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A heterogeneous orientation criterion for crack modelling in cortical bone using a phantom-node approach

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ABSTRACT

Cortical bone can be considered as a heterogeneous composite at microscopic scale, composed of osteons that act as reinforcement fibres embedded in interstitial matrix. Cement lines constitute the interface between osteons and matrix, and they often behave as the weakest links along which microcracks tend to propagate. However, current simulations of crack growth using XFEM combined with usual orientation criteria as implemented in commercial codes do not capture this behaviour: they predict crack paths that do not follow the cement lines surrounding osteons. The reason is that the orientation criterion used in the implementation of XFEM does not take into account the heterogeneity of the material, leading to simulations that differ from experimental results. In this work, a crack orientation criterion for heterogeneous materials based on interface damage prediction in composites is proposed and a phantom node approach has been implemented to model crack propagation. The method has been validated by means of linear elastic fracture mechanics (LEFM) problems obtaining accurate results. The procedure is applied to different problems including several osteons with simplified geometry and an experimental test reported in the literature leading to satisfactory predictions of crack paths.

1. Introduction

The study of the mechanical response of bone is an active field of research for both biologists and engineers [1]. Bone fracture, principally caused by accidents, is a common trauma affecting young and elderly people. In an increasingly aging society, bone fracture (usually hip fracture) has a great social importance involving enormous costs [2,3]. The understanding of bone fracture at different length scales is still a challenge and its modelling may reveal insight into the fracture behaviour of bone at microscale. In this field, finite element modelling can help to predict and analyse the crack path under different conditions. Finite element simulations are also used in other biomechanical areas, such as bone remodelling [4,5].

Two main tissues can be distinguished within bone structure: the outer regions, composed of cortical bone and the inner regions composed of trabecular bone. The highly hierarchical structure of bone [6,7] makes it necessary to develop multiscale models where the different scales must be properly modelled [8,9]. On the one hand, cortical bone is a hard, dense and highly mineralized tissue, bearing the main compressive and bending loads. On the other hand, trabecular bone is made of a reticular, rod and plate-like structure tissue, that permits a global bone mass reduction and leads to a high surface area suitable for metabolic reactions [10–13].

The role of cortical bone is crucial in the global fracture behaviour of bone. Its analysis at the microscale helps to the understanding of the macro fracture of long bones. At the microscale (50–500 μm), cortical bone is a heterogeneous material with non-isotropic properties that can be considered as a biological composite, composed of fibres with high stiffness (in terms of Young's modulus) embedded in a matrix [14]. The different constituents of cortical bone have dissimilar mechanical properties and this has a strong influence on the crack path at this scale. The basic structural unit of compact bone at the micro level is the osteon (also known as Haversian system) that has a complicated hierarchical morphology at a lower scale [6,11]. In this work, only the Haversian canal and the cement line will be considered. We distinguish three relevant constituents (shown in Fig. 1 at different scales):

- Secondary osteons: recent osteons formed in the continuous process of bone remodelling. Their diameter ranges between 50 and 200 μm and length in the range 3–5 mm [11,15].

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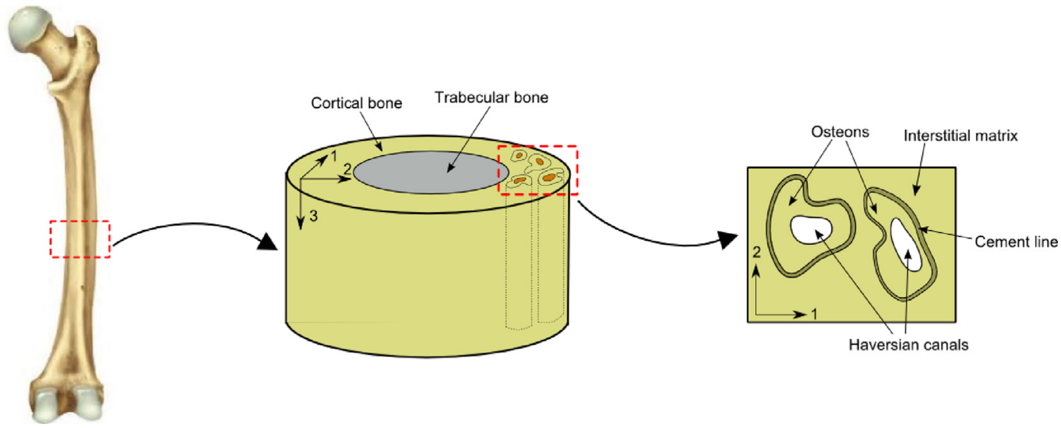

Fig. 1. Scheme of the cortical bone structure from macroscopic to microscopic scale.

- Interstitial matrix: it is mainly composed of old osteons with high mineral content and about 10–15% higher stiffness than secondary osteons [16,17].
- Cement line: a weak thin layer (about 1–5 μm thick [18]) surrounding the secondary osteons. The cement line constitutes the interface between secondary osteons and the interstitial matrix. This is a less mineralized zone which exhibits low toughness and stiffness properties, leading to propagation of cracks around secondary osteons [17–21].

The cement line has been analysed in the literature for being the constituent at the microscale that shows the highest risk of failure in cortical bone tissue (see for instance [20–25]). Fig. 2 shows an example of the crack propagation path following cement lines, reported in Ref. [24]. This interface between osteons and the interstitial matrix is often origin of cracks and its most probable propagation path [7,24,26,27], as it is a less mineralized tissue [20]. Some authors suggest that collagen fibres do not cross cement lines and thus it represents the weakest interface within the cortical bone tissue [22,23]. This approach is consistent with the phenomenon observed experimentally by which microcracks tend to follow the cement lines rather than crossing osteons [28]. Similarly, Nobakhti et al. [18] analysed the behaviour of cement lines in cortical bone tissue and claim that strain increases at these interfaces.

Despite the interest of experimental studies, the simulation of bone fracture is still a challenge both at macroscopic and microscopic scale. Modelling crack propagation in cortical bone requires the implementation of techniques able to account for the heterogeneous nature of bone, and there is a lack of an appropriate criterion to predict fracture paths in this type of heterogeneous materials, as discussed in this section.

Budyn et al. [29] analysed the crack propagation in osteons using the extended finite element method (XFEM). They predefined initial cracks into osteons and studied the subsequent propagation based on the maximum tangential stress (MTS) criterion, which is commonly used for homogeneous materials. The predicted crack path is straight and orthogonal to the prescribed displacement, without detecting the presence of heterogeneities such as the cement lines. The predicted path that crosses osteons is probably due to the propagation criterion used, which is not suitable for heterogeneous materials. Similar fracture paths were obtained in Ref. [30] accounting also for the effect of age in the porosity of the bone. Analogous results have been obtained by other authors [31–33], without obtaining a realistic path. The above references applied fracture criteria initially conceived for homogeneous materials. Also, XFEM combined with the MTS criterion is used in recent works [34], leading to non-realistic fracture paths, where the crack path is not affected by the presence of the cement line.

Guo et al. [35], applied principles of LEFM to study the dependence of fracture process on the material properties using a simplified model composed of an osteon and the interstitial matrix. Their results claim that low-stiffness osteons (newly formed) may toughen cortical bone tissue as microcracks tend to propagate towards them, limiting their growth [35].

Some authors have developed cohesive zone models to simulate material interface behaviour at different length scales in bone [9,36–39]. For example, Lin et al. [36] recently defined a cohesive zone model to define the mechanical behaviour at the nanoscale of the extrafibrillar matrix in bone and the interfacial interactions in a simplified

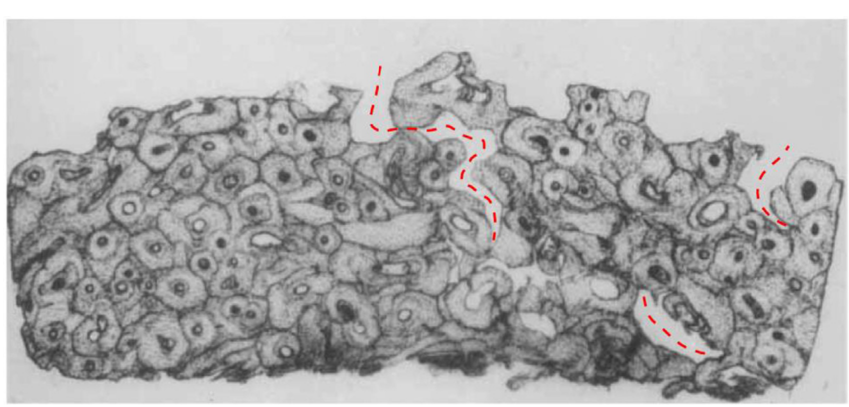

Fig. 2. Crack propagation path following the weakened interfacial zone (cement line). The crack does not cross the cement line. The main cracks are marked in red colour dashed lines. Reprinted from Ref. [24] with permission of John Wiley and Sons. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)