Available online at www.sciencedirect.com
SciVerse ScienceDirect
www.elsevier.com/locate/jmbbm

Research Paper

Micromechanical modeling of R-curve behaviors in human cortical bone

Kwai S. Chan, Daniel P. Nicolella*

Southwest Research Institute, 6220 Culebra Road, San Antonio, TX 78238, USA

ARTICLE INFO

Article history:
Received 12 June 2012
Received in revised form
19 September 2012
Accepted 22 September 2012
Available online 9 October 2012

Keywords:
Age-induced embrittlement
Microdamage
R-curve behavior
Human femur
Crack density
Porosity
Fracture risk

ABSTRACT

The risk of bone fracture increases with age because of a variety of factors that include, among others, decreasing bone quantity and quality due to increasing porosity and crack density with age. Experimental evidence has indicated that changes in bone microstructure and trace mineralization with age can result in different crack-tip strain field and fracture response, leading to different fracture mechanisms and R-curve behaviors. In this paper, a micromechanical modeling approach is developed to predict the R-curve response of bone tissue by delineating fracture mechanisms that lead to microdamage and ligament bridging by incorporating the influence of increasing porosity and crack density with age. The effects of age on fracture of human femur cortical bone due to porosity (bone quantity) and bone quality (crack density) with age are then examined via the micromechanical model.

1. Introduction

The incidence of skeletal fractures in humans increases with age due to a variety of factors that include reduced bone mineral density, impaired balance and reflexes, changes in bone geometry, porosity, architecture, and mineral and organic phases, as well as damage accumulation in the form of microdamage zones or microcracks (Schaffler et al., 1995; Burr et al., 1997; Schaffler and Jepsen, 2000; Parsamian and Norman, 2001; Akkus et al., 2003; Jepsen, 2003; Diab et al., 2006). Experimental evidence suggests that bone mass alone cannot account for changes in the observed fracture risk and that measures of bone mass should be supplemented with measures of bone quality (Van der Meulen et al., 2004). Both porosity and microcrack density in human femoral cortical bone increase with age (Schaffler et al., 1995; Courtney et al., 1996; Norman and Wang, 1997; Zioupos and Currey, 1998; Zioupos et al., 1999; Zioupos, 2001a, 2001b. Correlations of fracture properties of human femoral cortical bone with microcrack density (Zioupos and Currey, 1998; Zioupos et al., 1999) and age (Zioupos and Currey, 1998; Zioupos et al., 1999; Nyman et al., 2006; Wang et al., 2002; Wu and Vashishth, 2002; Nalla et al., 2004; Ritchie et al., 2005; Zimmermann et al., 2012) showed that decreases in fracture toughness of cortical bone with increasing age may be attributed to, at least partly, the accumulation of sub-micron-sized microcracks during the aging process (Schaffler et al., 1995; Norman and Wang, 1997; Zioupos and Currey, 1998). The microcrack density in bone tissues appeared to increase more rapidly in elderly women than in elderly men at the same age (Schaffler et al., 1995).

*Corresponding author. Tel.: +210 522 2053; fax: +210 522 6965.
E-mail address: kchan@swri.edu (K.S. Chan).

1751-6161/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jmbbm.2012.09.009

Recent work has shown that cortical bone exhibits a resistance-curve (*R*-curve) fracture behavior that varies with age (Nalla et al., 2004; Chan et al., 2009). Both the initiation toughness and the initial slope of the *R*-curve decrease with increasing age (Wu and Vashishth; 2002; Nalla et al., 2004, 2005; Chan et al., 2009). The *R*-curve behaviors in cortical bone originates from crack deflection and bridging of crack surfaces by uncracked ligaments at several length scales (Nalla et al., 2004, 2005; Ritchie et al., 2005; Chan et al., 2009), ranging from bridging by osteons, lamella, and a nanoscaled non-fibrous organic glue material found between mineralized collagen fibrils (Fantner et al., 2005). Despite these recent advances, the role of the bone microstructure, which is comprised of Haversian, lamellar and interstitial bone tissue, and the corresponding porosity and in-situ microcrack density accumulated over daily activities in affecting the risk of bone fracture still cannot be fully predicted quantitatively, even though their effects are understood qualitatively. For example, the fracture mechanics parameter commonly utilized for fracture toughness characterization is the stress intensity factor, *K*, which is strictly applicable for linear-elastic materials with little or no porosity. Human cortical bone can contain greater than 30% porosity (McCalden et al., 1993; Wang and Ni, 2003; Chan et al., 2009; Nicolella et al., 2011) and some microcracks; the applicability of linear-elastic fracture mechanics to treat fracture in bone tissues has not been addressed fully. The presence of in-situ microcracks in aged bone tissues requires consideration of the effects of both distributed pores and microcracks on fracture resistance of cortical bone.

There are at least three approaches that have been proposed for estimating the effective modulus of a cracked solid (Budiansky and O′Connell, 1976; Benveniste, 1987; Kachanov, 1992, 1994; Hu et al., 1993; Huang et al.,1994; Feng, 2001; Feng et al., 2003). The simplest one is the dilute or non-interacting solution (Kachanov, 1992, 1994; Huang et al., 1994; Feng, 2001; Feng et al., 2003), which treats the effect of individual microcracks on the main crack by summing the shielding or antishielding contributions of individual microcracks in a cracked solid without considering the interactions among the microcracks. Crack-tip shielding occurs when a microcrack lowers the local stress intensity factor, while antishielding occurs when a microcrack enhances the local stress intensity factor of the main crack. In the self-consistent method (Budiansky and O′Connell, 1976), the effect of crack interaction is taken into account approximately by embedding each microcrack in an effective medium. The differential method is an incremental form of the self-consistent method (Huang et al., 1994). The effective modulus of a heterogeneous medium with inclusions was treated by Mori and Tanaka (1973). This model can be extended to porous solids by treating the pores as inclusions with a zero modulus. In the generalized self-consistent method (Huang, et al., 1994), for each inclusion the effect of interaction from other inclusion is treated approximately by embedding the inclusions in a finite matrix which, in turn, is embedded in a composite. Recent reviews of the various methods (Kachanov, 1992, 1994; Hu et al. 1993; Huang et al., 1994; Feng, 2001, 2003) indicate that non-interacting (dilute) solution remains valid over a wide range of microcrack density. In addition, the Mori and Tanaka method (1973) yields a solution that is identical to the dilute solution for non-interacting microcracks in a cracked solid (Benveniste, 1987). These reviews also indicate that in general, the elastic properties of a porous or cracked solid subjected to uniform remote loading can be solved by decomposing the problem into two simpler problems: (1) a homogeneous problem in which the matrix subjected to the same remote loading in the absence of any crack, and (2) one or more perturbed problems in which only the crack or pore surfaces are subjected to pseudo-tractions that satisfy the traction-free boundary conditions on the crack or pore surfaces in the original, more complex problem (Hu et al., 1993; Huang et al., 1994). The final solution to the original problem is then obtained by superposition of the solutions to the two simpler problems. A graphical illustration of this approach is shown in Fig. 1(a) and Fig. 2 of Hu et al. (1993).

The objective of this article is to present the results of an investigation aimed at elucidating the effects of porosity and microcrack density on the *R*-curve behaviors of human cortical bone. The assumption of non-interacting pores or microcracks provides a simple means for estimating the reduction in the elastic modulus, fracture strength, and fracture toughness of human femur as a function of porosity and microcrack density. Since information on porosity and microcrack density are available as a function of age and sex, the influence of age on ductile to brittle fracture transition in human cortical bone can be elucidated by examining how porosity and micorcrack density affect the *R*-curve behavior for different age levels. In particular, the initiation toughness and the initial slope of the *R*-curve of bone are assessed by considering the corresponding increase of porosity and microcrack density as a function of age and sex. Since the ductile to brittle fracture transition as determined by the slope of the *R*-curve is also influenced by crack deflection, the dependence of interface toughness and the relevant elastic properties that dictate crack penetration or crack deflection at an interface is considered on the basis of the crack deflection analysis by He and Hutchinson (1989). The results of this investigation show that the decrease in the fracture resistance with increasing age in female cortical bone may be attributed to an increase in the accumulated number of microcracks, porosity, and changes to relevant material properties such as interface toughness and elastic modulus during aging.

2. Fracture mechanics of cracked porous materials

Despite the presence of pores in the microstructure, linear elastic fracture mechanics and the stress intensity factor, *K*, is commonly used to characterize the fracture resistance of cortical bone because of the lack of a methodology to account for the stress concentration effects of the porosity. The semi-brittle nature of bone is another complicating factor since it results in a non-linear fracture response that is commonly described in the form of a K_R curve (Vashishth et al., 1997) or simply *R*-curve (Nalla et al., 2004, 2005), which is a plot of stress intensity factor as a function of crack extension. A previous analysis has shown that the interaction of a crack