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How tough is bone? Application of elastic–plastic fracture mechanics to bone

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Abstract

Bone, with a hierarchical structure that spans from the nano-scale to the macro-scale and a composite design composed of nano-sized mineral crystals embedded in an organic matrix, has been shown to have several toughening mechanisms that increases its toughness. These mechanisms can stop, slow, or deflect crack propagation and cause bone to have a moderate amount of apparent plastic deformation before fracture. In addition, bone contains a high volumetric percentage of organics and water that makes it behave nonlinearly before fracture. Many researchers used strength or critical stress intensity factor (fracture toughness) to characterize the mechanical property of bone. However, these parameters do not account for the energy spent in plastic deformation before bone fracture. To accurately describe the mechanical characteristics of bone, we applied elastic–plastic fracture mechanics to study bone's fracture toughness. The J integral, a parameter that estimates both the energies consumed in the elastic and plastic deformations, was used to quantify the total energy spent before bone fracture. Twenty cortical bone specimens were cut from the mid-diaphysis of bovine femurs. Ten of them were prepared to undergo transverse fracture and the other 10 were prepared to undergo longitudinal fracture. The specimens were prepared following the apparatus suggested in ASTM E1820 and tested in distilled water at 37°C. The average J integral of the transverse-fractured specimens was found to be 6.6 kPa m, which is 187% greater than that of longitudinal-fractured specimens (2.3 kPa m). The energy spent in the plastic deformation of the longitudinal-fractured and transverse-fractured bovine specimens was found to be 3.6–4.1 times the energy spent in the elastic deformation. This study shows that the toughness of bone estimated using the J integral is much greater than the toughness measured using the critical stress intensity factor. We suggest that the J integral method is a better technique in estimating the toughness of bone.

Keywords: J integral; Bone; Elastic–plastic fracture mechanics; Linear–elastic fracture mechanics; Fracture toughness

Introduction

Understanding the fracture behavior and fracture mechanisms of bone is important to both medical science and the engineering community. For scientists working on building a better prosthetic bone implant, one of the key issues is having a material that matches the mechanical properties of bone. Bone has been shown to be relatively tough compared to ceramics or polymers because of its hierarchical microstructure and composite nature [1,2]. For years, researchers have employed different mechanical testing methods to study how and why bone fractures. Common parameters, such as stiffness, strength, and fracture toughness (critical stress intensity factor), have been widely used to quantify bone's properties [3–7]. However, bone is composed of minerals, organics, and water and is built in a complicated hierarchical structure with many toughening mechanisms [1,8–11]. Simple parameters, such as critical strain and strength, may not be sufficient to describe the fracture characteristics of bone since they do not characterize the actual fracture process of the materials. On the other hand, many researchers have applied fracture mechanics to answer the question: "How tough is bone?" [4,5,12–14]. They employed two widely used parameters, the critical stress intensity factor (K_c, also called fracture toughness) and the critical energy release rate (G_c), to estimate the toughness of bone. Most of these studies were done based on linear–elastic fracture mechanics (LEFM), which assumes the deformed materials have no, or small-scale, yielding before fracture. This LEFM

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assumption may not be true for bone since bone has been shown to exhibit a moderate amount of post-yield deformation [15,16]. Fig. 1 shows the stress–strain curve of a rectangular bovine femur cortical bone specimen fractured in three-point flexure. The curve shows that the amount of post-yield strain is close to the amount of strain before the offset yield point (σ_y, also called yield strength).

Recently, several researchers have reported rising *R*-curve (K_R, crack extension resistance) behavior in cortical bone [11,14,18,19]. *R*-curve behavior characterizes the resistance to fracture of materials during incremental stable, slow crack extension, and results from growth of the process zone as the crack extends from a sharp notch [20]. For materials with rising *R*-curve behavior, the greater stability results in additional crack extension and this may lead to greater measured fracture toughness values than the initiation fracture toughness [21]. Nalla et al. [11] evaluated the effect of aging on the fracture toughness of human humerus using *R*-curve behavior. They found both the initiation toughness and the growth toughness decreased as the age of the donors increased (34–99 years). Vashishth et al. [18] used compact tension (CT) specimens to measure *R*-curves of young bovine and adult human tibiae along longitudinal fracture. They demonstrated that the toughening mechanism in bone was microcracking. Malik et al. [19] used CT specimens to estimate the *R*-curve behavior of equine cortical bone along transverse fracture. They pointed out that, besides microcracking, mechanisms like osteon pullout, fiber bridging, and crack deflection may also have effects on the increment of fracture toughness.

Though K_R is a good parameter in characterizing bone's ability against crack propagation, the underlying assumption for K_R calculation, is also based on LEFM. For materials having a large amount of plastic deformation, such as bone and aluminum, LEFM can no longer be applied to accurately estimate their fracture toughness since the stress distribution near the fracture origin can no longer be accurately predicted by stress intensity factor analysis [22,23]. Plastic deformation, in this study, is used as a general term to indicate any inelastic, non-recoverable deformation which may be caused by numerous mechanisms such as local viscoelasticity or viscoplasticity, plasticity, microcracking, etc. In addition, Yang et al. [24,25] used a nonlinear fracture model and showed that LEFM cannot accurately describe the whole fracture process in human cortical bone.

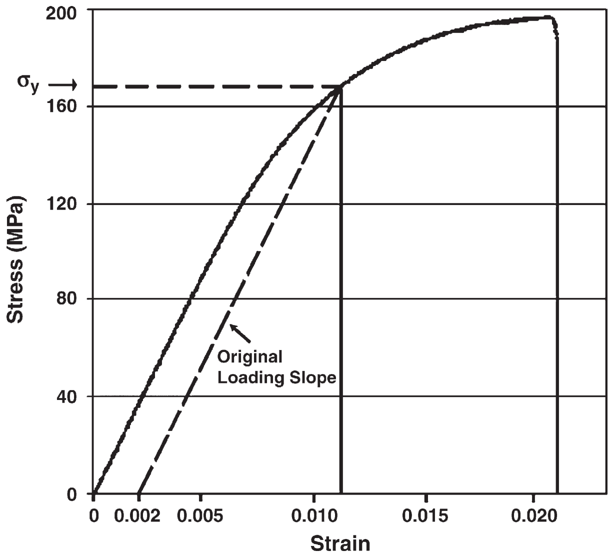

Fig. 1. Bone shows a moderate amount of post-yield strain in flexure tests. The stress–strain curve of an unnotched bovine femur cortical bone specimen tested in three-point flexure. σ_y is determined using the definition of 0.002 strain offset point (ASTM E399 [17]).

In order to accurately describe the fracture behavior of bone, we applied elastic–plastic fracture mechanics (EPFM) to study bone's toughness. EPFM can be used to analyze the toughness of materials with large post-yield deformation and it has been shown to better describe the fracture behavior of ductile materials than LEFM does [23,26]. In EPFM, the *J* integral is a parameter that can be used to quantify both the energies consumed in the elastic and plastic deformations of a strained object [27,28]. Given that bone has several toughening mechanisms and shows a moderate amount of plastic deformation before fracture, we think the J integral can be a better parameter in estimating the toughness of bone. The goals of this study were to estimate the *J* integral of bovine femur and to compare the results with previous studies based on LEFM.

Materials and methods

The *J* integral measurement was made following standard ASTM E1820 [28]. Twenty single-edge notched specimens were cut from the mid-diaphysis of two bovine femurs from two young adult cows (approximately 24 months). Ten of them, with dimensions 4×4×45 mm (thickness×height×length), were prepared to undergo transverse fracture (i.e., crack advances perpendicular to the major axis of the femur); the other 10, with dimensions 4×4×25 mm, were prepared to undergo longitudinal fracture (i.e., crack advances parallel to the radial direction of the femur). Fig. 2 shows where these specimens were cut from the femurs. While ASTM E1820 suggests using a support span, *S*, equal to four times the height, *W*, for metals, greater *S*/*W* ratios, 10 and 5, were chosen because of the composite nature of bone [29]. Longitudinal-fractured specimens were prepared with a smaller *S*/*W* ratio due to the curvature of the bone shaft. Though an $S/W=20$ is recommended for measuring the elastic modulus of bone [30], our previous studies [31,32], in which we used ultrasound and three point flexure ($S/W=10$) techniques, showed the difference in the elastic modulus of manatee rib bone between the two techniques to be within 10%.

The single-edge notch of each specimen was prepared using a diamond wheel followed by inducing a sharp notch with a razor blade. By using a scanning electron microscope (SEM), the radius of the notch tip was estimated to be approximately 1 μm (Fig. 2). All specimens were prepared to have the depth of the starter notches (a_o) equal to 2 mm, which is half the height of the specimens. The notches were cut to have fracture from the periosteal surface towards the endosteal surface. Besides starter notches, side grooves were also induced on both sides of the specimens to ensure that the cracks propagated along the original crack plane. The side grooves are important in controlling crack propagation since the fibers in bone can deviate the crack direction (a toughening mechanism) and cause large variances in the results. Each side groove was made 0.5 mm in depth. The total depth of the two side grooves was 1 mm, which corresponded to 0.25 times the thickness, *B*. All specimens were kept in a freezer or stored in physiological buffered saline solution at 4°C at all times until tested. During cutting and polishing, a constant spray of water was supplied to keep the specimens from heating and to keep them wet. All notched specimens were then fractured in three-point flexure using a universal testing machine (Instron Model 1125, Instron Corporation, Canton, MA). Flexural tests were conducted in distilled water at 37°C using a loading rate of 1.0 mm/min.