Studies on Impact Behavior of Cortical Bone using Charpy Test and Finite Element Simulation

Prateek Dubey, N. K. Sharma, Apoorv Rathi and Abhinav Kumar

***Abstract*— Bone is an anisotropic and heterogeneous material due to its non-longitudinal axial distribution of orientation of bone minerals and random distribution of other compositional parameters. It undergoes substantial changes in shape, structure and composition according to the mechanical and physiological environment. The investigation on response of bone tissue under different loading situations is important for clinical and engineering point of view. Stresses imposed on a bone can vary according to the work it is put into. Stresses generated during an impact can be far higher than those produced during traditional activities, making the study on impact behavior of cortical bone paramount. The effects of diaphysis location on impact strength of a young buffalo tibiae cortical bone has been studied through this paper, using experimental technique and finite element simulation of Charpy test. Impact resistance of the three diaphysis locations of cortical bone was evaluated and middle diaphysis showed the highest impact resistance among them. Similarly load-displacement behavior of the three diaphysis was studied using the FE model of Charpy test.**

***Index Terms*— Charpy test, Cortical bone, Finite Element Simulation, Impact resistance.**

I. Introduction

Bone anisotropy reflects the directionality in its microstructure and ultrastructure [1, 2]. It is generally considered as orthotropic material having three perpendicular planes of elastic symmetry. The mechanism of bone failure depends on number of parameters such as quality of bone, bone structure, composition and type of loading [3, 4]. The study of fracture in bone is important from mechanical as well as medical point of view. This is helpful for the material scientists to design and develop improved bone implants, on the other hand it is also helpful for the orthopedics to prevent bone failure and to improve the quality of bone. In order to have a better insight into fracture mechanics, toughness is the critical bone property instead of strength because it controls the behavior of the bone during impact conditions [9, 10, 11].

The main causes of bone's fracture during day to day life are falls, high energy trauma, transportation and individual accidents. These fractures are caused by the sudden appearance of an impact load that exceeds the impact strength of bone material, where impact strength is the ability of bone material to absorb energy during impact loading prior to fracture. In the process of studying bone fracture, the measurement of energy absorbed is the most critical area of focus, due to spontaneous loading during a simple fall. Charpy test [12, 13] is a standardized high strain-rate test used to determine the amount of energy absorbed by the testing specimen during fracture.

Although, the analysis of impact resistance of bone is important to improve the impact quality of bone, a limited literature is available in this direction. Most of the previous studies on impact behavior of bone were conducted on long bone specimens subjected to impact loading [5, 6]. These studies were limited to a specific anatomic location of bone diaphysis without providing overall dynamic response of bone material along its diaphysis.

The purpose of the present investigation is to study the effect of locational variation on impact resistance in cortical bone with the help of Charpy test and finite element simulation. Taking consideration to the hierarchical structure of the bone [7, 8], the charpy specimens are prepared such that, the local variations in the micro structural properties do not create large variations in the impact resistance of the bone. The impact resistances obtained from the experimental results and the load-displacement curves acquired from the finite element analysis have been used to analyze the impact behavior of cortical bone.

II. Material and Method

A. Sample Preparation

The present work is performed on the tibiae cortical bone obtained from a young buffalo of age between 24 to 36 months. The bones were obtained just after an animal's natural death and with the permission of the farm's administration where it was raised. Soon after the extraction of bone tissue from the body, the surrounding soft tissues were removed and bone tissue was wrapped in gauze, soaked in normal saline, wrapped with plastic wrap, and placed in sealed, airtight plastic bags. The bags were then placed in a freezer and stored at -20ºC within 1 hour after the bone had been harvested. The bones are kept hydrated in

Manuscript received March 17, 2016.
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a saline solution of 50% Ethanol and 50% Saline upon removal from the freezer upon all stages of tissue preparation.

The rough cuts were made with the help of hacksaw blade. The area affected by overheating during rough cut was removed by using wet sand paper. The flattening of the sample was then carried out by using belt sander. The whole bone diaphysis is divided into three equal parts namely; upper, middle and lower bone diaphysis. The specimens are cut from different locations from the circumference of the bone namely anterior, posterior, medial and lateral locations. For the specimen preparation, the epiphyses ends of the long bone were removed using vertical band saw leaving only the diaphysis section. In total thirty six specimens were obtained from different anatomic locations as shown in Table 1. The three strips extracted from different locations have a notch angle of 45°, notch depth of 0.8 mm, width of 9.08 mm, thickness of 2.9 mm and a span length of 34 mm.

TABLE I
BREAKDOWN OF SPECIMENS FROM DIFFERENT LOCATIONS

		Circumferential Location			
		Lateral	Medial	Anterior	Posterior
Diaphysis Location	Lower	3	3	3	3
	Middle	3	3	3	3
	Upper	3	3	3	3
Total Specimens		36			

B. *Experimental Testing*

Experimental tests were conducted on Zwick Pendulum Impact tester for sub-size specimens. It is a pendulum-type single—low impact test in which a notched specimen is supported at both ends as a single beam and is then broken by a falling pendulum. The energy transferred to the material can be inferred by comparing the difference in the height of the hammer before and after fracture. The Zwick Pendulum Impact tester is shown in Fig. 2.

Fig. 2. Zwick Pendulum Impact Tester for sub-size specimen

C. *Finite Element Simulation*

In this study, load-displacement behavior of Charpy specimens has been simulated using commercial based software known as ABAQUS. The three dimensional finite element modelling has been done to make the required

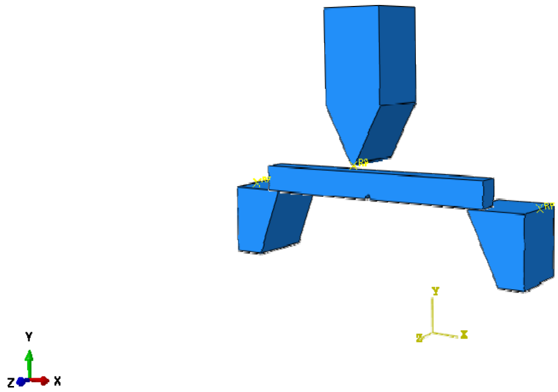

Fig. 3. Assembly of Charpy Impact test.

assembly consisting of V-notch specimen, Hammer and Anvils, out of which only the specimen is modelled as deformable while the hammer and anvils are modelled as discretely rigid. The three dimensional FE model of the assembly is shown in Fig. 3.

Interaction between hammer and specimen is defined by general contact and the interaction between specimen and anvils is defined by surface to surface contact that is contact pair algorithm in ABAQUS/Explicit. Meshing has been done using 8 node linear brick element with reduce integration and hourglass control. Anvils are kept fixed by using the boundary condition option Encaster (rigidly constrained) whereas the hammer is allowed to translate in the y – direction. Specimen has been locked in the z-direction as per the actual condition in order to avoid its slipping on application of load. For the present simulation, the values of density for the FE specimens of upper, middle and lower diaphysis are specified as 1.753 gm/cm^3, 1.998 gm/cm^3 and 2.017 respectively [14]. The wet density of bone material for three diaphysis locations were measured by cutting subsequent samples from the tested specimens. Young's modulus and poison's ratio are taken to be 22.19 GPa and 0.4 respectively for all the three specimens [14].

Experiment on Zwick Impact Testing machine provided the values of quantities such as Initial Energy, velocity and mass of hammer, which have been used in the finite element simulation. Hammer is given an initial energy of 15 J along with velocity and mass of 3.85 m/s and 2.02 kg.

III. RESULTS AND DISCUSSIONS

The specimens obtained from upper, middle and lower diaphysis were subjected to charpy impact test. The results obtained from the experimental Zwick Pendulum Impact Test are listed in Table 2, showing the Impact energy, Net cross-sectional area and the Impact resistance of the three diaphysis locations of a Buffalo tibiae cortical bone.

TABLE II
IMPACT RESISTANCE OF CORTICAL BONE ALONG THE LENGTH OF DIAPHYSIS

Bone Category	Location	Impact Resistance (KJ/m^2)
Buffalo Tibiae	Upper	1.08 ± 0.1158
	Middle	1.135 ± 0.3612
	Lower	0.957 ± 0.2112

ISBN: 978-988-14048-0-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Impact energy obtained from the experimental results is divided by the net cross sectional area of the specimen to convert it into Impact resistance. Experimental results of the Charpy test show that the impact resistance is maximum in middle diaphysis with a value of 1.135 kJ/m^2 followed by the upper diaphysis with a value of 1.08 kJ/m^2 and the minimum value was obtained for the lower diaphysis with a value of 0.957 kJ/m^2.

In the finite element simulation, the specimen is under impact loading due to inertia of hammer (pendulum). The deformed shape of the charpy specimen is shown with the help of its contour profile in fig.4.

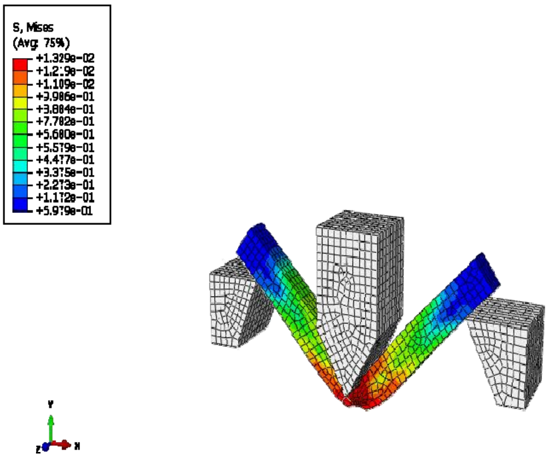

Fig. 4. Contour profile of the deformed shape of Charpy specimen.

From the simulation, the values of contact forces (load) and load point displacement (LPD) at the point of contact between hammer and specimen has been evaluated. Load at fracture, has been obtained. Load-displacement curves for upper, middle and lower diaphysis are shown in Figs. 5, 6 and 7 respectively. The curves have been then used to identify the maximum load for the three diaphysis's locations, values of which are clearly illustrated in Table 3.

TABLE III
RESULTS OBTAINED FROM FE SIMULATION OF CHARPY TEST

Diaphysis location	Maximum load (N)
Upper	850.74
Middle	860.49
Lower	840.20

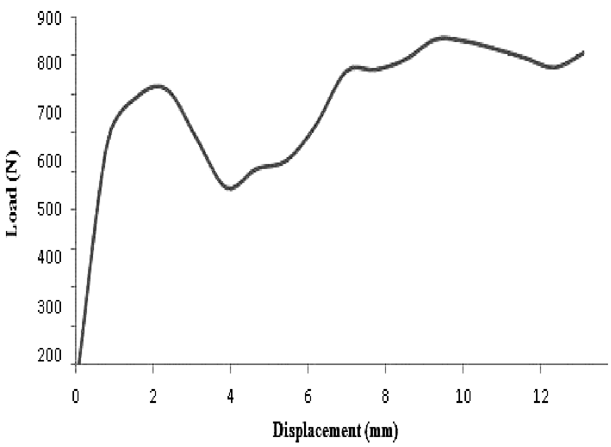

Fig. 5. Load-displacement curve of the Upper diaphysis obtained from FE simulation of Charpy test.

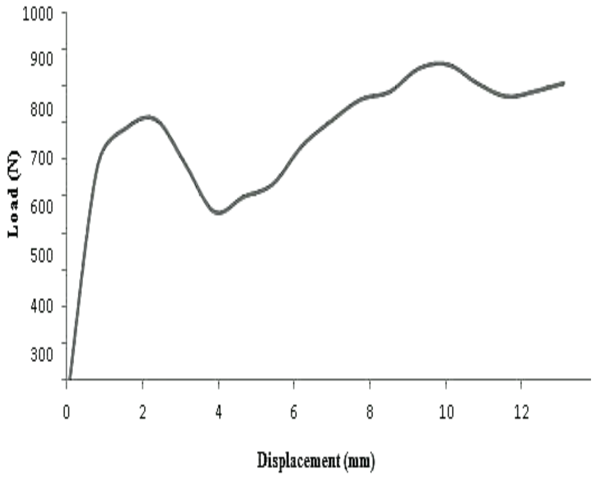

Fig. 6. Load-displacement curve of the Middle diaphysis obtained from FE simulation of Charpy test

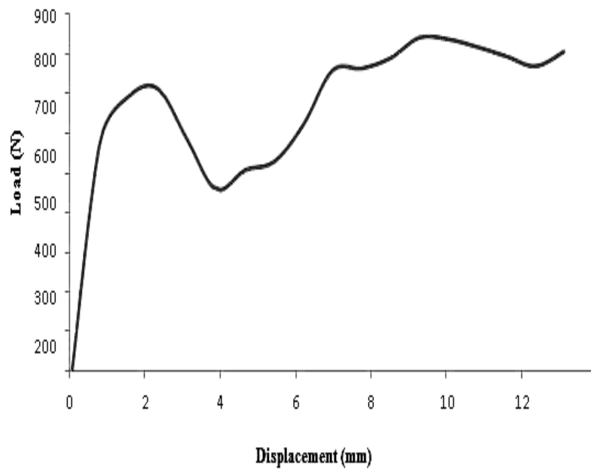

Fig. 7. Load-displacement curve of the Lower diaphysis obtained from FE simulation of Charpy test.

The results shows that the maximum load obtained is highest for the middle diaphysis that is 860.49 N followed by the upper diaphysis that is 850.74 N and least for the lower diaphysis that is 840.20 N.

IV. CONCLUSION

Based on the present investigation following conclusion are made;

i. Impact resistance is maximum for the middle portion of the bone whereas it is minimum for the lower portion of the bone.
ii. Maximum load is highest for the middle diaphysis and is least in the case of lower diaphysis.

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ISBN: 978-988-14048-0-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)