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# Cohesive finite element modeling of age-related toughness loss in human cortical bone

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**Abstract**

Although the age-related loss of bone quality has been implicated in bone fragility, a mechanistic understanding of the relationship is necessary for developing diagnostic and treatment modalities in the elderly population at risk of fracture. In this study, a finite element based cohesive zone model is developed and applied to human cortical bone in order to capture the experimentally shown rising crack growth behavior and age-related loss of bone toughness. The cohesive model developed here is based on a traction–crack opening displacement relationship representing the fracture processes in the vicinity of a propagating crack. The traction–displacement curve, defining the cohesive model, is composed of ascending and descending branches that incorporate material softening and nonlinearity. The results obtained indicate that, in contrast to initiation toughness, the finite element simulations of crack growth in compact tension (CT) specimens successfully capture the rising *R*-curve (propagation toughness) behavior and the age-related loss of bone toughness. In close correspondence with the experimentally observed decrease of 14–15% per decade, the finite element simulation results show a decrease of 13% in the *R*-curve slope per decade. The success of the simulations is a result of the ability of cohesive models to capture and predict the parameters related to bone fracture by representing the physical processes occurring in the vicinity of a propagating crack. These results illustrate that fracture mechanisms in the process zone control bone toughness and any modification to these would cause age-related toughness loss.


*Keywords:* Cortical bone; Fracture toughness; Aging; Finite element method; Microcracking

## 1. Introduction

Age-related loss of bone quality has been implicated as a significant contributor to bone fragility (Burr et al.,1997) but it is still unknown how changes in bone quality alter the propensity of bone to fracture. Such a mechanistic understanding is essential for developing and evaluating approaches for diagnostic and treatment modalities in the elderly population at risk of bone fracture.

Fracture mechanics approach has been commonly used to define the resistance of bone to fracture (for review see Bonfield, 1987; Melvin, 1993). These studies focused on a single parameter characterization of the fracture toughness including critical stress intensity factor and critical energy release rate. Melvin and Evans (1973) were among the first researchers to apply fracture mechanics to bovine bone by using a single-edge-notched (SEN) specimen. Following their study, Bonfield and Datta (1974) reported stress intensity factors using center-notched cylindrical (CNC) thin-walled tube specimens and SEN specimens for bovine bone (Bonfield and Datta, 1976). Wright and Hayes (1977)

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demonstrated the first study using compact tension (CT) specimen configuration measuring fracture toughness of bovine femur. CT specimens were employed in subsequent studies on human and other cortical bone (Bonfield et al., 1978, 1984; Norman et al., 1992, 1995; Vashishth, 2004; Vashishth et al., 1997, 2000, 2004; Yeni and Norman, 2000; Yeni et al., 1997, 1998; Wang et al., 1998; Brown et al. 2000; Nalla et al., 2004b).

Another area of research interest involved determining the change in fracture toughness properties with age. Studies on age-related changes in these parameters showed a decreasing trend with age (Zioupos and Currey, 1998; Brown et al., 2000). Brown et al. (2000) measured the change in tensile and shear energy release rate values with age in human femur and tibia using CT specimens and compact shear specimens, respectively. They reported a significant decrease in tensile fracture toughness for both femur and tibia. Zioupos and Currey (1998) measured fracture toughness and $J$-integral energy needed to form a crack using human femur and also reported a significant decrease in both of these values.

In recent studies, propagation toughness, defined as the change in fracture toughness of bone as the crack progresses, is given more emphasis for characterizing fracture in bone. These studies showed that toughening mechanisms play an important role in the fracture behavior of bone by increasing its fracture resistance to crack propagation (Vashishth, 2004; Vashishth et al., 1997, 2000, 2003, 2004; Nalla et al., 2003, 2004a, b, 2005; Kahler et al., 2003, Malik et al., 2003). Toughening behavior in human cortical bone was experimentally shown in previous studies resulting in a rising crack growth ($R$-curve) behavior (Vashishth et al., 1997; Nalla et al., 2004b). In addition to the observed toughening behavior, experimental results also showed age-related loss of cortical bone toughness both in the initiation as well as in propagation toughness (Vashishth et al., 2004; Nalla et al., 2004b). The study by Vashishth et al. (1997) used CT specimen geometry to show the rising $R$-curve behavior in human tibia due to toughening mechanisms during crack growth. The same test procedure was used by Vashishth et al. (2004) to study the age-related changes in fracture toughness of cortical bone for subjects ranging from 34 to 97 years of age. In that study, the decrease in propagation toughness was found to be more pronounced than the decrease in initiation toughness. The same observation was reported by Nalla et al. (2004b) using CT specimens for human humerus where both initiation and propagation toughness decreased with age for the age range of 34–99 years.

The toughening behavior of bone reported in crack propagation tests is a result of the physical processes taking place in the vicinity of a propagating crack. The goal of this study is to present a computational model that represents the effects of these physical processes and consequently captures the toughening behavior of bone and its age-related changes. Here, for the first time, we describe the development of a nonlinear finite element based cohesive model of bone fracture and demonstrate its successful application in capturing the experimentally measured rising $R$-curve behavior of human cortical bone (Vashishth et al., 1997; Nalla et al., 2004b) and age-related loss of bone toughness (Vashishth et al., 2004; Nalla et al., 2004b). Cohesive models have been a method of choice in engineering applications starting with the works of Dugdale (1960) and Barenblatt (1962) since they represent the physical processes occurring in the vicinity of a propagating crack by a simplified traction–displacement relationship and consequently isolate the fracture process from the surrounding continuum constitutive model. These applications varied from yielding in plastic plates (Dugdale, 1960) to cracking in concrete (Hillerborg et al., 1976), void nucleation in metallic materials (Needleman, 1987), plasticity effects in ductile materials, (Tvergaard and Hutchinson, 1992), dynamic fracture in brittle solids (Camacho and Ortiz, 1996; Ortiz and Pandolfi, 1999) and fatigue crack growth in metals (de Andres et al., 1999).

Our aim in this study is to develop a cohesive finite element model and show its predictive capability via crack growth simulations of CT specimens employing this model. Specifically, our goal is to demonstrate the rising $R$-curve behavior and age-related initiation and propagation fracture toughness loss in human cortical bone using a computational model based on independently measured parameters.

## 2. Methods

Crack growth simulations of CT specimens (Fig. 1a) were performed to capture the experimentally measured $R$-curve behavior and age-related loss of bone toughness in human cortical bone using the finite element method incorporating a cohesive model. The crack propagation is in the longitudinal direction (parallel to the long bone axis) as shown in Fig. 1(a). The cohesive model used here is similar to other models proposed in the engineering literature with an ascending and a descending branch making use of the effective traction and displacement concept which is a coupled representation of the normal and shear crack-opening displacements (Camacho and Ortiz, 1996, Ortiz and Pandolfi, 1999).

In the finite element approach, cohesive models can be implemented as interface elements that are compatible with regular solid finite elements. In two dimensions, the cohesive interface elements are composed of two line elements with zero thickness, which coincide in the reference configuration (Fig. 1b). Each line element has $n$ nodes, which gives $2n$ nodes for the cohesive element.