.7 Typical Load-Displacement diagram of miniature specimen in transverse direction (experimental)

Table 4.1 Miniature specimen test results

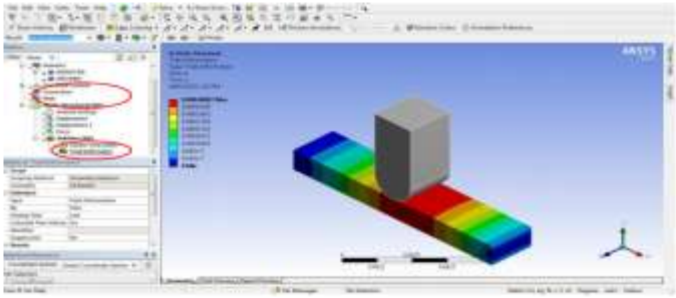
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Average value
Longitudinal specimen						
Maximum load (N)	165	167	164	161	169	165.2
Displacement at maximum load (mm)	0.436	0.443	0.440	0.438	0.433	0.438
Transverse specimen						
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Average value
Maximum load (N)	90	89	91	92	88	90
Displacement at maximum load (mm)	0.310	0.308	0.313	0.311	0.318	0.312

III. SIMULATION OF SMALL PUNCH TEST ON MINIATURE SPECIMENS OF CORTICAL BONE:LOADS

Load was applied on the indenter which will be directly transmitted on to the specimen. As the indenter is rigid load will be transformed to the specimen without the deformation of indenter. Load was applied as shown below:



IV. FINITE ELEMENT RESULTS AND DISCUSSIONS



Deformation plot of the specimen

Comparison of experimental and finite element results of miniature test.

Sl. No.	Specimen type	Miniature test results		FEM results	
		P_{max} (N)	δ_{max} (mm)	P_{max} (N)	δ_{max} (mm)
1.	Longitudinal	165	0.43	176	0.42
2.	Transverse	90	0.32	98	0.33

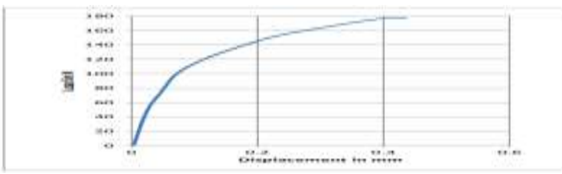


Fig.5
FEM predicted load – displacement diagram for a longitudinal specimen

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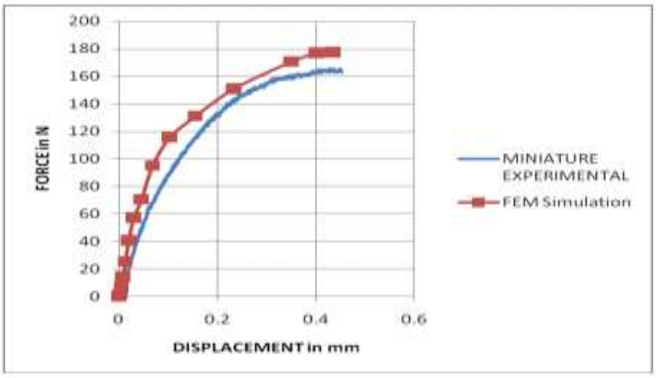

Comparison of experimental and FEM load – displacement curves in longitudinal direction

V. CONCLUSIONS

This work presents the experimental and simulation studies on mechanical properties of bovine cortical bone using miniature specimens. The important findings of the present work are as follows:

1. A simple rectangular shaped miniature specimen (1 mm thickness) has been designed and proposed for the use in evaluation of mechanical properties of bovine cortical bone. The specimen preparation requires less number of machining operations which is very crucial in bone samples because the samples would dry out soon leading to change in mechanical properties.

2. An experimental setup has been designed and successfully used in the present work to carry out the miniature test using rectangular specimen of thickness 1.0 mm. The development of miniature specimen punch test setup involves designing of dies, punch holder and punch, compression attachment, displacement measuring system etc.

3. The experimental values of maximum loads were noted to be 165 N and 90 N respectively for the longitudinal and transverse miniature specimens and the corresponding displacements were 0.43 mm and 0.32 mm respectively.

4. Finite element simulation of miniature small punch test on cortical bone in both longitudinal and transverse orientations have been conducted. The values of maximum load obtained through FEM simulation are 176 N and 98 N respectively for longitudinal and transverse specimens and the corresponding displacements are 0.42 mm and 0.33 mm respectively. The simulated miniature load-displacement diagrams are found to be in good agreement with the experimental diagrams.

5. One can easily create the data base of load-displacement curves for different materials using finite element technique. For any unknown material the load-displacement curve can be obtained using the miniature specimen testing as employed in the present work and the FEA simulated load-displacement curve can be matched with the experimental ones. In this way the tensile properties of the unknown material can be predicted.

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