ARTICLE IN PRESS

Engineering Fracture Mechanics xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Engineering Fracture Mechanics

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

Analysis of fracture processes in cortical bone tissue

Simin Li, Adel Abdel-Wahab, Vadim V. Silberschmidt *

Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Fracture toughness
Cortical bone
Extended finite element (X-FEM)
Anisotropy
Variability
J-integral

ABSTRACT

Bones are the principal structural components of a skeleton; they play unique roles in the body providing its shape maintenance, protection of internal organs and transmission of forces. Ultimately, their structural integrity is vital for the quality of life. Unfortunately, bones can only sustain loads until a certain limit, beyond which they fail. Understanding a fracture behaviour of bone is necessary for prevention and diagnosis of trauma; this can be achieved by studying mechanical properties of bone, such as its fracture toughness. Generally, most of bone fractures occur in long bones consisting mostly of cortical bone tissue. Therefore, in this paper, an experimental study and numerical simulations of fracture processes in a bovine femoral cortical bone tissue were considered. A set of experiments was conducted to characterise fracture toughness of the bone tissue in order to gain basic understanding of spatial variability and anisotropy of its resistance to fracture and its link to an underlying microstructure. The data was obtained using single-edge-notch-bending specimens of cortical bone tested in a three-point bending setup; fracture surfaces of specimens were studied using scanning electron microscopy. Based on the results of those experiments, a number of finite-element models were developed in order to analyse its deformation and fracture using the extended finite-element method (X-FEM). Experimental results of this study demonstrate both variability and anisotropy of fracture toughness of the cortical bone tissue; the developed models adequately reflected the experimental data.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Bone is a natural composite material with hierarchical organisation 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 in the form of lamellar layers of 5 μm thickness. Similar to a plywood structure, inside a layer, collagen fibres 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, lamellae are parallel and arranged along the cortical bone's circumference. On the other hand, the outside and inside circumferential lamellae form a region made of circular structures called *osteons*, formed from concentric lamellae within remnants of a bone's remodelling process called *interstitial matrix*. The interface between osteons and interstitial matrix is called *cement line*; it is a collagen-free and highly mineralised layer. Cement lines have an important effect on bone's behaviour, 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*.

* Corresponding author.
E-mail addresses: S.Li@lboro.ac.uk (S. Li), a.a.abdel-wahab@lboro.ac.uk (A. Abdel-Wahab), V.silberschmidt@lboro.ac.uk (V.V. Silberschmidt).

0013-7944/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engfracmech.2012.11.020

Please cite this article in press as: Li S et al. Analysis of fracture processes in cortical bone tissue. Engng Fract Mech (2013), http://dx.doi.org/10.1016/j.engfracmech.2012.11.020

Nomenclature

$^*_L$	longitudinal crack propagation direction
$^*_R$	radial crack propagation direction
$^*_T$	transverse crack propagation direction
a	crack length
$A_^*$	anterior quadrant
a_0	average initial crack length
B	thickness
CTOD	crack tip opening displacement
CZE	cohesive zone element
DCB	double-cantilever beam
E_1	Young's modulus for longitudinal direction (osteons direction)
E_2	Young's modulus for transverse direction (perpendicular to osteons direction)
EPFM	elastic–plastic fracture mechanics
FEM	finite-element models
G_{12}	shear modulus
K_{Ic}	critical stress intensity factor
L	total length of specimen
$L_^*$	lateral quadrant
LSD	least significant difference test
LVDT	linear variable differential transducer
$M_^*$	medial quadrant
p	probability value
$P_^*$	Posterior quadrant
S	span
SD	standard deviation
SEM	scanning electron microscopy
SENB	single-edge-notch bending
U_p	plastic component of area under plot of force versus specimen
VCCT	virtual crack closure technique
W	width
X-FEM	extended finite-element method
α	significance level
v	poisson's ratio
σ_{YS}	yield stress

The latter are responsible for exchange of nutrients and waste between osteocytes [3]. At the millimetre 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 to enhance macroscopic mechanical properties of bone tissue at the full-bone scale [4].

Microarchitecture of the cortical bone tissue is 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]. Since *in vivo* fractures are often initiated and/or promoted by cracks, fracture mechanics is considered an important tool in assessing bone tissue's integrity. Therefore, it can be used to enhance the diagnoses and treatment of bone fractures [5]. From a fracture toughness perspective, the cortical bone tissue has different fracture resistance for various crack-propagation directions relative to the long bone axis, i.e. it demonstrates 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 its tip [6–8], and crack deflection and blunting at cement lines that are weak interfaces at the boundaries of secondary osteons [9]. 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 [10–12]. Several authors reported that toughening mechanisms are highly dependent on a crack propagation direction; therefore, fracture toughness of long bones is significantly higher in transverse and radial directions compared to the longitudinal one [12–14].

From a point of view of numerical simulations, a limited number of numerical models were reported in literature studying initiation and propagation of cracks in cortical bone. For instance, Ural and Vashishth [15] developed a cohesive-zone-element model in order to capture an experimentally observed rising crack growth behavior and age-related loss of bone toughness. Later, the same authors used their previous model to investigate the effects of age-related changes and orientation of crack growth on a toughening behaviour of human cortical bone. In addition, the model was used to investigate changes in the anisotropy of toughening mechanisms with age. The used approach-cohesive-zone elements – has an inherent drawback: the crack-extension path must be predefined. Obviously, this is not the case in fracture of real bones, where a

Please cite this article in press as: Li S et al. Analysis of fracture processes in cortical bone tissue. Engng Fract Mech (2013), http://dx.doi.org/10.1016/j.engfracmech.2012.11.020

Download English Version:

https://daneshyari.com/en/article/7169971

Download Persian Version:

https://daneshyari.com/article/7169971

Daneshyari.com