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Variability and Anisotropy of Fracture Toughness of Cortical Bone Tissue

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Abstract. Bones form protective and load-bearing framework of the body. Therefore, their structural integrity is vital for the quality of life. Unfortunately, bones can only sustain a load until a certain limit, beyond which they fail. Therefore, it is essential to study their mechanical and fracture behaviours in order to get an in-depth understanding of the origins of its fracture resistance that, in turn, can assist diagnosis and prevention of bone's trauma. This can be achieved by studying mechanical properties of bone, such as its fracture toughness. Generally, most of bone fractures occur for long bones that consist mostly of cortical bone. Therefore, in this study, only a cortical bone tissue was studied. Since this tissue has an anisotropic behaviour and possesses hierarchical and complex structure, in this paper, an experimental analysis for the fracture toughness of cortical bone tissue is presented in terms of J-integral. The data was obtained using single-edge-notch bending (SENB) cortical specimens of bone tested in a three-point bending setup. Variability of values of fracture toughness was investigated by testing specimens cut from different cortex positions of bovine femur called *anterior*, *posterior*, *medial*, and *lateral*. In addition, anisotropy ratios of fracture toughness were considered by examining specimens cut from three different orientations: longitudinal, transverse and radial. Moreover, in order to link cortical bone fracture mechanisms with its underlying microstructure, fracture surfaces of specimens from different cortices and along different orientations were studied. Experimental results of this study provide a clear understanding of both variability and anisotropy of cortical bone tissue with regard to its fracture toughness.

1. Introduction

Bone is a natural composite material with hierarchical organization at different length scales. At the nano-scale, it consists of a collagen matrix impregnated with ceramic nano-particles known as carbonated hydroxyapatite [1, 2]. At the micro-scale, cortical bone is laid down in lamellar layers of 5 μm thickness. Similar to plywood composite structure, inside a layer, collagen fibers are parallel; however, their orientations are different for different layers. Across a bone section, not all lamellae are arranged in the same way, for instance, near the outer and inner surfaces, circumferential lamellae are parallel and arranged along the cortical bone's circumference. On the other hand, the outside and inside circumferential lamellae pack a region made of circular structures called osteons, formed from concentric lamellae impregnated in old remnants of a bone's remodeling process called interstitial matrix. The interface between osteons and interstitial matrix is called cement line; it is a collagen-free and highly mineralized layer. Cement lines have a paramount effect on bone's behavior, especially its fracture. Osteons are, on average, 200 μm in diameter and 1 cm long and parallel to the bone's longitudinal axis [3]. In addition, a network of canals and channels is formed across the bone's section and along its axis; these canals accommodate blood vessels and called Haversian canals. Moreover, bone has living cells called osteocytes that live within an interconnected network of microscopic channels called canaliculi. The latter are responsible for exchange of nutrients and waste between osteocytes [3]. At the millimeter length scale, bone consists of a dense and thick outer layer called cortical bone and a sponge-like structure called trabecular bone [4]. All these hierarchical levels work together in symphony to enhance macroscopic mechanical properties of bone tissue in the meter range [4]. Microarchitecture of the cortical bone tissue is quite complex and has a significant effect on its mechanical and fracture properties. Moreover, the preferential alignment of both collagen fibrils and nano-scaled mineral crystals causes anisotropy in both mechanical and fracture properties of the tissue [4]. From a fracture toughness perspective, the cortical bone tissue has different fracture resistance for various crack-propagation directions relative to the long bone axis that is called fracture toughness anisotropy. Various toughening mechanisms were reported for the cortical bone tissue including microcracks in the vicinity of the main crack due to stress concentrations ahead of the crack tip [5-7], and crack deflection and blunting at cement lines that are weak interfaces at the boundaries of secondary osteons [8]. Recently, it was reported that ligament bridging of crack in the wake zone is a dominant toughening mechanism in cortical bone as it reduces a driving force at the crack tip [9-11]. Several authors reported that toughening mechanisms are highly dependent on the crack propagation direction; therefore, fracture toughness of long bones is significantly higher in transverse and radial directions compared to the longitudinal one [11-13]. Despite interest for many researchers to fracture toughness of the cortical bone tissue, understanding of the causes of bone fracture is still not fully developed. Therefore, in this paper, fracture toughness of cortical bone tissue was studied as a function of both crack propagation direction and cortex position to promote our understanding for the origins of its fracture resistance a step further.

2. Materials and Method

2.1. Specimen preparation

The specimens in this study were cut from three fresh bovine femora (aged 1.5-2 years). The mid-part of three femurs (diaphysis) was extracted using a fine teeth band-saw. Then, the diaphysis part of each femur was sliced into four cortices – anterior, posterior, medial and lateral. Twenty-one specimens were cut from each cortex to allow crack growth along three different orientations relative to bone axis – longitudinal, transverse and radial as shown in Fig. 1. After cutting, specimens were ground under tap water using a series of grinding papers Standard ANSI grit: 240, 600, and 1200 to make sure that the surface is clean, without any scratches or irregularities. After preparation, the test specimens were put in a 0.9% physiological saline solution until tested. All specimens were prepared with the same dimensions for comparison according to the British Standard [14]: 25 mm x 5.43 mm x 2.72 mm (length × width × thickness). Also, a very fine slit of 2.7 mm x 5.43 mm was produced using a low-speed diamond saw for all specimens according to British Standard [14]. In this paper, specimens are labeled based on the crack propagation direction: longitudinal, transverse, or radial. Hence, specimens with crack propagating parallel to the bone axis is called longitudinal, perpendicular to it is called transverse and in the radial direction is called radial, see Fig. 1.

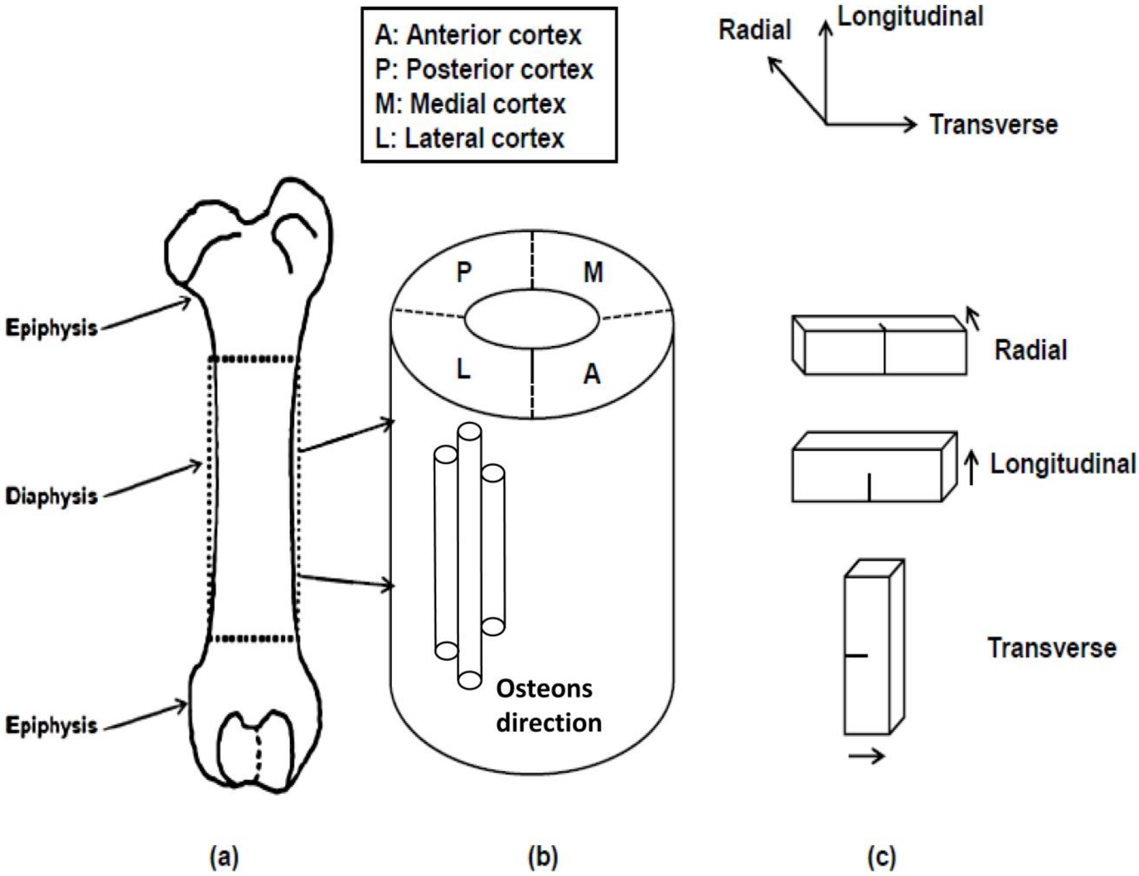

Figure 1. (a) Schematic illustration of bovine femur; (b) cortex positions in cortical bone; (c) specimens with different crack propagation directions. Specimens are labeled based on crack propagation directions depicted by arrows.

2.2. Fracture toughness measurements

The fracture toughness testing was performed using single-edge-notch bending on an Instron 3345 machine with a 5 kN load cell. All specimens were loaded to failure with a displacement rate of 1 mm/min. Specimens were loaded in three-point bending with load measured and recorded using the machine's load cell and the corresponding load-line displacement was simultaneously measured using a linear variable differential transducer (LVDT). The obtained load-displacement curves were analyzed according to the British Standard [14]. Specimens cut from the diaphysis part of bovine femur were tested with pre-notch in transverse, longitudinal and radial orientation for different cortex positions called *anterior*, *lateral*, *posterior* and *medial*. After fracture tests, fracture surfaces of all the specimens were investigated using scanning electron microscopy (SEM). Since cortical bone is not a conductive material, before investigation specimens were air dried and gold coated.

Plane strain fracture toughness, K_{Ic}, crack opening tip displacement (CTOD), or J-integral values can be determined using the specimen dimensions, depth of notch, 0.2% proof strength (σ_{YS}) and specific data from the force-displacement record of the fracture test. When the fracture follows elastic-plastic conditions, it is not possible to determine a valid K_{Ic} value to represent fracture toughness of a material. However, either critical CTOD or critical J-integral values can be calculated. Obtaining a valid K_{Ic} value depends on the shape of the force versus displacement record, the specimen size and form, and the 0.2% proof strength and toughness of the material at the temperature of interest. For a valid K_{Ic} measurement, the specimen dimensions (a nominal crack length (a), thickness (B) and the uncracked ligament $(W - a)$) each has not to be less than: $2.5\left(\frac{K_{Ic}}{\sigma_{YS}}\right)^2$ [14]. In this study, the behavior of all specimens was predominantly non-elastic and all specimens failed to satisfy the validation criterion of K_{Ic}. Therefore, elastic plastic fracture mechanics (EPFM) parameter, J-integral, was calculated based on British Standard [14].

3. Results and Discussion

This study focuses on evaluating fracture-toughness values for specimens with cracks growing parallel to bone axis, perpendicular to it and in the radial orientation. In addition, the anisotropy ratios of the fracture toughness values were calculated. Results of this study show that all specimens exhibited a non-linear elastic-plastic behavior. Therefore, based on the British Standard [14], the critical stress intensity factor K_{Ic} was not valid for all specimens, and the J-integral was used to quantify its fracture toughness. Table 1 lists the average levels and standard deviation of critical values of J-integral and their cortex dependency for all crack growth directions.

Table 1. Critical J-integral values (N/m) for specimens with longitudinal, radial and transverse crack growth in bovine femoral cortical bone tissue at different cortex positions.

	Anterior		Medial		Posterior		Lateral	
	mean	SD	mean	SD	mean	SD	mean	SD
Long.	1033.90	± 254.5	1768.47	± 98.8	1165.65	± 340.1	2034.27	± 509.9
Radial	1199.09	± 153.1	1418.22	± 97.2	982.97	± 369.5	2664.16	± 554.4
Trans.	4509.08	± 422.1	5925.47	± 802.9	3876.66	± 847.3	5661.61	± 452.7

It can be noticed from Table 1 that significant differences were found among the resistance to fracture of specimens cut from different cortices of bovine femur cortical bone. In general, bovine femoral cortical bone shows higher resistance to fracture when a crack grows perpendicular to osteons direction, see Fig. 1. Resistance to fracture is lower for cracks grow in both radial and longitudinal directions for all specimens. For cracks grow in the transverse direction, specimens cut from medial cortices showed the highest fracture toughness when those cut from posterior cortex exhibited the lowest resistance to fracture. The mean fracture toughness value for specimens cut from medial cortices is higher by some 34.58%, 23.9% and 4.45% relative to those cut from posterior, anterior and lateral, respectively. On the other hand, among specimens with radially extending cracks, those cut from lateral cortices demonstrated the highest resistance to fracture while those cut from posterior exhibited the lowest resistance. The former's mean fracture toughness value is some 54.99%, 46.77% and 63.1% higher compared to those of anterior, medial and posterior, respectively. Finally, for specimens with cracks extending parallel to osteons, similar to those with radial cracks, the mean fracture toughness value was the highest for specimens cut from lateral cortices. Dislike specimens with radially extending cracks, the mean fracture resistance value was the lowest for specimens cut from anterior cortices. The ratios of average fracture toughness values of specimens cut from anterior, medial and posterior cortices relative to that had the highest value were 49.18%, 13.1% and 42.6%, respectively. This implies that bovine femur has a non- uniform fracture resistance for cracks extend parallel to osteons, perpendicular to it and in the radial direction. Obviously, microstructure of cortical bone has a predominant effect on its resistance to fracture, which is the case for other mechanical properties, such as elastic modulus, yield stress, and ultimate strength [16]. Due to a natural loading regime exerted by animal's weight and muscle forces, long bones are exposed to combined loading conditions that are non-uniform. As it is well known from literature, bone is a dynamic tissue that reacts to mechanical loading by alternating its shape, internal microstructure and properties to meet external loading environment [17]. Therefore, the findings of this study demonstrated different crack resistance for specimens cut from different cortices with various underlying microstructures. Toughening mechanisms depend on crack growth orientation [17] for osteonal cortical bone. For cracks emerging in the transverse direction, toughening mechanisms such as crack deflection and twist are dominant, whereas for cracks extending in both longitudinal and radial directions, the dominating toughening mechanism is uncracked-ligament bridging [17]. In this study, it was found that the underlying microstructure of bovine cortical bone changed from one cortex to another and included primary, secondary and plexiform bones (see Fig. 2). Thus the interaction between the crack and different microstructures triggers even more toughening mechanisms that, in turn, were reflected in the form of different values of fracture toughness for specimens from different cortices. Also, this study demonstrated fracture toughness anisotropy ratios of specimens with cracks growing longitudinally, transversely and radially, see Table 2.

Table 2 introduces anisotropy ratios of fracture toughness values for specimens with cracks growing in longitudinal, transverse and radial orientations and cut from different cortex positions.

Table 2. Values of anisotropy ratios of fracture toughness values of longitudinal, transverse and radial crack growth directions of bovine femoral cortical bone tissue at different cortex positions

	Anterior	Medial	Posterior	Lateral
Trans/Long	4.36	3.35	3.33	2.78
Trans/ Radial	3.76	4.18	3.94	2.13

It was noticed from table 2 that bovine cortical bone demonstrated high anisotropy ratios of J-integral values. Anisotropy ratios were calculated by relating fracture toughness values of specimens with transverse cracks to those with cracks extending longitudinally and radially. It was also found that anisotropy ratios were different for different cortices. Specimens cut from lateral cortices with cracks growing radially showed the lowest anisotropy ratio, while those cut from anterior cortices exhibited the highest ratio.

At the microstructure level, specimens cut from lateral and medial cortices revealed secondary osteonal bone with cement-line layers that trigger the deflection-of-crack toughening mechanism. This is a possible interpretation of the higher J-integral values of lateral and medial cortices specimens. Liang et al. [15] suggested that osteons, which were newly formed and had low stiffness, strengthened the cortical bone tissue via promoting crack propagation toward osteons, thus causing the crack arrest in the cement lines.

Fracture surfaces were studied using scanning electron microscopy (SEM) for the crack growth regions for all the specimens. Generally, higher energy consumption during crack growth was linked with rough and uneven surfaces while flat surfaces were indication of low levels of energy (see Fig. 2). The most common mode of bone fracture is the transverse fracture where a crack cuts across osteon direction [18]. Figure 2 shows the fracture surfaces of specimens from four different cortex positions with cracks growing perpendicular to dominant orientation of osteons (bone axis). This study demonstrates that different fracture resistances are underpinned by microstructure adaptations of cortical bone to applied mechanical loadings.

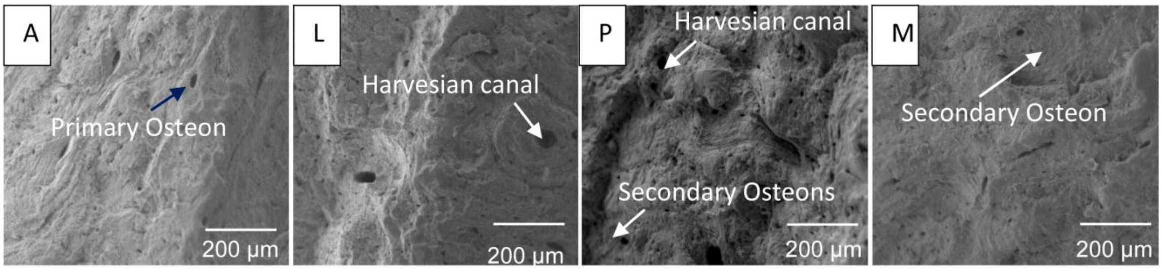

Figure 2. Fracture surfaces of specimens cut from different cortex positions with cracks growing in transverse direction (⊥ bone axis). A: anterior, L: lateral, M: medial and P: posterior.

In summary, bone is designed to resist cracks to different extent and by employing diverse mechanisms for various crack-growth orientations. In addition, bone's underlying microstructure plays an important role in the fracture process. In the future research, we will try to reveal the fracture mechanisms caused by the interaction of cracks with different microstructures of the cortical bone tissue.

4. Conclusions

In the present study, the fracture toughness of bovine femoral cortical bone was evaluated, and the effect of its microstructure on fracture toughness values was examined. Based on the current study, the following conclusions were made:

- Bovine femoral cortical bone demonstrated non-uniform fracture toughness for specimens cut from different cortices and for cracks extending along bone axis, perpendicular to it and in the radial direction. Different fracture resistances values are linked to cortical bone's underlying microstructure.
- Bovine cortical bone demonstrated high anisotropy ratios of J-integral values. It was also found that anisotropy ratios were different for different cortices.

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References

[1] Currey JD. J Exp Biol. 1999;202:3285-94.
[2] Fratzl PG, H. S.; Paschalis, E. P.; Roschger, P. Structure and mechanical quality of the collagen–mineral nano-composite in bone. J Mater Chem 2004;14:2115-23.
[3] Ethier CR, Simmons, C. A. . Introductory biomechanics: from cells to organisms Cambridge Unversity Press; 2007.
[4] Peterlik H, Roschger, P. , Klaushofer, K., Fratzl, P. . Orientation dependent fracture toughness of lamellar bone. Int J Fract. 2006;139:395-405.
[5] Zioupos P aCJ. J Mater Sci. 1994;29:978-86.
[6] Zioupos P WXT, Currey JD. Clin Biomech. 1996;11:365-75.
[7] Vashishth D TKE, Bonfield W J Biomech. 2003;36:121-4.
[8] Liu D WS, Wanger HD. J Biomech. 1999;32:647-54.
[9] Nalla R K KJH, Ritchie R O. Nat Mater. 2003;2:164-8.
[10] Nalla R K KJJ, Ritchie R O. Bone. 2004;34:790-8.
[11] Nalla R K KJJ, Kinney J H, Ritchie R O. Biomater. 2005;26:217-31.
[12] Martin R B B, D L. J Biomech. 1993;26:1047-54.
[13] Behiri JC B, W. J Biomech. 1989;22:863-72.
[14] BRITISH STANDARDS INSTITUTE B-FMTTMfDoK, Critical CTOD and Critical J Values of Metallic Materials. London: British Standards Institute.
[15] Liang L, Guo, XE, Goldstein, SA. J Biomech Eng. 1998;1:112-7.