EXPERIMENTAL AND NUMERICAL STUDIES ON MECHANICAL BEHAVIOUR OF BOVINE CORTICAL BONE USING RECTANGULAR MINIATURE SPECIMENS

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CERTIFICATE

This is to certify that the thesis entitled **Experimental and Numerical Studies on Mechanical Behaviour of Bovine Cortical Bone Using Rectangular Miniature Specimens** being submitted by **V. Chitti Babu** to the **Indian Institute of Technology Delhi, New Delhi (India)** for the award of the degree of Doctor of Philosophy in Applied Mechanics Department is a bonafide research work carried out by him under our supervision and guidance. The research reports and the results presented in this thesis have not been submitted in parts or in full to any other University or Institute for the award of any degree or diploma.

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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. To date, the mechanical behavior of cortical bone has not been described by using miniature specimen technique which is very handy in describing the mechanical behavior of metallic alloys. 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.

The present study deals with the design, development and application of a miniature specimen test technology for predicting the mechanical properties of cortical bone using rectangular miniature specimens. The study involves numerical as well as experimental

investigation of bovine cortical bone with respect to its mechanical behaviour including fracture aspects. The matured bovine cortical bone has been described as a transversely isotropic material. For the present investigation rectangular shaped miniature specimens of sizes 10mm (length) X 2mm (width) X 1mm (thickness) were carefully prepared from the middle third portion of the matured Bovine tibia in longitudinal and transverse (circumferential) directions. The samples were machined by low speed Buehler Isomet linear precision diamond saw under continuous water spray to minimize the thermal damage. Specimens were subjected to Small Punch Testing at room temperature in wet condition using an MTS (858 model) table top machine. A specially designed fixture was used to hold the specimens in the MTS machine and the load vs load point deflection measurements were taken during the test. The experimental data obtained from miniature specimen tests were further analysed to obtain the standard mechanical properties of the cortical bone such as the yield strength and fracture toughness. The results obtained from miniature specimen tests were validated by conducting tensile tests and fracture toughness tests on large size specimens from mid diaphysis of bovine cortical bone in both longitudinal and transverse directions. A good agreement was found between the results of miniature test and standard specimen tests. Further, finite element simulation was employed to obtain load-load point deflection diagrams in the miniature specimens by using the elastic-plastic deformation data from the standard tensile tests conducted in the longitudinal as well as the transverse direction of the specimens from the cortical bone. The simulation results were found to be in good agreement with experimental results from miniature tests. The results have been discussed and the main findings have been outlined. The chapter wise organization of the thesis is presented as follows.

CHAPTER-1: INTRODUCTION

This chapter discusses the mechanical properties of cortical bone and significance of the topic of present research in the biomechanical engineering applications. The structure of bone, the background of miniature specimen approach and the motivation for the present study have been outlined. The summary of the proposed work is also included.

CHAPTER-2: REVIEW OF LITERATURE

This chapter deals with an extensive review of literature concerning the mechanical properties (i.e. strength, stiffness, fracture toughness, deformation behavior etc.) of compact bone and the effect of different variables on the mechanical behavior of cortical bone. Further the literature pertinent to the small specimen test technique based on the past researches is presented. The techniques for the analysis of mechanical behavior of metallic alloys during in-service degradation are also discussed. The empirical equations developed by earlier investigators based on experiments and numerical modeling are presented. The literature pertinent to finite element simulation and the inverse finite element simulation of miniature test are also reported. Further the aims and objectives of the present research have been outlined.

CHAPTER-3: DETERMINATION OF TENSILE PROPERTIES AND FRACTURE TOUGHNESS OF CORTICAL BONE: EXPERIMENTAL PROGRAMME & RESULTS

This chapter deals with the tensile testing, fracture toughness testing, lateral deflection tests of cortical bone specimens in longitudinal and transverse directions to determine the mechanical properties in both the directions. It contains a description of the specimen such as dimensions, preparation, storage etc., the testing machines and the test procedures for the above mentioned tests. Two types of specimens namely longitudinal and transverse ones were prepared from the outer periphery of compact bone for tensile tests and lateral deflection tests. Compact tension specimens and three point bend specimens were prepared for the determination of longitudinal and transverse fracture toughness of cortical bone. The longitudinal tensile test experiments were conducted on Zwick universal testing machine which was interfaced with the computer. The transverse tensile test and fracture toughness tests were conducted on MTS model 858 table top system which was also interfaced with the computer. Lateral deflection tests were conducted on 5 KN capacity INSTRON machine. All tests were performed at room temperature with the specimens kept moist at all times before and during the tests. Experimental determinations of tensile properties as well as fracture toughness values based on large test specimens were used to compare with the values obtained from the miniature test results.

CHAPTER-4: DESIGN AND DEVELOPMENT OF MINIATURE SPECIMEN TEST SETUP

This chapter describes the details of the development of a small specimen punch experimental setup used for testing. The rectangular miniature specimens were employed in the present investigation having dimensions of 10 mm (length), 2 mm (width) and 1 mm (thickness). The specimen and setup design are aimed at to make the test technique simple and practicable. The design and details of different components such as specimen holder, punch with punch holder and the clamp used for measuring the displacement are described. The specimen holder is designed such that it can accommodate wide range of specimen thicknesses.

CHAPTER-5: EXPERIMENTAL INVESTIGATION ON MINIATURE SPECIMENS OF CORTICAL BONE

This chapter deals with the miniature test in both longitudinal and transverse directions of bone using the test setup described in Chapter-4. A description of the testing machine and the test procedure for the miniature test are given. The miniature test experiments were conducted on

MTS model 858 table top machine which was interfaced with the computer. The miniature test outputs were obtained in the form of load vs displacement diagrams for both the orientations. Empirical correlations are proposed for the estimation of yield strength and fracture toughness using the results of miniature test. The yield strength values obtained from this relation are compared with those obtained from existing empirical relations from the literature and also from standard tensile tests. The fracture toughness values also are compared with the standard fracture toughness tests. The values obtained from the proposed empirical correlations are found to be in good agreement with the standard test results.

CHAPTER-6: SIMULATION OF SMALL PUNCH TEST ON MINIATURE SPECIMENS OF CORTICAL BONE

This chapter describes how the numerical modeling of the miniature test is carried out using finite element based commercial software ABAQUS/STANDARD. The ABAQUS standard finite element analysis has been employed to simulate 3-D model of the miniature specimen test set up. The punch was modeled as 3D rigid body having the reference point at the top. The boundary conditions for the punch were applied at the reference point. The loading on miniature specimen is applied with the help of time amplitude increments option of the code. The finite element results of the miniature test are validated with the experimental data of load vs displacement and a good comparison between the experimental and the FEM simulated diagram is noticed.

CHAPTER-7: DEVELOPMENT OF AN INVERSE FINITE ELEMENT PROCEDURE FOR THE DETERMINATION OF MECHANICAL BEHAVIOUR OF CORTICAL BONE

This chapter describes the application of inverse method in solving engineering problems. In this technique the experimental output from the miniature specimen test i.e. load–displacement curve is fed as input. The experimental load vs displacement curve is matched with the finite element one in an iterative linear piecewise manner. When the complete match is found between the experimental and finite element output in the elastic region, the Young's moduli would be obtained for any unknown material. In the inverse finite element simulation, the value of Young's modulus in one direction is assumed and keeping constant all other elastic constants. Resulting finite element analysis (FEA) load-displacement curves/data are compared with miniature specimen experimental load-displacement curve/data. Assumed Young's modulus value is iterated, till the complete match is obtained in the elastic region between the FEA simulated load-displacement diagram and the finite element one. Similarly the procedure is repeated for finding the Young's modulus in other direction as well. The computed values of Young's moduli are compared with uniaxial tensile test data for standard specimens and are found to be in good agreement. The empirical equation for the prediction of fracture toughness based on equivalent fracture strain obtained from finite element simulation is proposed. The fracture toughness values predicted from the proposed empirical equation are in excellent agreement with the values obtained by standard tests. It may be noted that existing empirical equations for the prediction of fracture toughness for metallic alloys are not suitable for the prediction of fracture toughness of cortical bone.

CHAPTER-8: CONCLUSIONS AND RECOMMENDATIONS

This chapter gives the important conclusions drawn from the present study and also offers suggestions for future research in the light of the findings of the above study.

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