available at www.sciencedirect.com

ScienceDirect

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

Research paper

Effects of age and loading rate on equine cortical bone failure

Robb M. Kulin[a], Fengchun Jiang[b], Kenneth S. Vecchio[b,*]

[a] *Materials Science & Engineering Program, University of California – San Diego, 9500 Gilman Dr., La Jolla, CA 92093-0418, United States*
[b] *Department of Nano Engineering, University of California – San Diego, 9500 Gilman Dr., La Jolla, CA 92093-0448, United States*

ARTICLE INFO

Article history:
Received 21 May 2010
Received in revised form
14 September 2010
Accepted 17 September 2010
Published online 21 September 2010

Keywords:
Fracture
Equine bone
Toughness
Aging
Hopkinson bar
Loading rate effects
Compression
Confocal microscopy

ABSTRACT

Although clinical bone fractures occur predominately under impact loading (as occurs during sporting accidents, falls, high-speed impacts or other catastrophic events), experimentally validated studies on the dynamic fracture behavior of bone, at the loading rates associated with such events, remain limited. In this study, a series of tests were performed on femoral specimens obtained post-mortem from equine donors ranging in age from 6 months to 28 years. Fracture toughness and compressive tests were performed under both quasi-static and dynamic loading conditions in order to determine the effects of loading rate and age on the mechanical behavior of the cortical bone. Fracture toughness experiments were performed using a four-point bending geometry on single and double-notch specimens in order to measure fracture toughness, as well as observe differences in crack initiation between dynamic and quasi-static experiments. Compressive properties were measured on bone loaded parallel and transverse to the osteonal growth direction. Fracture propagation was then analyzed using scanning electron and scanning confocal microscopy to observe the effects of microstructural toughening mechanisms at different strain rates. Specimens from each horse were also analyzed for dry, wet and mineral densities, as well as weight percent mineral, in order to investigate possible influences of composition on mechanical behavior. Results indicate that bone has a higher compressive strength, but lower fracture toughness when tested dynamically as compared to quasi-static experiments. Fracture toughness also tends to decrease with age when measured quasi-statically, but shows little change with age under dynamic loading conditions, where brittle "cleavage-like" fracture behavior dominates.

1. Introduction

Bone is a complex hierarchical material with a highly anisotropic structure and mechanical response that varies depending on loading rate and orientation (Saha, 1982). Beginning at the nano-scale regime, the main constituents of collagen and calcium phosphate mineral are assembled in successively larger structures forming a material that adapts to support bodily loads, allows ingrowth of tendons and ligaments, resists fracture, and even self heals (Martin et al., 1998; Rho et al., 1998; Ritchie et al., 2006). However, its complex architecture and ability to adapt locally and globally to external loads (Les et al., 1997, 1998) has led to a poor understanding of how bone's hierarchical structure interacts

* *Corresponding author.* Tel.: +1 858 822 7922; fax: +1 858 534 9553.
E-mail address: kvecchio@ucsd.edu (K.S. Vecchio).

1751-6161/$ - see front matter
doi:10.1016/j.jmbbm.2010.09.006

at its various length scales to influence bulk mechanical behavior and fracture resistance. This is especially true when varying strain rates and donor age are considered.

Past research into the fracture behavior of bone have primarily focused on experiments performed quasi-statically, despite most clinical bone fractures occurring under dynamic loading conditions. The majority of these studies focused on measuring the fracture toughness, K_{IC}, or other single value fracture toughness measurements of bone using various geometries and specimen orientations with respect to the osteonal growth direction (Behiri and Bonfield, 1989; Bonfield et al., 1978; Brown et al., 2000; Lucksanasombool et al., 2001; Phelps et al., 2000; Wright and Hayes, 1977). More recently, however, measurements of rising R-curve behavior have shed even more light on crack propagation in cortical bone and demonstrated the importance of crack bridging, microcracking, and other mechanisms in resisting cortical bone fracture (Koester et al., 2008; Nalla et al., 2005a,b; Vashishth, 2004; Vashishth et al., 1997, 2000, 2003; Zioupos et al., 2006).

The complex microstructure of cortical bone plays an important role in resisting both crack initiation and propagation. Mature cortical bone primarily consists of Haversian systems (osteons) that tend to grow along a single axis, such as the long axis in long bones, creating a nearly fiber-like structure consisting primarily of secondary osteons. Secondary osteons (150–250 μm in diameter) are created during bone remodeling and are composed of individual lamellar layers built up around a central nutrient canal (25– 50 μm in diameter). Osteons bond with surrounding tissue through a 1–1.5 μm poorly organized, calcium phosphate interface termed the 'cement line'. It should be noted that there is some debate as to the actual composition of the cement line, and whether it is collagen free and hypermineralized (Davies, 1996, 2003, 2007; Skedros et al., 2005) or a region of reduced mineralization and sulfated muco-substances (Burr et al., 1988; Schaffler et al., 1987). However, regardless of the actual composition, it has been accepted as an interface of differing properties from the surrounding bone matrix and osteons, and thus has significant effects on mechanical behavior. According to those who believe it is a hypermineralized region, this interface differs from the smaller interlamellar boundaries within osteons in that it is devoid of collagen, and thus tends to form a more brittle path for crack propagation (Yeni and Norman, 2000). This more brittle nature tends to allow cracks to propagate more freely along the orientation of Haversian systems and their surrounding cement lines, thus affecting the apparent fracture toughness dependence of the material on test orientation. Donor age has also been shown to have a distinct influence on the quasi-static fracture behavior of cortical bone. However, what causes this change is not fully understood; collagen properties, increased mineralization, bulk density and secondary osteon concentration and size all appear to be important factors (Currey et al., 1996; Nalla et al., 2006, 2004a; Ritchie et al., 2006; Wang et al., 2002b, 1998; Zioupos and Currey, 1998; Zioupos et al., 1996).

Another factor that has been shown to have a profound effect on the fracture toughness of cortical bone is crack velocity. Initial research into this behavior focused on relatively low rates with crack velocities of 10^{-5}to10^{-3} m/s (Behiri and Bonfield, 1980, 1984; Bonfield et al., 1978). It is only recently that experiments at more extreme loading rates have been performed (Adharapurapu et al., 2006; Tanabe et al., 1998). However, the viscoelastic, yet relatively brittle, behavior of bone exacerbates technical difficulties regarding loading "rise time" for specimens to reach stress equilibrium, and characterization at high constant strain rates. This applies for both high strain rate compressive experiments, as well as dynamic fracture toughness measurements. This may be in part due to the ductile to brittle transition that occurs in bone, presumably around 10^{-2} to 10^{-1} s^{-1} (Evans et al., 1992; Kirchner, 2006; Zioupos et al., 2006), but also shown to be as high as 20 s^{-1} in compression (Hansen et al., 2008). Adharapurapu et al. (2006) approached this problem using a modified split-Hopkinson pressure bar (SHPB) with a novel pulse shaping technique that achieved constant stress intensity rates of 2×10^5 MPa $m^{1/2}s^{-1}$ in three-point bending fracture toughness tests, and constant strain rates of 10^3 s^{-1} in compression experiments. Results showed a strong reliance of fracture toughness and compressive mechanical behavior on loading rate for both hydrated and dried bovine bone specimens.

The purpose of the present study is to begin to address the effects of age on the strain rate dependent behavior of equine bone under compressive loading, as well as the age and loading-rate dependence on fracture toughness, with a focus on the overall dynamic mechanical response with respect to age. At a gallop, thoroughbred race horses have been shown to regularly achieve strain rates as high as 0.15 s^{-1} (Rubin and Lanyon, 1982), though higher and lower values of strain rate may be achieved. For this reason, this study aims to characterize the compressive and fracture behavior of equine bone over a broad range of loading rates, ranging from the quasi-static regime ($\sim 10^{-3}$ s^{-1}), to the reported region of the transition from ductile to brittle behavior (~ 1 s^{-1}), to impact speeds as might occur in a violent collision ($\sim 10^3$ s^{-1}). It does so over a broad age range to monitor for changes occurring with age, and also aims to further characterize fundamental changes in fracture behavior between dynamic and brittle fracture. As most bone fractures are related to impact events, understanding bone's response to dynamic loads is critical in preventing fractures, and for the design of implant or biomimetic materials.

2. Methods

2.1. *General methodology*

A series of mechanical tests were performed to examine the mechanical response of cortical bone under varying loading conditions with regards to horse age. In general, the tests performed can be grouped as either compression or flexure experiments. Compression experiments were performed at strain rates of 10^{-3} s^{-1}, 10^0 s^{-1} and 10^3 s^{-1} in order to examine the mechanical response of bone at varying strain rates. Tests were performed with loading applied either transverse to or along the osteonal growth direction. Flexure experiments were performed under four-point bending using single-notched and double-notched specimens under either