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Effect of micro-morphology of cortical bone tissue on fracture toughness and crack propagation

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Abstract

Specific features of crack propagation in human cortical bone depend on many factors; bone micro-morphology is one of the main features. A bone compact-tension simulation model with zero-thickness cohesive element is employed in this study to investigate the effect of micro-morphology of cortical bone on fracture toughness and crack propagation. Various groups of bone sample – from young, senior, diseased and treated patients – were studied. It was found that the young group has the best performance in terms of fracture resistance, with the initiation fracture toughness ($\boldsymbol{K_0}$) and slope of 1.45 MPa(m)$^{1/2}$ and 1.16 MPa(m)$^{1/2}$/mm, respectively. The cracks in this group propagate mostly along the cement line to protect osteons from crack penetration.

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Keywords: Bone; Micro-morphology; Fracture toughness; Crack propagation

1. Introduction

A traditional method to measure fracture resistance of human cortical bone is by evaluation of its mineral density. Still, this single factor is insufficient to predict bone fracture because of heterogeneous properties and a hierarchical

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structure of human cortical bone. So, a stress intensity factor, KC, related to extrinsic toughening mechanisms, is also used to quantify its fracture resistance. This parameter could be obtained experimentally employing a compact tension method (Vashishth et al. 1997 and Nalla et al. 2004) or bending tests (Koester et al. 2008). In recent papers, human cortical bone was treated as a composite material due to its unique microstructure, which could resist crack propagation through it. For example, an interstitial matrix, which surrounds bone's basic units called *osteons*, has the highest Young's modulus of bone constituents, which could prevent crack formation and consume the energy of crack propagation (Schaffler et al. 1995). However, the understanding of the effect of micro-morphology of osteonal micro-structure on fracture toughness of human cortical bone is still not fully established. The experiment analysis is not suitable for this investigation, because of the difficulty to record a crack path at micro-level and to quantify this effect without accounting for mechanical properties of cortical bone and its constituents.

Hence, various novel computational methods, including extended finite element method (X-FEM) and a cohesive element methods) were considered and adopted to simulate a cracks propagation process in domains with a direct account for bone's micro-morphology (Budyn & Hoc 2007 and Ural & Vashishth 2006). Still, some limitation of these methods make them not fully suitable for crack propagation simulations. For instance, the cohesive element method should predefine the path of crack propagation, so the crack in cortical bone in such simulations could not grow randomly based on stress contribution. The X-FEM, which depends on the presence of elements in the simulation model, does not allow for empty areas affecting the crack direction. so, another approach was selected -a zero-thickness cohesive element method. It embeds cohesive elements in each solid elements' edge and simulates crack propagation based on stress concentration and allows empty area in the model. Ural and Mischinski (2013) employed this simulation method to investigate the effect of mechanical properties on crack propagation at micro-level. However, Haversian canals (empty areas in bone) and a cement line (with 5 μm thickness) were neglected in the model, though they could influence the crack propagation process. Hence, in this paper, a simulation model of compact tension of cortical bone with a microstructured domain with direct introduction of main constituents including also Haversian canals and cement lines, was used to investigate a relationship between osteonal structure's micro-morphology and bone's fracture toughness.

2. Methodology

The simulation models with randomly distributed elements of microstructural cortical bone were generated with a developed MATLAB program, based on statistical analysis of microscopy images of female's proximal femoral diaphysis (Figure 1.a). Dimensions of simulation models, which consists of homogenous and microstructural domains, were as follows: thickness B=1 mm, width W= 6.4 mm and initial crack length a=1.28 mm (Figure 1.b), according to ASTM E399 (ASTM 1997) to calculate fracture toughness of human cortical bone. The microstructural domain consisted of osteonal areas with a volumetric fraction of about 58% and porosity area with one of about 5.6%, as obtained from the microscopic images. The microstructural constituents of human cortical bone were treated as homogeneous isotropic materials, with their elastic properties based on experimental data by Budyn and Hoc (2007) (Table 1). Cement lines as a weak tissue due to their chemical composition had a 25% lower Young's modulus than that of osteons, while their Poisson's ratio was a 25% higher. The principle strain for the crack's initiation was 0.4% in the homogenous and microstructural domains. This compact tension models were used with displacement loading of 0.01 mm.

3. Results and discussion

As describe above, the load-displacement data were obtained by employing the developed compact-tension simulation models to analyse the fracture toughness, $\boldsymbol{K}$, of human cortical bone with crack extension Δa. The linear fitting method was used to described a rising R-curve of fracture toughness employing two parameters: the crack initiation toughness $\boldsymbol{K}_0$ and the slope of R-curve. The mean values of the crack initiation $\boldsymbol{K}_0$ and the slope of R-curve in young group are 1.45 MPa(m)$^{1/2}$ and 1.16 MPa(m)$^{1/2}$/mm, (see Table 2). These results correspond to the experimental data from Chan's paper (Chan et al. 2009), whose crack initiation fracture toughness changed from