STUDIES ON ORIENTATION EFFECT AND LOCATIONAL VARIATION IN MECHANICAL AND FRACTURE PROPERTIES OF CORTICAL BONE

by

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CERTIFICATE

This is to certify that the thesis entitled '**Studies on Orientation Effect and Locational Variation in Mechanical and Fracture Properties of Cortical Bone**' being submitted by *Mr. Nitin Kumar Sharma* to the **Indian Institute of Technology Delhi** for the award of the Degree of Doctor of Philosophy in Applied Mechanics Department is a record of 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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(Nitin Kumar Sharma)

ABSTRACT

The present study is based on the mechanical and fracture behavior of cortical bones. The mechanical characterization of cortical bone is important from both the clinical and engineering point of view for the development of better implantation and to understand the effect of age, drug treatment, disease etc. The present investigation has been conducted on four different categories of bones obtained from young buffalo and bovine of the age group between 24 to 36 months. These four categories are divided as bovine femur (BoF), bovine tibia (BoT), buffalo femur (BuF) and buffalo tibia (BuT).

Bone is treated as a heterogeneous, anisotropic material with hierarchical structure that changes from nano scale to macro scale. Due to heterogeneity associated with bone, in order to understand the locational variation in its fracture and mechanical properties, the whole length of bone diaphysis is divided in to three parts namely upper, middle and lower diaphysis. The material properties of bone are considered to be transversely isotropic in nature and to analyze the effect of orientation on different mechanical properties, samples from different locations are further categorized as longitudinal (load being applied along the long axis of bone) and transverse (load being applied along the perpendicular direction to the long axis of bone) specimens. Shear modulus at different locations of bone diaphysis is determined with the help of Iosipescu shear test method. This shear test method has now become well accepted among the researchers in characterization of composite materials. The micro-mechanisms of cortical bone under tensile and shear loading have been examined using scanning electron microscope (SEM).

For the evaluation of fracture properties compact tension and single edge notch bend specimens are employed to undergo longitudinal and transverse fracture. It has been observed that bone contains good amount of non linearity during deformation. This non linearity is considered to be due to several toughening mechanisms such as micro-cracking, crack deflection due to weak interfaces, fiber bridging, sacrificial bonding and presence of water in the bone material. Due to moderate amount of apparent plastic deformation in bone material before facture, elastic-plastic fracture mechanics (EPFM) using crack tip opening displacement (CTOD) approach has been applied to accurately describe the fracture properties of bone in terms of CTOD and *J*- toughness values. The SEM examination of fracture surfaces is carried out to investigate the micro-fracture mechanisms in cortical bone for different orientation of cracking. From different SEM images, various toughening mechanisms involved during cortical bone failure are identified and discussed.

Different statistical methods have been applied in the present investigation to observe the complexity associated in bone material due to its heterogeneous and anisotropic nature. The mechanical and fracture properties of different diaphysis locations and categories of cortical bone are analyzed using single-factor analysis of variance (ANOVA), unpaired t-test and paired t-test analysis. The statistical parameters such as coefficient of variation and standard error of mean are used to observe the variation in experimental results.

In this study the trend of mechanical heterogeneity is observed to be the same for various categories of cortical bones. The different mechanical properties are found to be maximum at the middle location and minimum at the lower location of bone diaphysis. The mechanical properties are also observed to be highly anisotropic in nature as the tensile properties are found to be significantly greater for longitudinal orientation of loading and the transverse shear modulus is found to be significantly greater as compared to the longitudinal shear modulus.

The CTOD and J – toughness values of cortical bone are observed to be significantly different for three representative locations of cortical bone diaphysis. The trend of variation of these fracture properties at different diaphysis locations is found to be same (maximum at the middle location and minimum at the upper diaphysis location) for various categories of cortical bones. The variation in arrangement of collagen fibrils and mineral particles and in the amount of mineralization and crystallinity at different locations of bone diaphysis is considered as the main cause of this locational variation in fracture properties of cortical bone.

The micro-structure of bone specimens from buffalo and bovine cortical bone was found to be plexiform in nature that is found predominantly in large, rapidly growing animals. The bone lamellae and the planes of vascular networks were mainly oriented along the long axis of the bone facilitating crack growth in the longitudinal direction with less amount of energy consumption and producing a smooth fracture surface in this case. In case of transverse fracture the blood vessels and vascular networks serve as barrier to the crack growth producing an uneven fracture surface and leading to significant amount of energy consumption. Therefore, the cortical bone is shown to be having higher toughness for transverse orientation as compared to that of longitudinal orientation of fracture. The toughening mechanisms observed in the present study from various SEM images are micro-cracking, crack deflection, crack twist and sacrificial bonding.

The mechanical and fracture properties of cortical bone are considered to be related to its compositional parameters such as density, porosity, minerals, organics etc. Therefore, different compositional parameters of cortical bone are also evaluated for three different locations of bone diaphysis. These compositional parameters are correlated to different corresponding mechanical and fracture properties of bone using linear and multi-linear regression analysis. The transverse compositional parameters of cortical bone are observed to be more inhomogeneous along the bone diaphysis as compared to the longitudinal compositional parameters. The locational variation in porosity and mineralization is considered as the main cause of compositional heterogeneity in bone material as the variability in percentage of water is observed to be higher at different diaphysis locations of various cortical bones.

The mechanical and fracture properties of cortical bone are found to be positively correlated with the apparent density and mineral content and negatively correlated with the organics and percentage of water. The corresponding results of linear regression analysis are presented in the form of linear regression equations, coefficient of determination (COD) r^2 and p (probability)-values of model utility tests. The multiple regression models are used to analyze the effects of more than one significantly correlated compositional parameters on different mechanical and fracture properties of cortical bone. The multiple regression equations are presented along with different explanatory parameters such as coefficient of multiple determination (R^2), adjusted R^2 and p-values. The multiple regression models are found to be having good explanatory capabilities for different mechanical and fracture properties.

The experimental investigation on small size specimens of cortical bone has been carried out using small punch test method. These specimens are prepared from both longitudinal and transverse directions of the bone diaphysis to analyze the directional effect on deformational behavior of cortical bone. Three different thicknesses (2.0 mm, 1.5 mm and 1.0 mm) of specimens are considered for this study. The small punch test is performed on MTS 858 Table Top Machine at a displacement rate of 0.05 mm/min and the load-displacement behavior of cortical bone are observed for both longitudinal and transverse orientations of specimens. Based on the experimental results, new empirical relations are developed for the estimation of longitudinal and transverse elastic moduli.

Computational simulations in biomechanics are important due to difficulty of obtaining experimental or clinical results. Due to limited information on plastic properties of cortical bone most of the finite element analyses are based on assumptions of linearity of constitutive behavior of bone tissue whereas few investigators have obtained somewhat accurate results by considering non-linear material properties of cortical bone. Further, the uniaxial and biaxial finite element models of cortical bone are created to take into account multi-axial loading. For finite element simulation, the bone material has been considered to be transversely isotropic in nature having five elastic constants. The Hill's criterion has been used to simulate the anisotropic yield behavior of cortical bone. The finite element study shows that cortical bone has higher stiffness values in longitudinal and transverse directions for biaxial loading as compared to that of uniaxial loading.

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