Effect of Orientation on Elastic-plastic Fracture Toughness of Cortical Bone

N.K. Sharma, D.K. Sehgal, and R.K. Pandey

Abstract— **Bone material is heterogeneous and anisotropic in nature. It also has a hierarchical structure that changes from nano-scale to macro-scale. Bone material contains good amount of non linearity during deformation. This nonlinearity may be due to several toughening mechanisms and presence of water in the bone material. Many researchers used critical stress intensity factor, critical energy released rate and crack growth-resistance curve approaches based on linear elastic fracture mechanics to examine toughness of bone. These approaches are inadequate to characterize fracture in presence of substantial nonlinearity preceding fracture. Crack tip opening displacement (CTOD) approach based on elastic-plastic fracture mechanics has been applied in the present work to provide an estimate of fracture toughness of buffalo cortical bone for longitudinal as well as transverse orientation of cracking. The elastic modulus and yield strength of buffalo bone are also evaluated for the transverse as well as longitudinal orientation of loading and compared with the values available in the literature. The average CTOD toughness (δ_c) for transverse orientation was found to be 63 µm, which is 61% more than that of longitudinal orientation of cracking (39 µm). The equivalent *K*-fracture toughness values obtained from the δ_c values in case of transverse orientation (12.68 MPa.m$^{1/2}$) was found to be 141% more than that of longitudinal orientation of cracking (5.26 MPa.m$^{1/2}$). The *J*-toughness values are calculated employing the corresponding δ_c values in the two orientation of cracking and compared with the values of *J*-toughness available in the literature. It is suggested that the CTOD (δ_c) and *J*-toughness are better parameters to predict the realistic fracture resistance of bone.**

Index Terms— **Bone, CTOD toughness, Elastic-plastic fracture mechanics, *J*-toughness, Linear-elastic fracture mechanics**

I. Introduction

The mechanical properties of bone such as stiffness, strength, toughness, and fatigue resistance are of greatest importance in order to understand the effect of age, drug treatments, disease and for the development of implantation. Bone is a very complex material. Bone material is anisotropic and heterogeneous in nature. Bone matrix consists of two components i.e. the organic matrix and the mineral substance. The organic matrix of bone contains type I collagen fibrils, which account for over 90% of the whole matrix while the remaining 10% is the noncollagenous proteins, proteoglycans and phospholipids [19]. The mineral substance of bone is calcium phosphate hydroxiapatite. The organization of the collagen/crystal system is responsible for many hierarchical levels of micro structural arrangement and relationship. This hierarchical structure of bone results in a wide range of mechanical properties [5]. The main cause of anisotropic nature of bone material is the non-longitudinal axial distribution of orientation of bone minerals [10].

Evaluation of fracture properties of bone i.e. its resistance to fracture has been an important field of study. Fracture toughness of bone may be different according to the orientation of cracks and defects. In most of the literature longitudinal and transverse specimens are considered to evaluate the toughness of bone [8, 11, 17]. In case of longitudinal specimens crack is oriented along the long axis of bone whereas for transverse specimens crack is oriented perpendicular to the long axis of the bone. There are various techniques to assess the fracture properties of bone. Many researchers have examined toughness of bone material employing the critical stress intensity factor and critical energy released rate which are based on linear-elastic fracture mechanics (LEFM) [3, 7, 11, 20, 21]. Ritchie et al. [17] considered many techniques for evaluating toughness of bone and assessed their specific relevance and application to the mechanical testing of small animal bones. In other literatures crack growth resistance of bones is assessed using the crack growth-resistance curve approach (R-curve) for the longitudinal as well as transverse fracture and it has been observed that increment of fracture toughness may be due to micro-cracking, osteon pullout, fiber bridging, and crack deflection [2-4, 16]. These studies are also based on LEFM. However the bone material is found to contain good amount of non linearity during deformation [12, 13]. The stress intensity factor approach is therefore inadequate to characterize fracture in presence of substantial non linearity preceding fracture [1]. The non linearity in case of bone may be due to several toughening mechanisms like plasticity, micro-cracking, viscoelasticity etc. Yan *et al.* [8] have applied elastic-plastic fracture mechanics (EPFM) to study bone's fracture toughness. They used J integral approach estimate the energy consumed during fracture.

In the present work the crack tip opening displacement (CTOD) approach has been applied to provide an estimate of fracture toughness of cortical bone tissue. The CTOD approach is also based on elastic-plastic fracture mechanics. A comparison has been further made with the findings available in the literature.

II. Materials and Method

In this investigation, the study has been conducted in the tibial bones obtained from young buffalo of age about 24

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months. The single edge notch bending (SENB) and compact tension (CT) specimens were prepared following the British standard [9] for the CTOD testing. In all ten specimens were cut from the mid diaphysis. Five specimens were obtained with dimensions 3 mm (thickness) x 15 mm (width) x 60 mm (length) for the SENB test to undergo transverse fracture (i.e., crack advances perpendicular to the long axis of tibia). The other 5 specimens with dimensions 3 mm (thickness) x 20 mm (width) x 19 mm (length) were obtained for CT test to undergo longitudinal fracture (i.e., crack advances parallel to the long axis of tibia). A very fine slit of appropriate length as per the British standard simulating the fine crack is induced in the sample using a diamond wheel (Isomet 4000). Fig. 1 shows the location and orientation of the CTOD specimens prepared from the tibial bone.

For the uniaxial tensile test dumbbell shape specimens were prepared from the mid diaphysis of tibia. Two strip type longitudinal specimens were prepared for conducting the tensile test in longitudinal direction (load being applied along the long axis of tibia) with gauge length 25 mm, gauge width 4 mm and total length 80 mm, whereas the other two specimens were prepared for the transverse tensile test (load being applied perpendicular to the long axis of tibia) with gauge length 8 mm, gauge width 4 mm and total length 22 mm. Poisson’s ratio in each direction was tested with the help of biaxial extensometer of gauge length 25 mm.

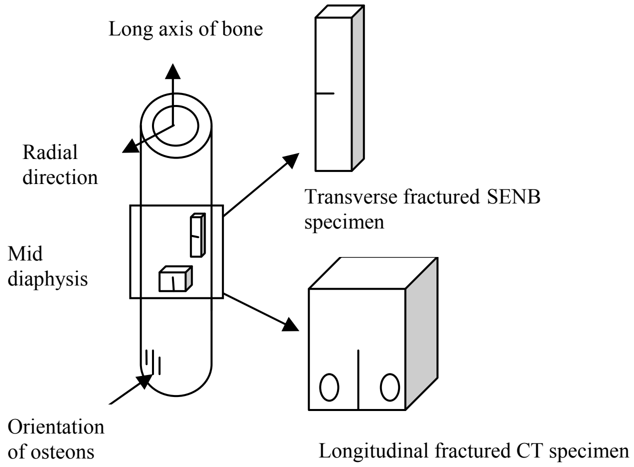

Fig.1. Diagram showing the tibia diaphysis from where the transverse fracture and longitudinal fracture specimens were cut for SENB and CT tests respectively.

All specimens were stored at room temperature in a solution of 50% saline and 50% ethanol at all time until testing. In order to keep the specimens wet and to avoid heating during cutting and polishing a constant spray of water was supplied. The SENB and compact tension tests were performed on MTS 858 Table Top Machine. The crack mouth opening displacement (CMOD) was measured with the help of a clip gauge during the test. The load-CMOD (P-CMOD) diagrams were recorded and analyzed for the evaluation of CTOD. Uniaxial tensile test was performed on Zwick 7250 Universal Testing Machine. Fig. 2 shows the stress-strain curves for longitudinal and transverse specimens in case of uniaxial tensile test. The yield strength values were obtained corresponding to 0.2% permanent set.

Typical P-CMOD diagrams for cortical bone are shown in Fig. 3. As per the standard British standard, first load maxima/pop-in point has been taken as the critical point in P-CMOD diagram [9].

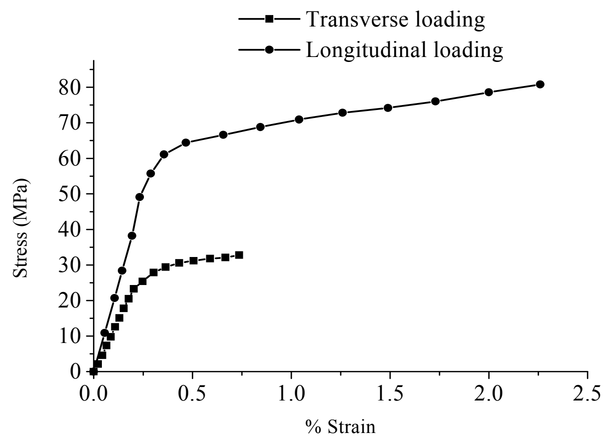

Fig.2. Stress-strain curve for buffalo cortical bone specimens in case of longitudinal and transverse testing.

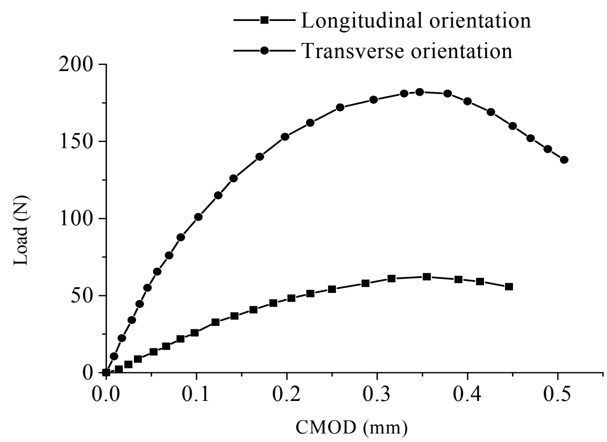

Fig.3. Load-CMOD curve for transverse and longitudinal fractured specimens obtained from the mid diaphysis of cortical tibia.

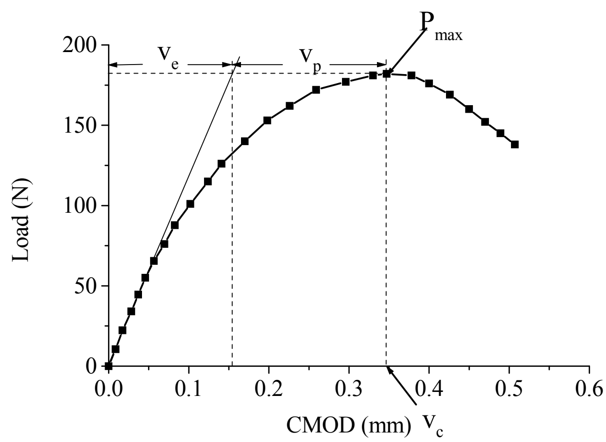

Fig.4. Load-CMOD curve showing the elastic (v_e) and plastic (v_p) parts of CMOD.

In the present case no pop-in point was noticed on P-CMOD diagram and the CMOD value is found to increase

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steadily with load in the elastic-plastic situation. Hence, the CTOD corresponding to the maximum load point was employed for the evaluation of CTOD.

For the computation of CTOD from the CMOD value, the total CMOD corresponding to maximum load point was divided in to two parts: one is CMOD corresponding to the elastic part (v_e) and other one is CMOD corresponding to the plastic part (v_p) of crack opening. Fig. 4 shows the elastic and plastic parts of CMOD on the load-CMOD curve.

The elastic (δ_e) and plastic (δ_p) parts of CTOD were calculated using equations (1) and (2) respectively [9].

$$\delta_e = \frac{K_I^2(1-\upsilon^2)}{2E\sigma_{ys}} \quad (1)$$

where K_I is the stress intensity factor corresponding to the critical load, E is the elastic modulus, σ_{ys} is the yield strength and υ is the Poisson's ratio.

$$\delta_p = \frac{v_p}{\frac{a}{r(W-a)}+1} \quad (2)$$

where v_p is the plastic component of CMOD corresponding to the critical load, a is the original crack length, W is the width of the specimen and r is the rotation factor which may be taken as 0.4 as per the standard [9].

Total CTOD (δ_c) was calculated using equation (3) as given below;

$$\delta_c = \delta_e + \delta_p \quad (3)$$

Stress intensity factors in case of SENB and CT tests were calculated using equation (4a) and (4b), respectively [9].

$$K_I = \frac{PS}{BW^{3/2}} f_1 \text{ and } K_I = \frac{P}{BW^{1/2}} f_2 \quad (4a,b)$$

where f_1 and f_2 are the function of $\alpha = (a/W)$ and given as:

$$f_1 = \frac{3\alpha^{0.5}\left[1.99-\alpha(1-\alpha)\right]\left[2.15-3.93\alpha+2.7\alpha^2\right]}{2(1+2\alpha)(1-\alpha)^{1.5}}$$

$$f_2 = 29.6\alpha^{0.5} - 185.5\alpha^{1.5} + 655.7\alpha^{2.5} - 1017\alpha^{3.5} + 639\alpha^{4.5}$$

where P is the maximum load, S is the span length and B is the thickness of the specimen.

III RESULTS

The fracture toughness value for the tibial mid diaphysis was calculated as described above for both the longitudinal and transverse orientations of fracture. Table 1 lists the elastic modulus (E), yield strength (σ_{ys}) and Poisson's ratio (υ) of buffalo tibia diaphysis determined with the help of uniaxial tensile test in both longitudinal and transverse directions. Table 2 lists the elastic part of CTOD (δ_e), plastic part of CTOD (δ_p) and the total CTOD (δ_c).

The equivalent fracture toughness in terms of critical stress intensity factor ($K_{\delta c}$) was calculated using the δ_c value applying the following relation [9],

$$K_{\delta c} = \sqrt{2\delta_c E\sigma_{ys}} \quad (5)$$

and the corresponding $K_{\delta c}$ values are also reported in Table 2.

To determine whether the specimen thickness (B) was sufficient to meet the requirement of plane strain condition, the following equation was used [9],

$$B \geq 25(\delta_c) \quad (6)$$

It is noticed that the maximum thickness requirement for plane strain in the present case is about 1.6 mm whereas the actual specimen thickness is 3.0 mm. Therefore, all the specimens are meeting the plane strain condition and reported δ_c values are the plane strain values

TABLE 1
Elastic modulus (E), yield strength (σ_{ys}) and Poisson's ratio (υ) of buffalo tibial cortical bone specimens for mid diaphysis

	Longitudinal orientation	Transverse orientation
E (GPa)	19.6	11.5
σ_{ys} (MPa)	65.1	31.0
υ	0.38	0.35

The values listed are the average of two values.

TABLE 2
The elastic CTOD (δ_e), plastic CTOD (δ_p) and the total CTOD (δ_c), along with the equivalent fracture toughness ($K_{\delta c}$) of buffalo cortical tibia bone for longitudinal and transverse fracture orientations

	Longitudinal orientation (n=5)	Transverse orientation (n=5)
δ_e (mm)	0.003±0.0005 (0.004-0.002)	0.0067±0.001 (0.008-0.006)
δ_p (mm)	0.036±0.0043 (0.04-0.03)	0.056±0.006 (0.06-0.05)
δ_c (mm)	0.039±0.0047 (0.044-0.033)	0.063±0.0068 (0.071-0.054)
$K_{\delta c}$ (MPa.m$^{1/2}$)	5.26±0.33 (5.62-4.83)	12.68±0.69 (13.47-11.74)

The results reported are the average of five values. Standard deviation are also given. The range are shown in the bracket

IV DISCUSSION

A. *Effect of orientation on tensile properties*

It may be noticed from Table 1 that the elastic modulus of buffalo mid diaphysis is about 1.7 times higher in the longitudinal orientation as compared to that of the transverse orientation. Similarly the yield strength in the longitudinal orientation is about two times of the one in the transverse orientation. It is also shown in the previous reports that the mechanical properties of cortical bone depends on loading direction of the samples [6, 14]. For example in case of bovine cortical bones [8], the elastic modulus and yield strength are found to be 17.5 GPa and 166 respectively for the longitudinal orientation of loading. In case of transverse orientation, the corresponding values are 12.1 GPa and 93 MPa respectively. This leads to a ratio of elastic modulus of 1.4 for the longitudinal to transverse orientation. Similarly a ratio of 1.8 is noticed for the yield strength in the two orientations. Interestingly the values show a close resemblance with the results obtained in the present

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investigation for the buffalo tibial bone. The increased value of elastic modulus and yield strength in longitudinal orientation is considered to be due to orientation of collagen fibers and osteons along the longitudinal direction [15].

B. Effect of orientation on fracture toughness

Table 2 presents the CTOD fracture toughness for the buffalo tibial bone in the longitudinal and transverse orientation of cracking. The average fracture toughness (δ_c) in the transverse orientation of cracking is 63 µm whereas for longitudinal orientation of cracking is only 39 µm. In terms of equivalent fracture toughness, $K_{\delta c}$ (i.e. K_{Ic} computed from δ_c values), the toughness values are 12.68 MPa.m$^{1/2}$ and 5.26 MPa.m$^{1/2}$ for the transverse direction and longitudinal direction of cracking respectively. It is apparent from the P-CMOD diagram (Fig. 3) that there is significant non-linearity preceding instability/cracking in both the orientations of fracture. This non-linearity may be due to several toughening mechanisms like plasticity, micro-cracking, and viscoelasticity. The presence of water in bone material may also have a contribution to this non-linearity. The significant non-linearity causes the *K*-approach inapplicable in this material and any attempt to determine *K*-toughness will results in an unrealistically low value. For example, the K_c toughness value reported for bovine cortical bone are 5.6-7.7 MPa.m$^{1/2}$ in the transverse orientation and 2.4-5.2 MPa.m$^{1/2}$ for the longitudinal orientation of cracking [18, 21]. A comparison of these values from the results of present investigation shows that obtained $K_{\delta c}$ values of 12.68 MPa.m$^{1/2}$ and 5.26 MPa.m$^{1/2}$ in the two orientations are almost twice the corresponding values of literature for the cortical bone. This demonstrates that the K_I approach cannot be used to characterize toughness in the bone material and therefore only elastic-plastic fracture mechanics toughness parameters i.e. CTOD or *J*-integral have to be employed to represent the fracture behavior.

A comparison of δ_c values in the two orientations indicates that the CTOD toughness is about 1.6 times higher for the transverse orientation of cracking as compared to the longitudinal orientation of cracking in case of buffalo tibial bone. The increased resistance to fracture in the transverse orientation of cracking is considered to be due to various factors such as micro-cracking, crack deflection, fiber bridging etc. The organic matrix of bone has strong bonding with the apatite crystals and may also force the crack to deflect. The above mechanisms serve to deflect the main crack from its straight path and force the same to follow a tortuous/zig-zag path leading to significant amount of energy consumption.

An attempt was made to compute *J*- toughness values for the bone employing the corresponding δ_c values in the two orientations using the following relationship;

$$J_c^{\delta} = 2\sigma_{ys}.\delta_c \qquad (7)$$

where J_c^{δ} is the computed *J*-toughness from δ_c. Using the data for the yield strength and δ_c toughness from Table (1) and (2), the J_c^{δ} values were obtained. The same are found to be as under,

J_c^{δ} (transverse orientation) = 8.33 kN/m
J_c^{δ} (longitudinal orientation) = 2.42 kN/m

It is interesting to note that almost similar range of J_c toughness values have been reported for the bovine femoral bone in an earlier investigation [8].

J_c (bovine, transverse orientation) = 6.6 kN/m
J_c (bovine, longitudinal orientation) = 2.3 kN/m

Thus it is evident that the CTOD or *J*-integral toughness parameters are able to predict the realistic fracture resistance of bone as they are able to take into account effectively the non-linearity associated with fracture.

V CONCLUSION

Based on the present investigation following conclusions are made;

1) The elastic modulus and the yield strength values for the buffalo tibial bone are 19.6 GPa and 65 MPa respectively for the longitudinal orientation of loading.
2) For the transverse orientation of loading the modulus and yield strength values are decreased by a factor of 1.7 and 2 respectively showing a significant effect of directionality on these properties.
3) The fracture in the buffalo bone is found to be preceded by a good amount of non-linearity which renders the *K* – approach inapplicable for evaluation of fracture toughness in the bone materials (buffalo/bovine etc.)
4) The elastic-plastic CTOD fracture toughness has been evaluated for the buffalo cortical bone in the present work and the toughness values (δ_c) are 39 µm and 63 µm respectively in the longitudinal and transverse orientation of cracking.
5) The equivalent *K*-fracture toughness ($K_{\delta c}$) values as obtained from the δ_c values are 5.26 MPa.m$^{1/2}$ and 12.68 MPa.m$^{1/2}$ for the longitudinal and transverse orientation of cracking which appear to be more realistic.
6) The δ_c values have been used to determine the equivalent *J*-toughness. The values of *J*-toughness are 8.33 kN/m for the transverse orientation and 2.42 kN/m for longitudinal orientation of cracking which shows a reasonable good agreement with the reported *J*-toughness in case of bovine cortical bone.
7) The increased resistance to fracture in the transverse orientation is considered to be due to factor such as micro-cracking, crack deflection and fiber bridging etc. which provide a tortuous path leading to significant amount of energy consumption.

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