DESIGN AND DEVELOPMENT OF SMALL PUNCH TESTING FIXTURE TO PREDICT THE MECHANICAL PROPERTIES OF CORTICAL BONE

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ABSTRACT

A simple, versatile test rig for testing small bone samples was built up. This elaborates new features, in comparison to the previous one using big samples, as an alternative approach to predict the properties by using wide range of samples with varying thickness, shape and geometry. Testing fixtures are design and developed as per the shape of miniature samples. The displacement is measured with extensometer of precise range. The test rig is used on table top universal testing machine Tinius Olsen H50 KS. This technique gives a method of acquiring up-to-date mechanical properties of components expending a little measure of material in contrast with prerequisite for standard conventional methods. In most cases, the full-size specimen is generally obtained by decimating the parts. In these cases, small specimen testing innovation has advanced out of need to create material of parts used in nuclear power generation system, petroleum industry, chemical plants, thermal power station etc.

Keywords: Cortical bone; Fixture; Deflection; Small punch testing; extensometer.


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1. INTRODUCTION

It is presented that no work has been reported for evaluation of mechanical properties and fracture toughness in bones using small specimen technique. The small punch test gives off an impression of being best strategy existing at show which is fir for the giving the several mechanical properties of materials and components. Acquiring standard size specimens from bones is a very tough task since, they come in various shapes and sizes, and neither of them
has the geometry and gross morphology of a proper mechanical test specimen. The matter of truth is that the asymmetrical shape and the compact size of the bone make the conventional testing difficult to apply and interpret. Knowledge of mechanical properties of bones is essential for designers of prosthetic devices. The possibility of determining these properties by small specimens is particularly interesting since it would allow designers to personalize and so improve the design of prosthesis. [1, 2, 3]

Bone is treated as a heterogeneous, anisotropic 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 into 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 anatomic locations are taken into consideration [4]. The miniature specimen technique can be especially appealing in investigating the effect of non-uniformity of bone mechanical properties. This may likewise be utilized for concentrate natural biological materials that are not accessible in sufficiently extensive volumes for traditional mechanical testing. Smaller than expected example test strategy has developed to take care of this commonsense issue. The present examination depends on the mechanical test of cortical bones. The mechanical characteristics of cortical bone is critical from both the clinical and designing perspective for the advancement of better implantation and to comprehend the impact of age, drug treatment, and sickness and so on. The investigation manages the plan, improvement and use of a small scale example test innovation for anticipating the mechanical properties of cortical bone utilizing rectangular smaller than normal examples.

The study involves numerical as well as experimental investigation of bovine cortical bone with respect to its mechanical behavior. The experimental investigation on small size specimens of cortical bone has been carried out using small punch test method. These specimens are prepared in longitudinal directions of the bone diaphysis to analyze the directional effect on deformational behavior of cortical bone. The small punch test is performed on Tinius Olsen H50 KS Table Top Machine at a displacement rate of 0.05 mm/min and the load-displacement behavior of cortical bone. Based on the experimental results, new empirical relations are developed for the estimation of mechanical properties of cortical bone [5,6,7]. The results obtained from miniature specimen tests were validated by conducting tensile tests on large size specimens from different diaphysis of bovine cortical bone.

2. MATERIAL AND METHODS

A simple flexible set up for testing small specimen utilizing small punch test strategy is composed and created. The points of interest of such a setup for tentatively deciding the mechanical conduct of materials are researched and portrayed; it joins a few new highlights, for the most part found in past plans. In the present investigation, the small punch example test system used for wide extraordinary of small specimen geometry. The small specimen holders are outlined according to the state of small specimens. A unique installation is intended to test little examples ordinarily in the pivotal ways. This contraption is exceptionally flexible to test unclamped or completely clamped small specimens on Tinius Olsen H50 KS universal testing machine[7,8,9,10,11,12,13].

The points secured incorporates the experimental details of the apparatus designed and developed for SSTT incorporates the outline set up for the small specimen punch test method. Specimen preparation, elements of the testing machine, and distinctive methods for estimation and so on. Small specimen holders are outlined keeping in mind the specimen geometry.
Furthermore, an uncommon kind of apparatus is intended to test small specimens in the longitudinal way.

3. EXPERIMENTAL SETUP FOR SMALL PUNCH SPECIMEN TEST

3.1. Design Features of SPSTT Apparatus

The essential parts of the testing technique are punch and specimen holders known as a die, punch holder for load application and load v/s displacement measuring devices. The small specimen is supported by a rectangular slot in the die. The load is applied by a punch which is attached to the punch holder. This assembly is gripped in the universal testing machine. Appropriate load cells are selected to accurately record the load application on the specimen [14, 15, and 16]. The displacement of the specimen upon load application is measured precisely.

3.2. Bone Preservation

Bone has a structure which changes with the compositional parameters. The water content in bone is approximately 6% of weight whereas, for hydrated bone, water amount can rise up to 11% of the volume [17, 18, 19, 20]. An environmental condition affects the mechanical properties. Due to this, storage and handling was done very carefully. For the present study, femur bone of young bovine is taken and after the removal of waste and tissues, it was wrapped with a cloth soaked in saline water and further wrapped with plastic wrap and kept in sealed, airtight plastic bags. These plastic bags are then placed in a freezer and stored at -20° within an hour of harvesting the bone.

The small samples have been prepared as following. The whole bovine cortical bone diaphysis is shown in Fig. 1 and Fig. 2. The diaphysis of the bovine tibia was cut with a hacksaw to a length of 80 mm perpendicular to the longitudinal axis of the bone for each upper, middle and lower part. The 80 mm diaphysis bone was cut into rectangular segments in longitudinal directions of the bone. The rectangular segments as shown in Figure 3 were polished on a water cooled grinding table with 320 grit silicon carbide paper into straight beams with a rectangular cross-section of width 16mm and thickness 2 mm. The samples are cut longitudinally keeping an allowance to remove the overheated portion of the bone[21].

![Figure 2](image-url) unfinished rectangular section of bone
![Figure 1](image-url) bovine cortical bone (diaphysis)

![Figure 3](image-url) bone specimens in saline solution.

![Figure 4](image-url) rectangular small specimen
At all stages in this procedure, the bone was either immersed in or kept moist with saline solution. Finally, longitudinal small specimens of length 16mm and cross-section 2mm X 2mm as were cut on a Buehler Isomet 5000 low-speed linear precision saw. The deviation in thickness was maintained within 1%. Prepared rectangular specimens of cortical bone are shown in Fig. 4 and Figure 5.

3.4. Design for Specimen Holder
The specimen being very small could not be directly gripped in the machine, as the die holder requires for this as shown in Fig. 6. The outer dimension of the sample holder is taken in a way that the holder fits smoothly on the fixture plates. Die inner bore is provided with a circular pocket of 10mm diameter to allow the specimen to be displaced into the pocket when the load is applied by the punch as well as for measuring the specimen displacement. The slot to put the specimen in the die can be adjusted with a special adjustment which can help in testing specimens for different effective length. The adjustment can be made to test a specimen of length up to 4mm. Small specimens of varying thicknesses and lengths can be accommodated by these specimen holders. These holders can accommodate rectangular specimens with varying dimensions.

The specimen is tested without supporting the outer edges which present a situation of shear. During testing of small specimens, various degrees of fixity can be created by the present setup. The top view of specimen holder is shown in Fig. 7 and picture of specimen holder are shown in Figure 8.
A special die holder is designed in order to support the die while the tests are performed. The holder has a bore of 20 mm so that the part of the die can be fitted in the holder. The die holder is facilitated with the slot at lower end for easy removal of samples after performing the test. The die holder has high dimensional stability after heat treatment. The die holder was austenitized at 1000°C, cooled own through the process of air cooling followed by tempering at 700°C for an hour, to achieve the hardness. The details of die holder are shown in Fig. 9.

3.5 The Design and Development of Punch holder and Punch

The punch and punch holder are important parts of the experimental 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 to accommodate the punch tightly. The punch holder has a 15 mm cylindrical hole with 6.3 mm diameter.

The designed tip of the punch is cylindrical in shape. The cylindrical headed tip punch is manufactured of heat treated tool steel. To attain the desired hardness and strength, the punch was heat treated as follows. The steel was austenitized under argon atmosphere for 30 minutes at 1000°C for an hour followed by oil quenching to get the final hardness of HRC 65 at the tip of punch. The lower part of punch is of 15 mm long with 6.3 mm diameter and this is precisely maintained for correct fitting in the punch holder. The detailed dimensions of the cylindrical headed punch are shown in Figure 11.
3.6 The Design and Development of Small Specimen Testing Technique (SSTT) Fixture

The tests on small samples are performed on a universal testing machine. The difficulties were noted in the alignment of punch, small 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 and die axis of symmetry be coincident
(b) Design tolerances for the punch and dies
(c) Uniform thickness of the sample

The test fixture with two plates having center holes: the diameter of the hole and outer diameter of the die is same as i.e. 30 mm. These plates are attached to two cylindrical bars; the plates would come closer to one as shown in Fig.12 in the assembled mode. The sample holder with a small sample, the punch holder, and the punch can be fitted or removed at any stage from the test fixture without any difficulty. Fig. 13 shows the fixing of the fixture on a Tinius Olsen H50 KS Universal Testing Machine.

3.7 The Measurement of Displacement under the Punch

It was noticed that the total displacement of the small sample was quite small. Therefore, care to be taken for measuring the displacement of the samples during loading. The displacement can be measured using the following techniques;
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(a) The measurement may be done using the x-y recorder through the movement of crosshead. Since the total displacement in the specimen is so small (~0.1-0.5 mm), this technique gives an undue error in the measurement. So the crosshead movement was not employed for the displacement measurement.

(b) The dial gauge with an accuracy of 0.001 mm should be fixed to the lower plate of small punch test fixture. However, the measurements are to be recorded manually in this case which may involve some error. So the use of dial gauge was not preferred.

(c) In the present investigation, the displacement of the sample was measured using an extensometer. An extensometer is fixed between the extension arm attached to the specimen and the knife edge mounted on the bracket attached to the fixture. The lower arm of extensometer is connected to another sharp knife edges. The least count of the extensometer used was 1µm. The load - displacement diagrams obtained from the experiments is recorded automatically in the Tinius Olsen Horizon software, interfaced with the Tinius Olsen H50 KS table top Universal Testing machine.

3.8 Testing Machines
In the present investigation, all the small specimen tests have been carried out in the Tinius Olsen H50 KS table top system of 1kN to 50 kN capacity. The machine has a versatile feature for varieties of tests. The Tinius Olsen H50 KS intelligent system software is connected to the machine using standard interface. The machine has two crossheads, the top crosshead is stationary and the bottom crosshead is movable along the downward vertical axis. All the inputs and the movements of the machine were conducted through the software. Before the testing, the computer system had to be switched on and the connection with the machine was established through Tinius Olsen Horizon H50 KS. The software contains a number of different modules for different types of tests with different load cells. The appropriate module had to be selected for carrying out the test to get the maximum possible accuracy. An extensometer was used to measure displacement during experimental procedure.

4. RESULTS
The results of small punch test were obtained in the form of load- load point displacement. The load displacement curves are shown in Fig.15. The values of maximum load ($P_{max}$) and maximum displacement ($\delta_{max}$) obtained from different load-displacement curves of the longitudinal specimens are reported in Table 1. The value of stiffness was calculated from the load per unit displacement values of the linear portion of load-displacement curve. The results of different parameters obtained from small punch test are shown in the form of box and whisker plots from Figure 16 and Figure 17.

![Figure 15 load-load point displacement curves for different diaphysis of cortical bone](image-url)
Table 1. Results of small punch testing in case of longitudinal specimens of cortical bone

<table>
<thead>
<tr>
<th>Different parameters</th>
<th>Specimen Location</th>
<th>ANNOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper</td>
<td>Middle</td>
</tr>
<tr>
<td>$P_{\text{max}}$ (N)</td>
<td>100.46 ± 9.278</td>
<td>120.40±10.423$^{a,b}$</td>
</tr>
<tr>
<td>$\delta_{\text{max}}$ (mm)</td>
<td>0.50 ± 0.011$^b$</td>
<td>0.59 ± 0.029$^{a,b}$</td>
</tr>
</tbody>
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$^a$Indicates a statistically significant difference compared with upper location ($p < 0.05$).
$^b$Indicates a statistically significant difference compared with lower location ($p < 0.05$)

Figure 16 box and whiskers plot of maximum load obtained from small punch test

Figure 17 box and whiskers plot of maximum deflection under the curve from small punch test

The mechanical properties $P_{\text{max}}$ (N) and $\delta_{\text{max}}$ obtained for different locations of cortical bone diaphysis from small punch testing indicate that one or more means of these properties are statistically different.

The values of different parameters reported in Tables 1 were compared with the help of unpaired $t$-test analysis for different diaphysis locations of critical bone specimens. The significance level was set at $p < 0.05$.

The $P_{\text{max}}$ (N) for middle diaphysis locations was significantly greater ($p < 0.05$) than the corresponding value of upper diaphysis. The value of $P_{\text{max}}$ (N), for upper diaphysis are found to be significantly same as ($p < 0.05$) the value of lower diaphysis.

The $\delta_{\text{max}}$ for middle diaphysis locations was significantly greater ($p < 0.05$) than the corresponding value of upper diaphysis. The value of $\delta_{\text{max}}$ for lower diaphysis are found to be significantly greater ($p < 0.05$) than the value of upper diaphysis.
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