Abstract—Detailed characterization of mechanical properties of cortical bone is important for engineering as well as medical point of view. This requires determination of mechanical properties for different anatomic locations of cortical bone using very small size of specimens. However, it is a challenging task to perform conventional tests on small size specimens of bone material due to various constraints. Small punch testing can be used in this direction to overcome these constraints. This technique has been employed in the present study along with the inverse finite element (FE) method to evaluate the elastic modulus of cortical bone at different anatomic locations. This way the load-displacement curves obtained from small punch testing were matched with the corresponding FE simulated curves to determine the elastic modulus of cortical bone at a particular anatomic location. This study shows that the predicted values of elastic modulus for different anatomic locations of the mid diaphysis of bovine tibiae cortical bone range from 20.4 GPa to 26.3 GPa. These results are almost similar to those obtained in previous investigations performed on bone material by using conventional tensile testing. Based on the results of the present study, it has been suggested that the same technique can be used to evaluate the anatomic variation in other mechanical and fracture properties of cortical bone.

Keywords—Cortical bone, Elastic modulus, Inverse finite element method, Small punch testing.

I. INTRODUCTION

Bone is a highly heterogeneous and anisotropic material [1]-[11]. The heterogeneity of bone material is responsible for variation in its mechanical properties from one anatomic location to another. The investigations on the anatomic distribution of mechanical properties of bone would not only be helpful for the clinical scientists but also for the engineers working on bio-inspired materials. Most importantly, the evaluation of key mechanical properties of bone such as its elastic modulus at different anatomic locations is required for the design and development of prosthetic bone implants and whole bone finite element models.

The anatomic variation in elastic modulus of cortical bone can be analyzed by conducting experiments on small optimum size specimens. The optimum dimensions of the small size specimen should be maintained by keeping continuity of the hierarchical level of bone in to consideration. However, it is a challenging task to evaluate the value of strain during experimental deformation of small size specimens. Further the irregularity in specimen shapes, incorporation of defects during sample preparation and difficulty of comparison of results are the other constraints [12]-[17]. These constraints may be overcome by incorporating small punch technique in bone material testing. Previously, many researchers have applied this technique to determine the mechanical and fracture behavior of various engineering materials. Recently, this technique has been employed by Sharma et al. [18]-[19] to investigate the deformational behavior of bone material.

The present study is focused on the application of small punch testing technique to evaluate the anatomic variation in load-displacement behavior of cortical bone. An inverse finite element technique is further applied to compute the values of elastic modulus from the experimental load-displacement curves obtained for different anatomic locations. This has been achieved by matching the initial slope of the load – displacement curve obtained from experimental setup with the corresponding finite element simulated load-displacement curve.

II. MATERIALS AND METHOD

The present study has been conducted in tibiae bone obtained from young bovine of age between 24 to 36 months. The bones were obtained under institutional permission from the farm raised just after animal’s natural death. In all, twenty small specimens were prepared from different anatomic locations (Anterior, Medial, Posterior and Lateral) of the middle diaphysis. These specimens were prepared with square dimension (10 mm x 10 mm) having 1.5 mm thickness as shown in Fig. 1. All these specimens were preserved in a solution of 50% ethanol and 50% saline at all time until testing.

The small punch test was conducted on MTS 858 Table Top Machine with very small strain rate of 0.5 mm/min. The small bone specimen fixed inside the specimen die is shown in Fig. 2.
(a), whereas, complete fixture for small punch testing is shown in Fig. 2 (b). The installation of small punch test fixture on MTS machine is shown in Fig. 3. The displacement during small punch testing was measured with the help of clip gauge and the loading was applied using hemispherical headed punch of tip diameter 2.309 mm.

A three dimensional finite element (FE) model is used for simulating small punch testing with a square shape small (fixed plate) specimen under quasi-static loading applied by a hemispherical headed rigid punch.

The dimensions of the small specimen are decided on the basis of the inner borehole cross-section of the specimen holder. The FE model is discretized with 8 nodded hexahedral elements (C3D8R) as shown in Fig. 4. The hemispherical headed punch of tip diameter 2.309 mm is modeled as analytically rigid.

All the nodes along the four edges of the small square shape specimen are fixed by boundary condition option ENCASTER (rigidly constrained). The top surface of square specimen is defined as SLAVE surface, whereas, hemispherical headed tip of rigid punch is defined as MASTER surface. A closed surface interaction of SLAVE and MASTER surface is developed by contact algorithm of ABAQUS. A tie interface is used to account for the contact between the punch head and specimen. The quasi-static loading is applied using amplitude option and small incremental steps are used at the reference node of hemispherical headed punch. The three dimensional FE model of small punch test is shown in Fig. 5.

The FE analysis is carried out using inverse finite element process which is an iterative process. During this process the time history of output variable is defined and using this the time history of corresponding input variable is determined. As
per our previous study, the load-displacement curve obtained from FE model was found to be closer to the experimental curve while considering bone as an isotropic material [19]. Therefore, in this study bone material is considered as an isotropic material.

The initial slope of the experimental load-displacement curve obtained from the small punch testing is matched with the slope of corresponding FE simulated load-displacement curve to obtain the elastic modulus of cortical bone at different anatomic locations. The FE load-displacement curve is generated in iterative manner by increasing or decreasing the value of elastic modulus such that curve matches with the corresponding experimental load-displacement curve. After final iteration when both the curve matches, prescribed input value of the elastic modulus should be equal to the elastic modulus of the bone material for the corresponding anatomic location. During this analysis the values of Poisson’s ratio are defined from our previous study [8].

### III. RESULTS AND DISCUSSION

The values of maximum load ($P_{\text{max}}$) and displacement corresponding to the maximum load ($\delta$) are determined from various load-displacement curves. These values are listed in Table 1 for different anatomic locations of the cortical bone. The small cortical bone specimens after conducting small punch testing are shown in Fig. 6. The experimental load-displacement curves for different anatomic locations of cortical bone are shown in Fig. 7. The values of elastic moduli obtained for different anatomic locations of cortical bone using inverse FE method are reported in Table 2 and the variation in elastic moduli across the cross-section of the cortical bone is shown in Fig. 8.

#### Table 1

<table>
<thead>
<tr>
<th>Anatomic location</th>
<th>Maximum load, $P_{\text{max}}$ (N)</th>
<th>Corresponding displacement, $\delta$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>$582.7 \pm 42.4$</td>
<td>$0.42 \pm 0.052$</td>
</tr>
<tr>
<td>Medial</td>
<td>$551.6 \pm 18.1$</td>
<td>$0.34 \pm 0.056$</td>
</tr>
<tr>
<td>Posterior</td>
<td>$662.7 \pm 24.0$</td>
<td>$0.37 \pm 0.057$</td>
</tr>
<tr>
<td>Lateral</td>
<td>$639.6 \pm 25.2$</td>
<td>$0.39 \pm 0.062$</td>
</tr>
</tbody>
</table>

ANNOVA $p < 0.05$ $p > 0.05$

The values listed are the average of five values. Standard deviation is also given.

#### Table 2

<table>
<thead>
<tr>
<th>Anatomic location</th>
<th>Computed elastic modulus $E$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>21.4</td>
</tr>
<tr>
<td>Medial</td>
<td>26.3</td>
</tr>
<tr>
<td>Posterior</td>
<td>20.4</td>
</tr>
<tr>
<td>Lateral</td>
<td>24.3</td>
</tr>
</tbody>
</table>

The values of maximum load obtained for different anatomic locations of bone diaphysis indicate that one or more means of these values are statistically different. The experimental results reported in Table 1 show that the value maximum load at posterior location is highest as compared to
the other locations, whereas, displacement corresponding to the maximum load is highest at anterior location. As per the t-test analysis, the values of maximum load for posterior and lateral locations are not found to be significantly different, similarly, the later values for anterior and medial locations are not found to be statistically different. However, maximum load for posterior location is found to be significantly greater ($p < 0.005$) than that for anterior and medial locations. The ANOVA result shows that the mean values of displacement corresponding to the maximum load are not statistically different along the cross-section of the bone diaphysis.

The values of elastic modulus determined using inverse FE analysis are reported in Table 2. As per these results, the elastic modulus is found to be highest for the medial and lowest for the posterior location. These predicted values of elastic moduli range from 20.4 GPa to 26.3 GPa. It is interesting to note that almost similar range of elastic moduli have been reported for the bovine cortical bone in earlier investigations [6], [8], [20], [21]. This shows that the realistic values of elastic modulus can be predicted for different locations of bone diaphysis using small punch testing and inverse FE approach. The same approach can be further applied to evaluate the locational variation in other mechanical and fracture properties such as yield strength, shear modulus and fracture toughness.

IV. CONCLUSION

The values of elastic modulus were evaluated for different anatomic locations of the cortical bone using small punch testing and inverse FE approach. The small punch testing was conducted on square cross-section small specimens of cortical bone having 1.5 mm thickness. These specimens were obtained from four different anatomic locations of the middle diaphysis. The results of small punch testing were obtained in terms of load-displacement curves for different anatomic locations. The values of maximum load were found to be significantly greater for posterior and lateral anatomic locations as compared to the anterior and medial locations. An inverse FE technique has been further applied to determine the values of elastic modulus for different corresponding anatomic locations. The values of elastic modulus so obtained were found to be consistent with the corresponding values obtained in other previous reports. Based on the predicted results for elastic modulus, this study suggest that small punch testing and inverse FE technique can be applied together to predict the locational variation in other important mechanical and fracture properties of cortical bone.

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REFERENCES