ESTIMATION OF THE ELASTIC CONSTANTS OF LAMELLAR BONE AS A FUNCTION OF THE MINERAL DENSITY IN A MULTISCALE APPROACH

Ana Vercher-Martínez, Ricardo Belda, Eugenio Giner

Centre of Research in Mechanical Engineering - CIIM, Department of Mechanical Engineering and Materials, Universitat Politècnica de València, Spain

Introduction

The assessment of fracture risk based on bone mineral density only is not enough for predicting bone fracture. This motivates the additional consideration of the apparent elastic properties of bone besides morphological parameters as other factors also involved in bone strength. Numerical models of bone can be created from segmented μCT images, and analyzed to obtain the apparent elastic constants of the bone structure. In this process, it is necessary to assign material properties to the bone tissue and that is not a trivial issue. Usually, no influence of the mineral content is considered and typical isotropic elastic constants are considered. In the bibliography, there are different multiscale models that estimate the elastic constants of lamellar tissue. However, in those models, the mineral content is a fixed value.

Objective

In this work, a multiscale approach is used to obtain analytical expressions for the elastic constants of lamellar bone considering a variable volumetric mineral content. The proposed model is applied to the cortical bone in order to validate it. The region of interest includes interstitial matrix and a secondary osteon that follows the Wagermaier's [1] pattern for the fibrils orientation and Granke's [2] bone mineral content registered radially (from the Havers' canal to the cement line).

Methods

In this work, the hierarchical structure of bone tissue is addressed from the sub-nanoscale to microscale.

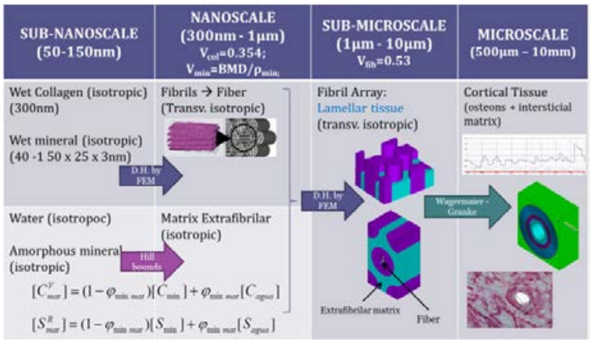

Figure 1: Summary of the steps performed in the multiscale approach of this work.

The main constituents of bone are arranged in different patterns and their concentrations vary according to different scale levels. In Figure 1, the workflow of this work is depicted. The estimation of the volumetric fraction of the constituents has been assumed following Martínez-Reina [3]. The techniques used to characterize the tissue at each level are: (1) Direct homogenization procedure by means of the finite element method (6 canonical load cases with periodical boundary conditions) and (2) analytical approach of Hill bounds. In order to model a unit cell of the cortical bone, a detailed mesh has been considered being able to represent the Wagermaier's pattern of fibrils as well as the Granke's mineral content across the osteon (see Figure 2).

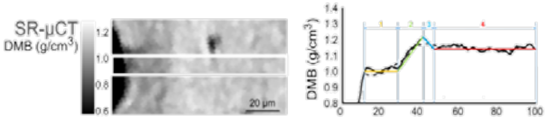

Figure 2: Radial BMD distribution in an osteon (Granke et al. [2]).

Results and Discussion

Analytical expressions for the five elastic constants of lamellar tissue (transversely isotropic) have been obtained for 3 ranges of mineral content. For $0 \leq$ BMD ≤ 1.1 gr/cm^3, the Young's moduli (in Pa) are:

$$E_x = E_y = (-18.2 \cdot \mathrm{BMD}^2 + 88.2 \cdot \mathrm{BMD} + 3.5) \cdot 1\mathrm{e}8$$
$$E_z = (36.2 \cdot \mathrm{BMD}^2 + 82.4 \cdot \mathrm{BMD} + 7) \cdot 1\mathrm{e}8$$

The proposed equations have been applied to estimate the elastic constants of cortical bone at the micro scale: E_x=E_y=3.25GPa, E_z=12.82GPa. Results are in agreement with the literature. The model could be also applied for lamellar tissue in cancellous bone.

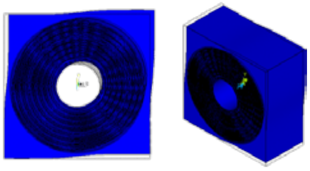

Figure 3: Unit cell of cortical bone. Shear load γxy

References

1. Wagermaier et al., Biointerphaces, Vol.1. No.1., 2006.
2. Granke et al., Plos One, Vol.8, Issue 3, 2013.
3. Martínez-Reina et al., Biomech Model Mechanobiol, 10:309-322, 2011.

Acknowledgements

The authors wish to thank the Ministerio de Economía y Competitividad for the support received in the framework of the project DPI2013-46641-R and to the Generalitat Valenciana, Programme PROMETEO 2016/007.