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Comparative Study of Tensile Properties of Cortical Bone Using Sub-size Specimens and finite element simulation

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***Abstract*—**Bone material is treated as heterogeneous and hierarchical in nature therefore appropriate size of bone specimen is required to analyze its tensile properties at a particular hierarchical level. Tensile properties of cortical bone are important to investigate the effect of drug treatment, disease and aging as well as for development of computational and analytical models. In the present study tensile properties of buffalo as well as goat femoral and tibiae cortical bone are analyzed using sub-size tensile specimens. Femoral cortical bone was found to be stronger in tension as compared to the tibiae cortical bone and the tensile properties obtained using sub-size specimens show close resemblance with the tensile properties of full-size cortical specimens. A two dimensional finite element (FE) modal was also applied to simulate the tensile behavior of sub-size specimens. Good agreement between experimental and FE model was obtained for sub-size tensile specimens of cortical bone.

***Keywords*—**Cortical bone, Sub-size specimen, Full size specimen, Finite element modeling.

I. INTRODUCTION

BONE is a smart composite material, anisotropic and heterogeneous in nature. Bone material mainly consists of a network of type I collagen with hydroxiapatite minerals that reinforce it [1]. Its structural nature is responsible for higher values of stiffness, strength and fracture properties. Non-longitudinal axial distribution of orientation of bone minerals is considered as the main cause of anisotropic nature of bone material [2]. The anisotropic properties of bone material depend on its spatial architecture and composition. Bone stiffness is strongly influenced by structure of mineral crystals in bone tissue. The stress-strain behavior of bone tissue is useful to investigate the effects of drug treatments, aging and disease at the tissue level. The elastic and yield properties are also required for developing computational and analytical models [3-5]. Bone is considered to be stronger in compression compared to tension [6] therefore tensile properties of bone require much more attention in order to avoid the fracture risk and for the development of better prosthetic implantations. Taking hierarchical structure of bone into consideration, the specimen size of cortical bone should be such that the local variations in microstructural properties do not create large variations in properties at the more macroscopic level to characterize its tensile properties. The specimen thickness 1.5-2.0 mm giving an overall cross-section 4-20 mm^2 can be used to analyze the mechanical properties of cortical bone because such specimens contain various haversian systems/lamellae to provide significant data [7]. Choi *et al.* [8] in their study conducted three point bend test to observe the effect of specimen size on cortical bone modulus. They observed that the elastic modulus for relatively large specimens (height greater than 0.5 mm) remains fairly constant. Many researchers have used specimens of large size [9-13] to characterize the mechanical properties of cortical bone whereas from the clinical point of view an optimum size of specimen is required that can be easily extracted and prepared to provide mechanical properties at a particular architectural level.

In the present work sub-size tensile specimen of less than one fifth length to that of the full-size specimen is used to analyze the mechanical properties of cortical bone. The results are further compared with the results obtained from full-size specimen testing. The finite element simulation of sub-size tensile test is also carried out using commercially available implicit version of ABAQUS code.

II. MATERIALS AND METHOD

A. Specimen preparation

The present work is performed on buffalo as well as goat femoral and tibiae cortical bones. These bones were obtained from young buffalo of age about 24 months and goat of age about 30 months. The tensile properties of cortical bone in longitudinal direction were evaluated using dumbbell shape strip type sub-size specimens. In all 32 specimens were cut from middle location of buffalo and goat bone diaphysis out of which sixteen specimens of thickness 2.5 mm and other dimensions as shown in Fig.1 were obtained from femoral bone and the other sixteen specimens with same dimensions from tibiae bone. Two holes of radius 1 mm were made, as shown in the figure, in order to provide gripping to the specimen on testing machine.

All the specimens were preserved at room temperature in a

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solution of 50% saline and 50% ethanol at all time until testing and a constant spray of water was supplied to keep the specimens wet during preparation and testing.

B. Experimental testing

The uniaxial tensile tests were performed on MTS 858 Table Top Machine (2.5 T capacity). A miniature extensometer of 5 mm gauge length was used to measure the strain values at the gauge region of tensile specimens. Sub-size tensile specimen mounted on MTS 858 Table Top Machine with the help of two fixtures is shown in Fig. 2.

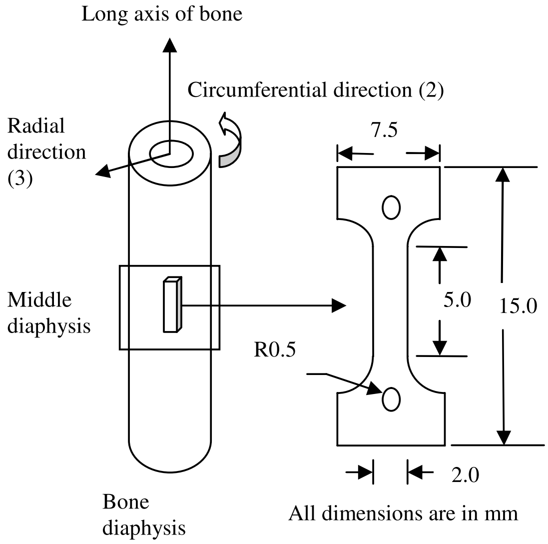

Fig. 1 Diagram showing the location of bone diaphysis from where the longitudinal sub-size specimen was prepared and dimensions of the specimen

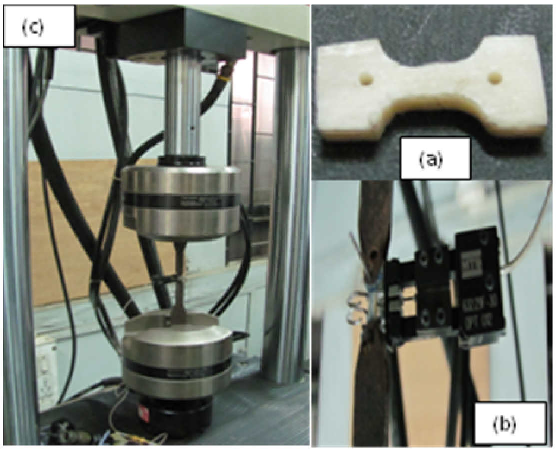

Fig. 2 Diagram showing (a) Sub-size specimen prepared for testing (b) Miniature extensometer and fixtures attached to the specimen (c) specimen mounted on MTS Machine

The results of sub-size tensile testing were compared with the results of full-size tensile testing where the specimens of dimensions 2.5 mm thickness, 25 mm gauge length, 4 mm gauge width and 80 mm total length were used. The tensile properties of full-size specimens of buffalo femoral and tibiae cortical bone at middle location of bone diaphysis were obtained from a separate study [14]. The comparisons of stress-strain behavior of buffalo femoral and tibiae cortical bone for sub-size and full-size tensile specimens are shown in Figs. 3 and 4 respectively where as for goat femoral and tibiae cortical bone it is shown in Figs. 5 and 6 respectively. Fig. 5 shows typical analysis of the stress-strain curve for cortical bone to obtain the values of elastic modulus (*E*), yield strength (σ_{yt}), yield strain (ε_{yt}), ultimate strength (σ_{ut}) and ultimate strain (ε_{ut}).

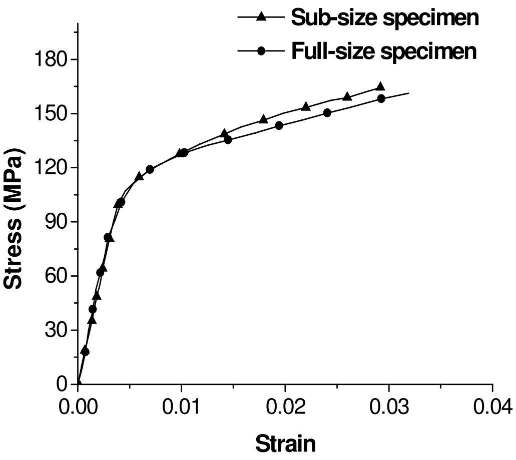

Fig. 3 Stress-strain behavior of sub-size and full-size tensile specimens for buffalo femoral cortical bone

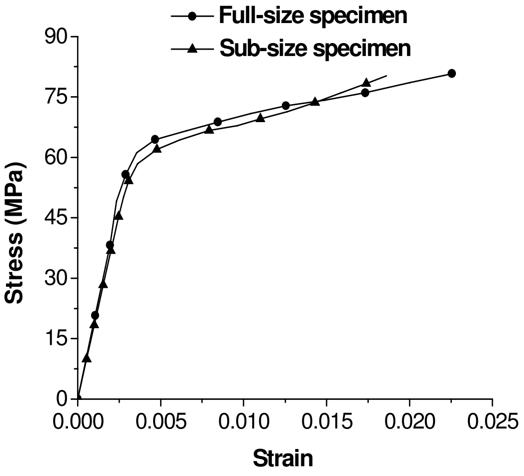

Fig. 4 Stress-strain behavior of sub-size and full-size tensile specimens for buffalo tibiae cortical bone

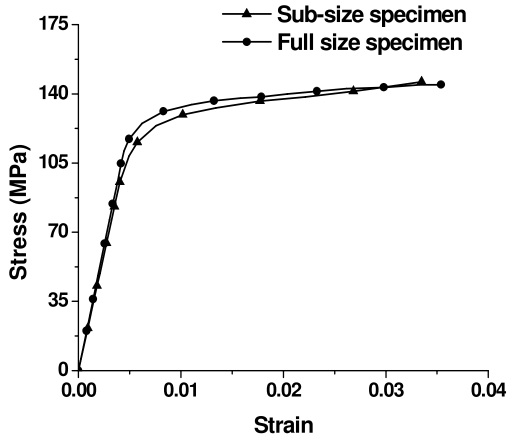

Fig. 5 Stress-strain behavior of sub-size and full-size tensile specimens for goat femoral cortical bone

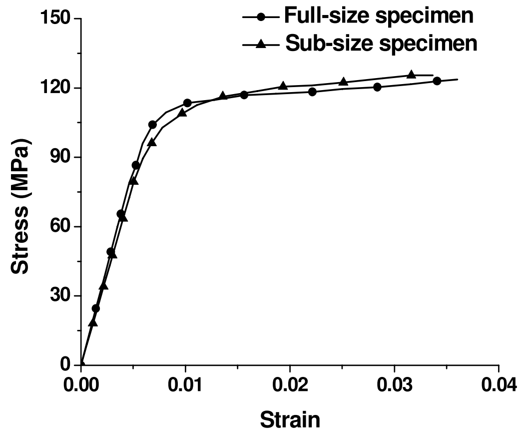

Fig. 6 Stress-strain behavior of sub-size and full-size tensile specimens for goat tibiae cortical bone

TABLE I
TENSILE PROPERTIES OF BUFFALO FEMORAL CORTICAL BONE FOR SUB-SIZE AND FULL-SIZE TENSILE SPECIMENS

	Sub-size specimen (n = 8)	Full-size specimen* (n = 4)	% Difference
E (GPa)	26.5 ± 1.86	27.3 ± 1.75	2.93
σ_{ys} (MPa)	116.1 ± 3.65	114.3 ± 2.53	1.57
ε_{ys}	0.0062 ± 0.0009	0.0061 ± 0.0008	1.63
σ_{us} (MPa)	164.4 ± 7.43	161.3 ± 8.62	1.88
ε_{us}	0.0291 ± 0.0067	0.0320 ± 0.0022	9.06

TABLE II
TENSILE PROPERTIES OF BUFFALO TIBIAE CORTICAL BONE FOR SUB-SIZE AND FULL-SIZE TENSILE SPECIMENS

	Sub-size specimen (n = 8)	Full-size specimen* (n = 4)	% Difference
E (GPa)	18.4 ± 1.13	19.6 ± 1.41	6.12
σ_{ys} (MPa)	62.9 ± 2.05	65.1 ± 1.58	3.37
ε_{ys}	0.0052 ± 0.0009	0.0054 ± 0.0004	3.70
σ_{us} (MPa)	80.6 ± 2.40	81.0 ± 4.12	0.49
ε_{us}	0.0187 ± 0.0012	0.0226 ± 0.0053	1.72

(*Data from Ref. 14)

TABLE III
TENSILE PROPERTIES OF GOAT FEMORAL CORTICAL BONE FOR SUB-SIZE AND FULL-SIZE TENSILE SPECIMENS

	Sub-size specimen (n = 8)	Full-size specimen (n = 4)	% Difference
E (GPa)	23.6 ± 2.38	25.2 ± 2.74	6.35
σ_{ys} (MPa)	121.7 ± 2.58	127.3 ± 4.31	4.39
ε_{ys}	0.0069 ± 0.0029	0.0071 ± 0.0004	2.81
σ_{us} (MPa)	146.1 ± 5.11	144.7 ± 7.28	9.67
ε_{us}	0.0333 ± 0.0028	0.0353 ± 0.0054	5.61

TABLE IV
TENSILE PROPERTIES OF GOAT TIBIAE CORTICAL BONE FOR SUB-SIZE AND FULL-SIZE TENSILE SPECIMENS

	Sub-size specimen (n = 8)	Full-size specimen (n = 4)	% Difference
E (GPa)	15.7 ± 1.98	17.1 ± 2.10	8.18
σ_{ys} (MPa)	105.9 ± 4.92	110.2 ± 6.68	3.90
ε_{ys}	0.0087 ± 0.0008	0.0084 ± 0.0072	3.34
σ_{us} (MPa)	124.8 ± 7.72	124.2 ± 4.40	0.46
ε_{us}	0.0339 ± 0.0071	0.0359 ± 0.0048	5.62

C. Experimental testing

In the present study the sub-size specimen, being very thin compared to the other dimensions, is modeled in two dimensional space as shown in Fig. 7. The sub-size specimen was modeled as deformable body and loading pins were modeled as analytically rigid body. As the model is half model (symmetric about Y axis) symmetric boundary condition was applied along the Y axis. The bottom loading pin was constrained in all directions while the top pin was allowed to move freely only in Y direction. Load was applied at the reference point of the top pin.

The values of true stress and true strain were obtained from the values of nominal stress (σ_{nom}) and strain (ε_{nom}) using equations 1 and 2 respectively. The relationship between true stress (σ_{true}) and true plastic strain (ε^{P}_{true}) used in the simulation is given in equation 3.

$$\sigma_{true} = \sigma_{nom}(1 + \varepsilon_{nom}) \tag{1}$$

$$\varepsilon_{true} = \ln(1 + \varepsilon_{nom}) \tag{2}$$

$$\varepsilon^{p}_{true} = \varepsilon_{true} - \frac{\sigma_{true}}{E} \tag{3}$$

where E is the Young's modulus of the static engineering stress-strain curve. The value of Poisson's ratio was assumed to be 0.4 for all cases.

The test specimen part was meshed with eight nodded plane stress quadratic quadrilateral elements. Plane stress elements were used because the thickness of the body or domain is small relative to its in-plane dimensions. The stresses are functions of planar coordinates alone and the out-of-plane normal and shear stresses are equal to zero. Plane stress elements were defined in X-Y plane, and all loading and deformation were also restricted to this plane. The modal consists of 566 elements and 1845 nodes. The finite element model of sub-size specimen in two dimensional space and along with the mesh is shown in Fig. 8. The contour profiles for buffalo and goat femoral as well as tibiae cortical bone specimens are shown in Figs. 9 and 10 respectively where S22 is the stress induced in Y direction.

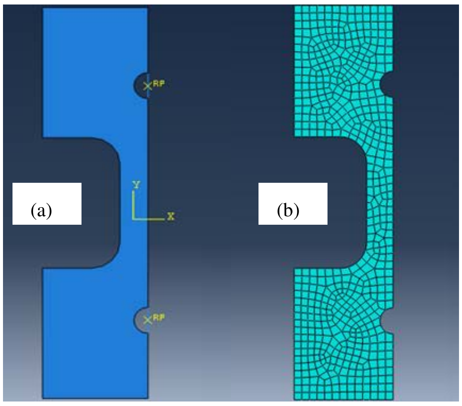

Fig. 7 Diagram showing the finite element model of sub-size specimen (a) two dimensional half model of sub-size specimen (b) modal of sub-size specimen along with mesh.

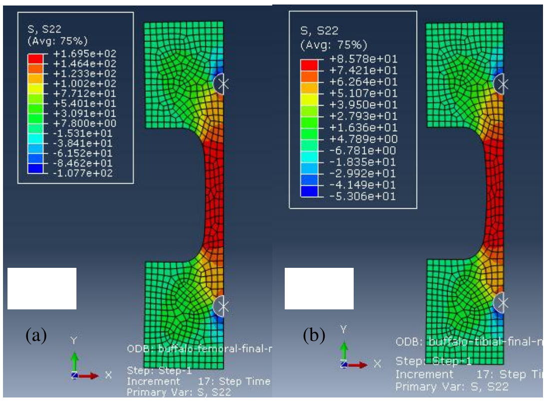

Fig. 9 Contour profile showing elongation in buffalo (a) femoral and (b) tibiae cortical bone specimens

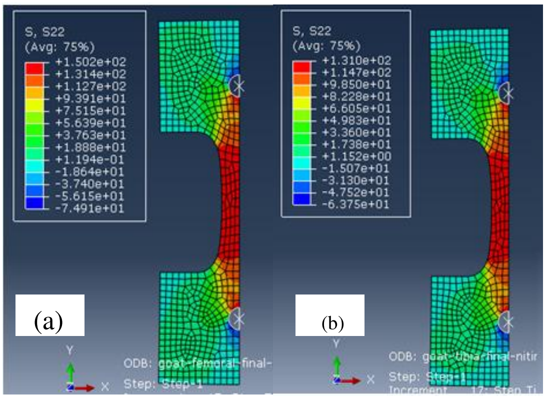

Fig. 10 Contour profile showing elongation in goat (a) femoral and (b) tibiae cortical bone specimens

The comparisons of stress-stain curves obtained from FE simulation and experiments for buffalo femoral and tibiae cortical bone are shown respectively in Figs. 11 and 12 whereas for the case of goat femoral and tibiae cortical bone are shown in Figs 13 and 14 respectively.

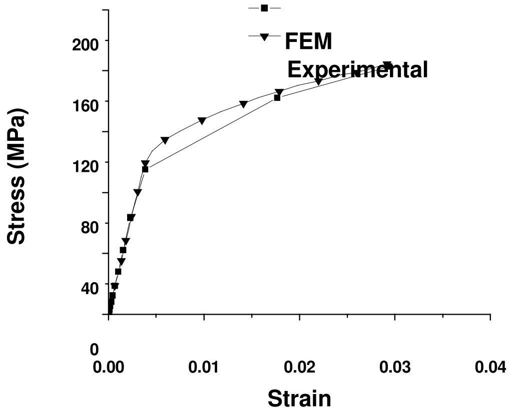

Fig. 11 Comparison of experimental and FE simulation stress-strain curves for buffalo femoral cortical bone

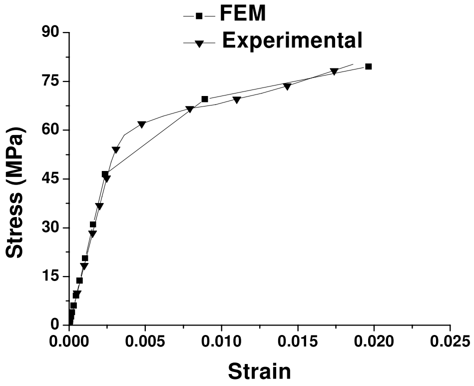

Fig. 12 Comparison of experimental and FE simulation stress-strain curves for buffalo tibiae cortical bone

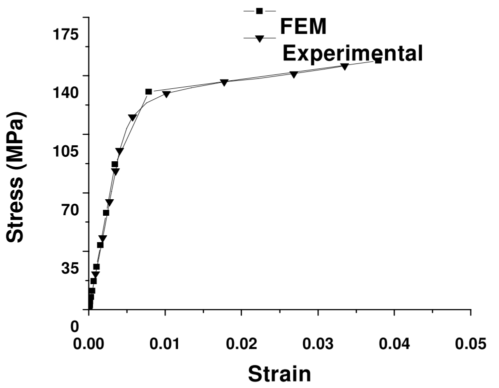

Fig. 13 Comparison of experimental and FE simulation stress-strain curves for goat femoral cortical bone

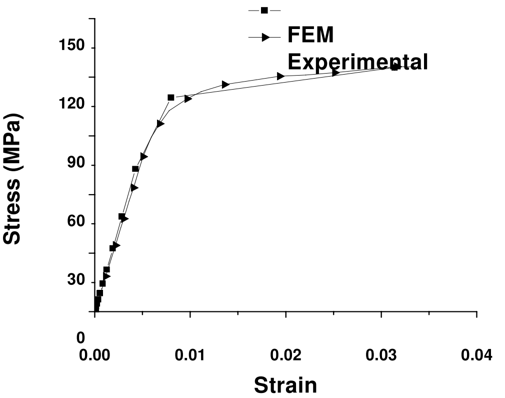

Fig. 14 Comparison of experimental and FE simulation stress-strain curves for goat tibiae cortical bone

III. RESULTS AND DISCUSSION

The tensile properties of buffalo as well as goat femoral and tibiae cortical bone are calculated using sub-size tensile specimens as described above. Full-size specimens for goat femoral and tibiae cortical bone are also tested. The values of elastic modulus (E), yield strength (σ_{ys}), yield strain (ε_{ys}), ultimate strength (σ_{us}) and ultimate strain (ε_{us}) in case of sub-size and full size tensile specimens as obtained above are listed in Tables 1 to 4. The results reported in all given Tables are the average values and n gives the number of samples tested. Standard deviations are also given.

The stress-strain curves obtained from FE simulation using two dimensional half model of sub-size specimen show good agreement with the experimental curves as shown in Figs. 11 to 14 for femoral as well as tibiae buffalo and goat cortical bones.

A. Comparison of tensile properties for femoral and cortical bone

It may be noted from Tables 1 to 4 that the values of elastic modulus (E), yield strength (σ_{ys}) and ultimate strength (σ_{us}) values for femoral cortical bone are higher as compared to the tibiae cortical bone. As per Tables 1 and 2 these values for buffalo femoral bone are found to be respectively 1.4, 1.8 and 2.0 times higher as compared to the corresponding values for buffalo tibiae cortical bone whereas according to Tables 3 and 4 these values are respectively 1.5, 1.1 and 1.2 times higher for goat femoral bone as compared to the corresponding values for goat tibiae cortical bone.

The values of yield strain (ε_{ys}) and ultimate strain (ε_{us}) for femoral bone as compared to the tibiae cortical bone are observed to be higher for the case of buffalo bone whereas lower for the case of goat bone.

These results show that femoral cortical bone is stronger in tension as compared to tibiae cortical bone but ultimate strain is higher for goat tibiae cortical bone.

B. Comparison of tensile properties for sub-size and full-size specimens

The results reported in Tables 1 to 4 shows no significant differences in the tensile properties obtained from sub-size and full-size tensile specimens.

The maximum percentage difference of 9.06 in ultimate strain and 6.12 in elastic modulus values of sub-size and full-size specimens were observed for buffalo femoral and tibiae cortical bone respectively. For goat femoral and tibiae cortical bone maximum differences of respectively 9.67 in yield strength and 8.18 in elastic modulus values were observed. The minor difference observed in tensile properties of sub-size and full-size tensile specimens may be due to the highly heterogeneous nature of bone material.

The results show that even after reducing the gauge area of full-size specimen up to one half and total length up to one fifth, the microstructural component does not cause large, discrete fluctuations in mechanical properties and therefore the tensile properties for sub-size specimens remains almost same to that of full-size specimens.

IV. CONCLUSIONS

Based on the present investigation following conclusions are made;

(i) Femoral bone is stronger in tension as compared to tibiae cortical bone for both buffalo and goat cortical bone.

(ii) The values of yield strain and ultimate strain for femur are higher as compared to the tibiae for buffalo cortical bone whereas for goat cortical bone these values are comparatively higher for tibiae.

(iii) No significant differences were noticed in tensile properties obtained from sub-size and full-size specimens whereas the reported differences are due to the highly heterogeneous nature of bone.

(iv) Sub-size specimen of comparatively one half gauge area and one fifth total length to that of full-size specimen can be used to characterize the tensile properties of cortical bone.

(v) The stress-strain curves obtained from FE simulation show good agreement with the experimental curves for all different cases.

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