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Microstructural mechanical study of a transverse osteon under compressive loading: The role of fiber reinforcement and explanation of some geometrical and mechanical microscopic properties

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ABSTRACT

This Finite Element study aims at understanding the transverse osteon as a composite microstructure, and at differentiating the actions of each of its main components and their interactions. Three components of the osteon have been distinguished: the lamellae mineral–collagen matrix, the lamellae mineral–collagen reinforcement fibers and the Haversian canal content made of intracortical fluid and soft tissues. Numerical compression experiments have been performed, varying the microstructure properties. Our results show that fiber reinforcement of transverse osteons is only efficient at resisting dynamic compressive loadings, but that the improvement of the static compressive properties is very poor. Furthermore, the modeled stress distribution within the matrix and reinforcement fibers may explain why transverse osteons are often limited to a small number of lamellae (<8) and why internal lamellae could be stiffer than external ones.

1. Introduction

Although the general macroscopic behavior of bone can be modeled by quite simple mechanical models, taking into account the microscopic scales of the bone's complex composite structure is nowadays considered necessary to describe and understand its specific properties.

Experimental observations have shown that the organization of an osteon differs dependent on the type of loading it has to endure. Each lamella is composed by composite collagen–mineral fibers aligned in a predominant direction, giving lamella a strong anisotropic behavior. Three classes of osteons can be distinguished (Ascenzi and Bonnucci, 1967; Martin and Ishida, 1989): longitudinal, transverse, and alternated (Fig. 1). Longitudinal osteon lamellae possess fibers that are globally parallel to the axis of the Haversian canal, their angle with this axis varying between -15° and 15° (changing for each lamella). Transverse osteons possess fibers that are globally perpendicular to the axis of the Haversian canal, their angle with this axis varying between 75° and 105°. Alternated osteons, finally, exhibit both kinds of lamellae, with changing orientation between each lamella. Furthermore, observations made on different reptiles or mammals have shown that the osteon type is directly related to the main cyclic loading the bone endures (Skedros et al., 1996; Bromage et al., 2003; Goldman et al., 2003, 2005; Lee 2004; McMahon et al., 2005; Traini et al., 2005). In particular, the proportion of transverse osteon is greater in regions where the bone is mainly loaded in compression.

The mechanical response of a single longitudinal, transverse, and alternated osteon has been studied in micro-tension and compression experiments (Ascenzi and Bonnucci, 1967, 1968). Results confirm the anatomical observations, showing that transverse osteons are more adapted to compressive loadings and longitudinal osteons to tensile ones. Note that the compressive elastic modulus of a transverse osteon is improved by about 50% as compared to the compressive elastic modulus of a longitudinal one (see Table 1). More recently, several experimental and numerical studies have been focused on the role of the intracortical fluid in the mechanical response of the osteon. The dynamic properties of bones are then modeled using a poroelastic model, with the bone's porosity being determined empirically (Weinbaum et al., 1994; Smit et al., 2002; Swan et al., 2003; Manfredini et al., 1999; Beno et al., 2006; Rémond et al., 2006). The authors however neglect the composite structure of the lamellae.

Numerous anatomical studies performed in the last 60 years describe the osteon as a complex composite structure. Mechanical experimentations showed that variations in this sub-microscopic structure have an important effect on the global osteon properties, but without being able to differentiate the role of each component of this structure.

Modeling the whole microstructure of the bone from the microscopic scale to the visible one does not seem to be possible with today's computation power. Even modeling the real microstructure

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