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Research paper

Fracture toughening mechanism of cortical bone: An experimental and numerical approach

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A B S T R A C T

In this investigation, the crack propagation mechanisms contributing to the toughness of cortical bone were studied using a combination of experimental and numerical approaches. Compact tension (CT) specimens were prepared from bovine cortical bones to achieve crack propagation in the longitudinal and transverse directions. Stable crack extension experiments were conducted to distinguish the crack growth resistance curves, and virtual multidimensional internal bond (VMIB) modeling was adopted to simulate the fracture responses. Results from experiments indicated that cortical bone exhibited rising resistance curves (R-curves) for crack extension parallel and perpendicular to the bone axis; the transverse fracture toughness was significantly larger, indicating that the fracture properties of cortical bone are substantially anisotropic. Microscopic observations showed that the toughening mechanisms in the longitudinal and transverse directions were different. When the crack grew in the transverse direction, the crack deflected significantly, and crack bifurcations were found at the crack wake, while, in the longitudinal direction, the crack was straight and uncracked ligaments were observed. Numerical simulations also revealed that the fracture resistance in the transverse direction was greater than that in the longitudinal direction.

1. Introduction

Bone fracture is a serious impediment to human health. Although it more often occurs in seniors as a consequence of osteoporosis, it also develops in people via trauma and stressed fractures. In fact, over 20% of athletes suffer from stress fractures (see, e.g., Burr and Milgrom, 2001; de Carmejane et al., 2005). Consequently, it is essential to understand the fracture behavior of bone. The properties of cortical bone are potentially of greatest interest as it is responsible for bearing the majority of any loading.

Conventional mechanical tests such as tensile, compressive, and three-point bending tests (see, e.g., Kotha and

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Guzelsu, 2003) for examining the strength of bone have facilitated the understanding of the mechanical behavior of bones as continuous materials. It is also of great interest to know how cracks initiate and propagate in bones. As a result, fracture toughness tests have historically served as the predominant method for characterizing the fracture resistance of cortical bones (Wright and Hayes, 1977; Behiri and Bonfield, 1984, 1989; Norman et al., 1995; Phelps et al., 2000; Yan et al., 2007). Recent studies have shown that the fracture toughness of cortical bone increases with crack extension, i.e., cortical bone exhibits a rising resistance curve (R-curve) (Vashishth et al., 2000; Malik et al., 2003; Pezzotti and Sakakura, 2003; Nalla et al., 2004a,b, 2005; Koester et al., 2008; Launey et al., 2010; Morais et al., 2010). This rising R-curve behavior has been attributed to multiple toughening mechanisms. Vashishth et al. (2000) reported that microcracking was responsible for the rising R-curve. However, Nalla et al. revealed that toughening for crack propagation in the longitudinal direction (cracks that extended parallel to the medullar canal) was attributed mostly to uncracked ligament bridging in the crack wake (Nalla et al., 2004a,b, 2005).

While a large number of studies have been reported on the fracture behavior of cortical bone, only a few have examined the characteristics of toughening in the transverse direction. Indeed, achieving stable crack extension in the transverse direction is difficult due to crack deflection. In addition, due to the large loads there are problems if a linear fracture mechanics model is adopted for analysis (Yan et al., 2007; Koester et al., 2008; Launey et al., 2010). Koester et al. (2008) studied crack propagation in the longitudinal and transverse directions within human cortical bone and concluded that the transverse fracture toughness was significantly higher. Toughening of cracks in the transverse direction occurred primarily by crack deflection. That investigation was limited to an experimental evaluation of the fracture behavior.

Numerical modeling is an approach for complementing experimental studies on the fracture behavior of cortical bone. Ural and Vashishth used a cohesive zone model to simulate the fracture of cortical bone (Ural and Vashishth, 2006, 2007). The primary drawbacks of these results are that the cohesive elements must be predefined along the path of crack extension and that the material is considered as a homogenous continuum. Although cortical bone is homogeneous at the macro scale, it has a complex hierarchical structure (Yao and Gao, 2007), and the deformation and fracture behaviors are closely related to the mechanical properties from the microscale to the macroscale. The virtual internal bond (VIB) modeling technique proposed by Gao and Klein (1998) utilizes a naturally multiscale model and has proved to be an effective method to simulate the fracture behavior of materials (Lin and Shu, 2002; Thiagarajan et al., 2004). However, in the VIB model, Poisson's ratio was fixed as a constant, which is not applicable to many materials. Zhang and Ge subsequently developed a virtual multidimensional internal bond (VMIB) model by considering the shear effects of bonds (Zhang and Ge, 2005, 2006, 2007). This modification enables a variation of Poisson's ratio according to the material and has broadened the use of the VMIB method. Nevertheless, this method has not been employed in studying bone fracture.

In this study, the crack growth resistance behavior of cortical bone was studied using a combination of experimental and numerical approaches. The primary objectives of the investigation were to develop reliable experimental approaches which can effectively evaluate the fracture behaviors of cortical bones in both the longitudinal and the transverse directions. The crack growth responses for extension in the longitudinal and transverse directions were also modeled based on the theories of linear and nonlinear fracture mechanics. Lastly, the VMIB method was introduced to numerically simulate the crack propagation. The results from the experimental and numerical approaches were consistent with each other.

2. Materials and methods

Fresh femurs were obtained from mature bovine (1–3 years of age) within 12 h of slaughter. No information regarding age or diet were available for the animals. Several blocks were sectioned from the mid-diaphysial region using a small programmable slicer machine (EC400, Shenyang Kejing Instrument Co., Ltd, China) with diamond abrasive sectioning wheels. Microscopic observation was conducted using an optical microscope to inspect the microstructure of the sections. Sections with plexiform microstructures were discarded and only osteonal bone sections were selected. Compact tension (CT) specimens were prepared with two orientations (Fig. 1) to achieve crack propagation parallel and perpendicular to the bone axis. A side groove was machined to reduce the incidence of fracture at the loading pins and as well as to guide the direction of crack propagation. The notch tip of the CT specimens was sharpened using a razor blade, after which they were subjected to cyclic loading within a hydration bath (22 °C) using a BOSE Model ELF 3300 until a fatigue crack with length of 200 μm was achieved. Extension of the crack from the notch tip was used to reduce notch effects during further quasi-static loading.

Previous investigations for fracture toughness evaluation of cortical bones were mostly based on ASTM standards (Nalla et al., 2004a,b, 2005; Koester et al., 2008). However, the ASTM standard is based on an isotropic assumption and is suitable primarily for metallic materials (ASTM Standard E1820-01, 2001). Behiri and Bonfield (1984) found that the specimen thickness had no effect on the evaluation of the fracture behavior of bones, while Norman et al. (1995) opposed this statement. In this study, instead of using the ASTM standards, a three-dimensional (3D) finite element model was developed to establish equations for estimating the stress intensity factor in the bone CT specimens with respect to the crack length in terms of the energy release rate. The material constants of the bovine cortical bone used in the modeling are listed in Table 1 (Lasaygues and Pithioux, 2002). Using a nonlinear least square fitting method, the equations to describe the stress intensity factors K_I with respect to crack length a propagating in the longitudinal and transverse directions are described by

$$K_I = \frac{P}{B_g\sqrt{W}}\sqrt{\frac{B_g+1}{B+1}}\left[16.5017 - 127.683\left(\frac{a}{W}\right)\right.$$