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Fracture and microstructural study of bovine bone under mixed mode I/II loading

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Abstract

Understanding the fracture behavior and associated crack growth mechanism in bone material is an important issue for biomechanics and biomaterial researches. Fracture of bone often takes place due to complex loading conditions which result in combined tensile-shear (i.e. mixed mode) fracture mechanism. Several parameters such as loading type, applied loading direction relative to the bone axis, loading rate, age and etc., may affect the mixed mode fracture resistance and damage mechanism in such materials. In this research, a number of mixed mode I/II fracture experiments are conducted on bovine femur bone using a sub-sized test configuration called "compact beam bend (CBB)" specimen to investigate the fracture toughness of bone under different mode mixities. The specimen is rectangular beam containing a mid-edge crack that is loaded by a conventional three-point bend fixture. The results showed the dependency of bone fracture toughness on the state of mode mixity. The fracture surfaces of broken CBB specimens under different loading conditions were studied via scanning electron microscopy (SEM) observations. Fracture surface of all investigated cases (i.e. pure mode I, pure mode II and mixed mode I/II) exhibited smooth patterns demonstrating brittle fracture of bovine femur. The higher density of vascular channels and micro-cracks initiated in the weakened area surrounded by secondary osteons were found to be the main cause of the decreased bone resistance against crack growth and brittle fracture.

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Keywords: Bovine femur, Compact beam bend specimen, Mixed mode fracture, SEM analysis

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1. Introduction

Natural bone is subjected to variable amplitude static and cyclic physiological loading, possibly combined by wear and other sources of degradation Therefore fracture and crack growth is a common mode of catastrophic failure in these materials initiated by micro / macro cracks. The onset of sudden crack growth in cracked bone is related to a key parameter called “fracture toughness” that shows the resistance of bone material against crack propagation. In practice, bone materials in the skeleton of human and animals are subjected to multi-axial loads and the fracture phenomenon often takes place under mixed modes I/II state. The fracture behavior of cracked materials like bone or other biomaterials is investigated by means of multiple test methods. For example, the compact tension specimen [1-4], single edge notch beam [4-7],edge cracked beam subjected to four point bend loading [8,9] and double cantilever beam specimen [10] are some of the test geometries used for conducting either mode I (tensile/opening type) or mixed mode I/II (opening-shearing mode) fracture toughness experiments on bone materials. Different influencing parameters such as loading type, environmental condition, age of bone source, direction of applied loading, etc. have been studied to characterize the fracture behavior of bone materials using the aforementioned test specimens. Majority of these studies have focused on investigating the crack growth resistance of bone by determining the fracture toughness or critical stress intensity factors under mixed mode I/II.

Microstructural aspects are also known to be of great importance in this regard. Zimmerman et al. [8] studied R-curve behavior for the human cortical bone. By employing an environmental scanning electron microscope (ESEM), coupled with fractographic and synchrotron X-ray computed tomography techniques, they showed that the orientation and crack size are two major parameters affecting the crack growth resistance of cortical bone at different strain rates and hydration levels. Abdel-Wahab et al. [11] proposed a numerical model for simulating osteons and interstitial matrix in bone samples in transverse and longitudinal directions. Koester and co-workers [12] analyzed SEM fractoghraphy images of human cortical bone under pure mode I and pure mode II fracture and studied the propagation of fracture path for both modes. Vashishth et al. [13] investigated the role of micro-cracking in a cortical bone as a toughening mechanism by conducting SEM observation and analyzing the distribution of micro-cracks ahead of the crack process zone.

The previous studies have provided valuable insight into the role of various parameters in bone fracture mechanism. However, there are limited works regarding mixed mode fracture study of bones from both mechanical and microstructural aspects and hence in this research a novel test specimen was used to conduct mixed mode I/II fracture experiments on bovine femur bone; the effect of mode mixity on the fracture surfaces of tested bone samples and their fracture behavior was also investigated.

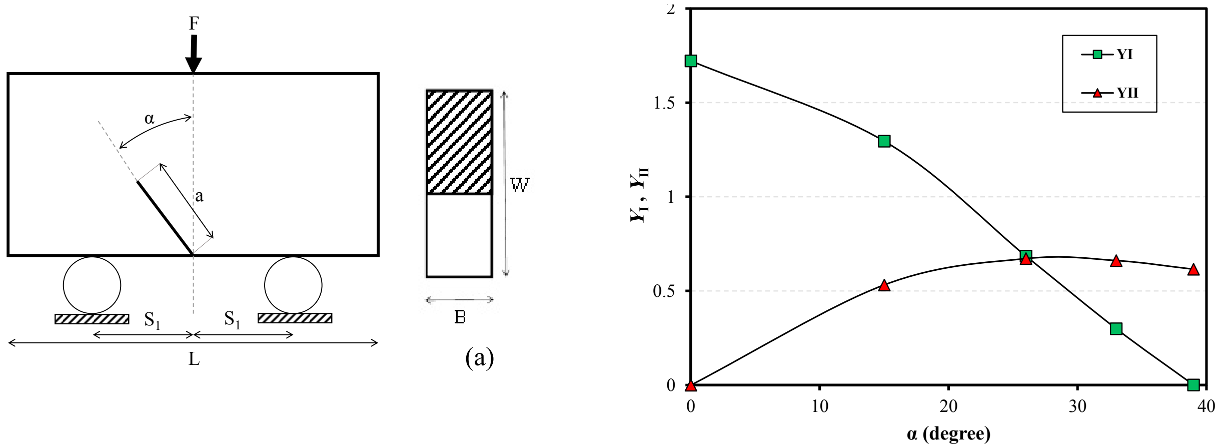
2. Mixed mode bone fracture toughness specimen

A suitable mixed mode bone fracture toughness specimen should have small size and it should be able to simulate different combinations of mode mixities from pure mode I to pure mode II. Furthermore, convenience of specimen manufacturing and also easy test set up are two major requirements of a suitable test specimen for bone fracture toughness testing. Hence, a short rectangular shaped specimen containing an inclined edge crack and subjected to symmetric three-point bend loading is utilized in this research for mixed mode I/II bone fracture toughness study. The geometry and loading conditions of the “compact beam bend- CBB” test specimen are presented in Fig. 1a. In this configuration, in which the length to width ratio (i.e. *L/W*) of rectangle is less than 2.5, the state of mode mixity can be simply altered by changing the crack inclination angle (α). The finite element analyses of this configuration reveals that full combinations of mode mixities ranging from pure mode I to pure mode II can be provided when the inclination angle changes from zero (i.e. pure mode I case) to approximately 40° that corresponds to pure shear or pure mode II sliding of crack flanks. The stress intensity factors (K_{I} and K_{II}) for the CBB specimen are determined from:

$$K_I = \frac{F}{B.W}\sqrt{\pi a}Y_I(\alpha, \frac{a}{W}, \frac{S1}{W}) \tag{1}$$

$$K_{II} = \frac{F}{B.W}\sqrt{\pi a}Y_{II}(\alpha, \frac{a}{W}, \frac{S1}{W}) \tag{2}$$

in which Y_I and Y_{II} are the geometry factors that are functions of pre-crack inclination angle (α), crack length ratio (*a/W*) and loading support distance ratio (*S/W*). Variations of Y_I and Y_{II} for typical case of $a/W = 0.5$ and $S1/W = 0.5$ (computed from our finite element analyses) have been presented in Fig. 1b. Based on this Figure, full combinations of mode mixities ranging from pure mode I (i.e. $Y_I > 0$ and $Y_{II} = 0$) to pure mode II (i.e. $Y_I = 0$ and $Y_{II} > 0$) can be fully covered by the CBB specimen.



(b)

Fig. 1: a) Geometry and loading configuration of compact beam bend (CBB) specimen utilized for mixed mode I/II fracture study of bone materials; b) Variations of Y_I and Y_{II} in the CBB specimen.

3. Experimental fracture toughness study

Samples from the compact regions of a fresh bovine femur bone with unknown age were sectioned into rectangles (30 mm long, 12 mm wide and 4 mm thick) using a band saw and milling machine. The length of rectangular samples was parallel to the long axis of the femur bone. A small notch was introduced as initial crack of length $a = 6$ mm at the edge of each specimen, using a 0.2 mm diameter fret saw. All the samples were kept inside a freezer at -10 ºC for 6h prior to being tested in dry condition. The crack inclination angles were chosen as follows $\alpha = 0^o$ (pure mode I), $\alpha = 26^o$ (mixed mode I/II, $K_I = K_{II}$) and $\alpha = 39^o$ (pure mode II). Quasi-static three-point bend tests (with loading rate of 1 mm/min) were conducted on a universal testing machine equipped with a lab-designed especial bending fixture with loading span of $S_1 = 6$ mm (i.e. $S_1/W = 0.5$) and at least three specimens were tested for each mode mixity. Fracture toughness values were calculated by replacing the fracture loads into Eqs. (1) and (2). Corresponding values of K_{Ic} and K_{IIc} were obtained as $6\,MPa\sqrt{m}$ and $4MPa\sqrt{m}$, respectively that are in good agreement with the reported fracture toughness data of bovine femur [5,7]. Fig. 2 shows the fracture trajectories of tested samples at different mode mixities. Based on these observations, while crack under pure mode I propagates along the initial crack plane, pure mode II and mixed mode fracture trajectories deviate from the pre-crack direction and extend along a curvilinear path starting from the notch tip and terminate close to the location of upper loading point.

Pure mode I | Mixed mode | Pure mode II

Fig. 2: Fracture path of CBB specimens made of bovine femur bone tested under different mode mixities.

Furthermore, the fracture surfaces of tested CBB samples were studied by a scanning electron microscope (SEM). Fracture surfaces of the investigated bovine bone after three-point bend tests are shown in Fig. 3 for different mode mixities (i.e. pure mode I, mixed mode I/II and pure mode II cases). The fracture surfaces of all mode mixities exhibit a rather smooth pattern demonstrating brittle fracture under pure and mixed mode loading condition. Indeed, the fracture patterns observed in Fig. 3 for the bovine femur bone are very similar to cleavage fracture in brittle materials. Such that the micro cracks propagate through the weak paths of cement line leading a tensile type brittle fracture. It is well established that the propagation stage of growing crack under mixed mode I/II loading case is governed mainly by the mode I (K_I) component and a tensile type fracture K_I controls the process of mixed mode crack propagation [14]. The obtained fracture surfaces for all mode mixities ranging from pure mode I to pure mode II support this argument since the fracture surface of all investigated mode mixities have similar features. The cross sectional micro-structure of femur bone with higher magnification is shown in Fig. 4. In this figure, different parts including osteons (O), vascular or haversian canal (HC), volkmann canal (VC) and secondary osteons (SO) can be observed. The microstructure of investigated bovine femur is similar to the previous observations [7, 12]. The diameter of "HC" and "O" are typical in the range of 15 and 100 μm. However, the size of secondary osteons that are embedded in the interstitial bone is much greater and their area is approximately 500 μm^2. These regions are often surrounded by the cement lines and are vulnerable to propagation of micro cracks as shown in Fig. 5. While around the primary osteons some evidences of delamination with higher amount of energy and toughness for fracture is observed, the relatively bigger and flat regions between secondary osteons (that are occupied by the interstitial bone), have greater degree of low toughness mineral contents and behave as brittle material. Consequently, the higher the proportion of interstitial flat bone region in the femur bone, the higher the risk of fracture and lower fracture resistance. In addition, higher density of vascular canals results in accelerated growth rate of fracture and failure in the femur bone, since these vascular canals act as stress concentrator by which crack propagation path might be deflected. Similarly, the existence of larger amounts and greater sizes of Volkmann canals may decrease drastically the failure load bearing capacity of the bone. Since these elongated voids in the texture of bone are the main source of initiation and then coalescence of micro-cracks along the main fracture surface of the broken one (as shown in Fig. 6).

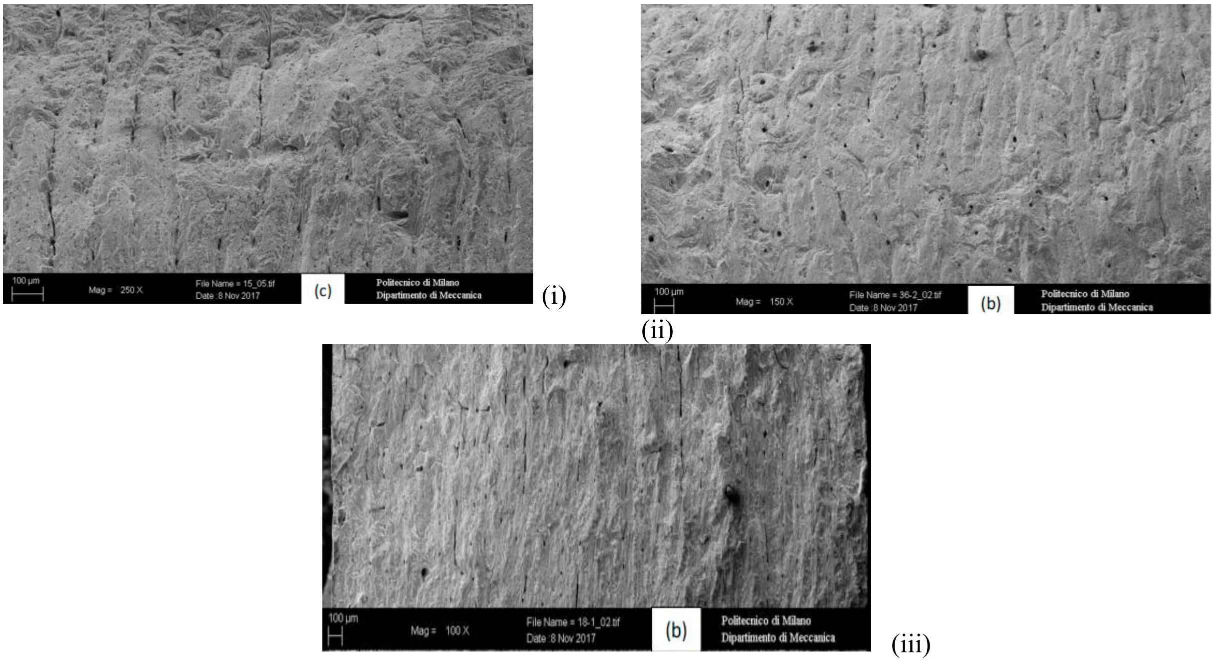


Fig. 3: Fracture surface of bovine femur tested under (i) pure mode I, (ii) mixed mode I/II and (iii) pure mode II loading conditions.

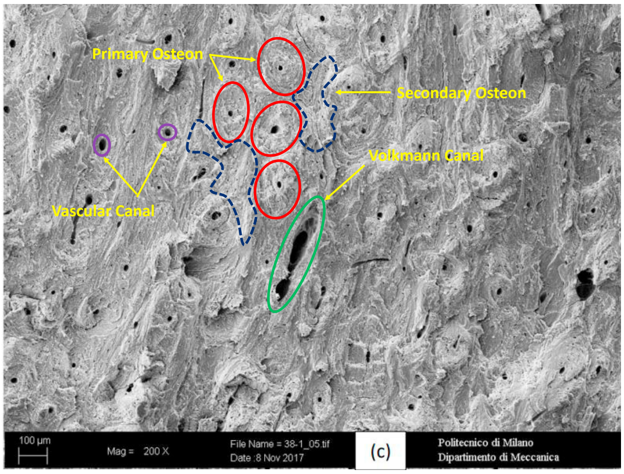


Fig. 4: Cross-sectional microstructure of fractured femur bone.

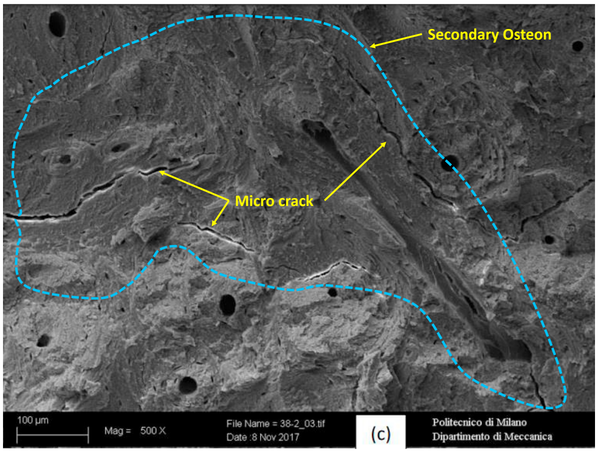


Fig. 5: Initiation of micro-cracks around the secondary osteon boundaries.

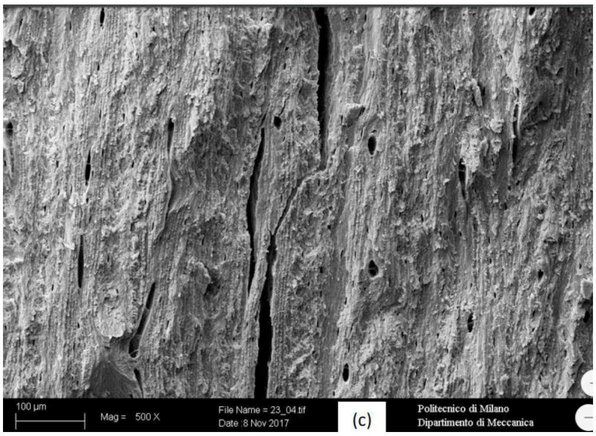


Fig. 6: Coalescence of micro-cracks from the tip of elongated voids and canals.

4. Conclusion

- Mixed mode fracture toughness of bovine femur samples was obtained using compact beam bend specimen. This sub-sized specimen can produce full combinations of mode mixities from pure mode I to pure mode II.
- Mode II fracture toughness value (K_{IIc}) of tested femur bone samples was smaller than the corresponding K_{Ic}. In addition the fracture trajectory of tested samples was highly affected by the state of mode mixity.
- Fracture surfaces of investigated bone samples were studied using SEM observation, demonstrating dominantly brittle fracture with quite flat and smooth fracture patterns affected by the presence of vascular and Volkmann canals.

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