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Haversian cortical bone model with many radial microcracks: An elastic analytic solution

A. Raeisi Najafi [a], A.R. Arshi [a,*], M.R. Eslami [b], S. Fariborz [b], M. Moeinzadeh [c]

[a] Department of Medical Engineering, Amirkabir University of Technology, Tehran, Iran
[b] Department of Mechanical Engineering, Amirkabir University of Technology, Tehran, Iran
[c] Department of Industrial and Enterprise Systems Engineering, University of Illinois at Urbana-Champaign, USA

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Abstract

In this study, the fracture micromechanics of Haversian cortical bone has been considered. To this effect, a two-dimensional micromechanical fibre–ceramic matrix composite tissue materials model has been presented. The interstitial tissue was modeled as a matrix and the osteon was modeled as a fibre, followed by the application of linear elastic fracture mechanics theory. The solution for edge dislocations, in terms of Green's functions, was adopted to formulate a system of singular integral equations for the radial microcracks in the matrix in vicinity of the osteon. The problem was solved for various configurations and the corresponding stress intensity factors were computed. The results of this study indicated that the interaction between microcracks and an osteon was limited to vicinity of the osteon. Furthermore, the effect of microstructure morphology and heterogeneity on the fracture behavior has been established. The interactions between microcracks were also analyzed for various configurations. These selected configurations exhibited the effects of stress amplification and stress shielding.
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Keywords: Haversian cortical bone; Microcrack interaction; Linear elastic fracture mechanics; Microstructure; Edge dislocation

1. Introduction

Bone undergoes microdamage in the form of microcracks due to fatigue and cyclic loading [1–3]. The microcracks can coalescence causing a reduction in the mechanical properties of the bone [4,5]. The weakness caused by microcracks has been accepted as a primary assumption in the study of mechanical properties of this tissue [5–7]. This will increase the possibility of fracture [8–10]. The relationship between the microcracks and the parameters governing fracture, e.g. those associated with toughness, has not as yet been fully understood and analyzed [11–13].

Formation and growth of microcracks are related to the bone microstructure [1,14]. The human Haversian cortical bone has been considered as a composite material and modeled as fibre–ceramic matrix in microstructural studies [15–17]. Osteons are considered as fibres and interstitial tissue as matrix in this composite material. The interface between the osteons and interstitial tissue is a third type of tissue forming the cement line.

Fracture phenomena in Haversian cortical bone are primarily affected by the morphology and heterogeneity of the microstructure [12–14,18]. However, variations in these parameters caused by the aging process can make the problem rather more complicated [12,19,20]. For example, the aging process increases the differences in the mechanical properties of osteons and interstitial tissue [19]. This has a profound effect upon the fracture behavior of bone [12,13]. It is thus necessary to enhance the understanding of the mechanisms governing fracture in Haversian cortical bone [18].

In this study, linear elastic fracture mechanics (LEFM) theory was adopted for the analysis of fracture in composite fibre–ceramic matrix materials [21]. This theory has also been used in determination of the bone resistance to fracture [22–24]. However, only a limited number of studies have considered fracture micromechanics in the Haversian cortical

* Corresponding author. Tel.: +98 21 88883772.
E-mail address: arshi@aut.ac.ir (A.R. Arshi).

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bone [13,25–27]. Amongst such investigations, Lakes et al. have reported that the fracture behavior of microcracks with lengths of 250–500 μm in Haversian cortical bone can not be predicted by LEFM of a uniform material [25]. Furthermore, Martin and Burr have reported microcrack growth-arrest by the cement line [27]. Guo et al. have reported on the osteonal effect on a microcrack that was oriented perpendicularly to the external load [13]. However, a detailed description of the relationship between microcracks and fracture behavior has not as yet been provided. To understand this relation, it is necessary to begin by formulating a sufficiently encompassing description of microcrack governing micromechanics, accompanied by the description of the interaction between existing microcracks.

The objectives of the current study have been to provide a realistically simple model of Haversian cortical bone microstructure, so as to obtain a clearer description of the rules governing the mutual interaction amongst microcracks assuming LEFM theory. Furthermore, interaction between an osteon and radial microcracks was studied to establish the susceptibility of fracture behavior to microstructure.

2. Methods

The assumption of plane strain conditions and linear elastic fracture mechanics in a two-dimensional model of the bone could be justified by the similarities between Haversian cortical bone and the composite fibre–ceramic matrix materials. The osteons were represented as fibres and the interstitial tissue was considered as a matrix and the cement line was excluded in this model. All the tissues were assumed homogenous. Furthermore, the osteonal interaction was ignored by considering a single osteon. Exclusion of the Haversian channel structure, on the other hand, leads to the single osteon being represented by a solid cylinder.

The model consists of a single osteon with the radius $R_0 = 100$ μm [17], and constants of K_2 and G_2 situated within a matrix resembling the interstitial tissue with constants K_1 and G_1, as shown in Fig. 1, where G_i are the shear moduli and K_i, with respect to Poisson's ratio (ν_i) in plane strain condition, are computed as $K_i = 3–4\nu_i$. Here (n) radial microcracks, each having a length $2L_i$, where L_i is assumed to be 50–150 μm [9], were situated within the interstitial tissue. A uniform tensile load of $\sigma_0 = 10$ MPa was applied to the model at the infinity [16]. The interface between the osteon and the interstitial tissue was also assumed to be a perfectly bonding.

Mechanical properties of bone constituents are greatly affected by such factors as bone type and anatomical location. The average elastic moduli in human diaphyseal femoral bone, for example, are found to be 19.3 ± 5.4 GPa in osteonal and 21.2 ± 5.3 GPa in interstitial lamellae [28]. In the neck, the average moduli are 15.8 ± 5.3 GPa in osteonal, 17.5 ± 5.3 GPa in interstitial lamellae [28]. Table 1 shows the various mechanical properties of individual constituents in the model.

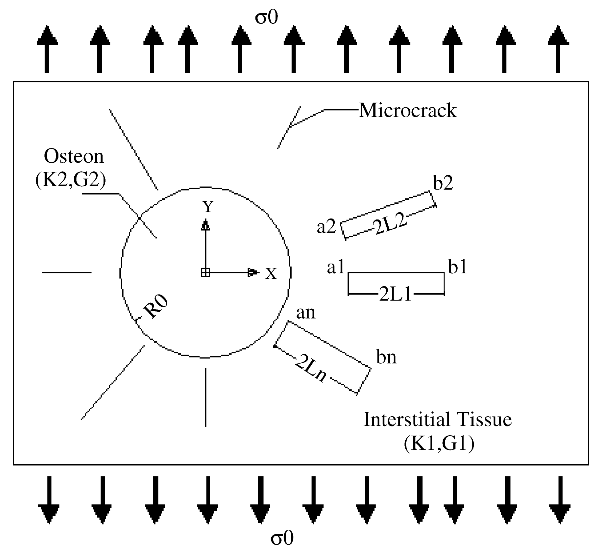

Fig. 1. Osteon-interstitial tissue model.

It was thus possible to solve the problem as a superposition of two distinct problems. In the first problem, an elastic osteon situated within an infinite elastic plane, similar to interstitial tissue, and without any microcracks was considered. This problem was solved for an external load of σ_0.

The second problem described stress disturbance due to microcracks in the interstitial tissue. Here, the external loads were limited to the microcrack surface tractions. The external loads were equal in magnitude and opposite in sign to the obtained stress in the presumed location of microcracks as described by the first problem. It should, however, be noted that formulation of stress equations for individual microcracks does entail the effects of other microcracks. It is apparent that the second problem contains a singularity.

2.1. Solutions of equations of elasticity, in polar coordinates

Solution of the first problem for a uniaxial tension at infinity is as follow [29]:

$$p_{\rm rr} = \sigma_0 \left[\cos^2\theta - 2G_1\left(\frac{A}{r^2} + \left(-\frac{3B}{r^4} + \frac{2C}{r^2}\right)\cos 2\theta\right)\right] \tag{1a}$$

Table 1
Mechanical properties of model constituents

	Effective elastic modulus (GPa)		Effective shear modulus (GPa)	
	Osteon fibre[a] (E_2)	Interstitial tissue[a] (E_1)	Osteon fibre[a] (G_2)	Interstitial tissue[a] (G_1)
Soft osteon	19	21	7.31	8.08
Stiff osteon	19	16	7.31	6.15

[a] Poisson's ratio $\nu_1 = \nu_2 = 0.3$.

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