available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jmbbm

ELSEVIER

Research paper

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

Bingbing An[a], Yang Liu[b], Dwayne Arola[c], Dongsheng Zhang[d,e,*]

[a] *Shanghai Institute of Applied Mathematics and Mechanics, Shanghai, 200072, China*
[b] *Department of Orthopaedics, Shanghai Changzheng Hospital, Shanghai, 200003, China*
[c] *Department of Mechanical Engineering, University of Maryland Baltimore County, Baltimore, MD 21250, USA*
[d] *Department of Mechanics, Shanghai University, Shanghai, 200444, China*
[e] *Shanghai Key Laboratory of Mechanics in Energy Engineering, Shanghai, 200072, China*

ARTICLE INFO

Article history:
Received 11 October 2010
Received in revised form
16 February 2011
Accepted 22 February 2011
Published online 28 February 2011

Keywords:
Cortical bone
Fracture toughness
Compact tension
Numerical modeling

ABSTRACT

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

* *Corresponding author at:* Department of Mechanics, Shanghai University, Shanghai, 200444, China. Tel.: +86 21 66135258; fax: +86 21 6613 5258.
E-mail address: donzhang@staff.shu.edu.cn (D. Zhang).

1751-6161/$ - see front matter
doi:10.1016/j.jmbbm.2011.02.012