

A multiscale homogenization procedure using the fabric tensor concept

M. Marques^{a,b}, J. Belinha^{c,a,*}, A.F. Oliveira^d, M.C. Manzanares Céspedes^e, R.N. Jorge^{a,b}

^a INEGI – Institute of Science and Innovation in Mechanical and Industrial Engineering, Porto, Portugal

^b FEUP – Faculty of Engineering of University of Porto, Porto, Portugal

^c ISEP – School of Engineering, Polytechnic of Porto, Porto, Portugal

^d ICBAS – Institute of Biomedical Sciences Abel Salazar, Porto, Portugal

^e Muscular and Skeletal Pathology Research, Human Anatomy and Embryology Unit, Universitat de Barcelona, Barcelona, Spain

Received 26 September 2017; accepted 25 January 2018

Abstract

Bone is a heterogeneous material in which structural levels can be identified, from the microscale to macroscale. Multiscale models enable to model the material using homogenization techniques. In this work, an innovative homogenization technique for trabecular bone tissue is proposed. The technique combines the fabric tensor concept and a bone phenomenological material law, linking the apparent density with the trabecular bone mechanical properties. The proposed methodology efficiently homogenizes the trabecular bone highly heterogeneous medium, allowing to define its homogenized microscale mechanical properties and to reduce the analysis computational cost (when compared with classical homogenization techniques). In order to verify the efficiency of the technique several examples were solved using a confined square patch of trabecular bone under compression. In the end, the results obtained with a classic homogenization technique and the proposed methodology were compared.

© 2018 Sociedade Portuguesa de Materiais (SPM). Published by Elsevier España, S.L.U. All rights reserved.

Keywords: Fabric tensor; Homogenization; Multiscale

1. Introduction

Bone biomechanics, one of the main biomechanics field of study, is based on the idea that load bearing bone tissues are structurally optimized for their mechanical function [1,2]. It is normal to classify bone as a hierarchical structure, where the different structural levels that can be identified as belonging to macroscale or a microscale level [3]. The entire bone (macroscale) and the trabecular architecture level (microscale), can be defined by different physical properties due to its different functional requirements. At the trabecular level, microscale, is possible to recognize the bone trabecular non-homogeneous structure, which after being homogenized allows to define local anisotropic homogeneous mechanical properties, such as apparent density and directional Young moduli.

Bone is a tissue that renews itself by a biological process called bone remodelling [4]. This bone remodelling is pro-

gressive and induces adaptation of bone morphology to any new external stimulus. Wolff in 1886 reported the concept that strain/stress induces bone remodelling [5]. Thus, Wolff reported that the orientation of trabecular bone coincides with the direction of the stress trajectories, proposing that external loads were, somehow, sensed by the bone. This principle is known as Wolff's law. In 1939 Wolff's law was firstly described in vitro by Glucksmann in 1939 [6] and was described mathematically in 1965 by Pauwels [7]. Later, this formulation was computationally implemented by Pettermann et al. [8]. In their bone remodelling algorithms, many authors have considered bone as an isotropic material, a simplistic approach on the behaviour of trabecular bone, disregarding the importance of orientation in the remodelling process [9–12].

Meanwhile other models were created linking material density and orientation with its anisotropic mechanical properties, allowing to overcome the material isotropy simplification. These remodelling models not only avoid any a priori assumption on material but also take into account the trabecular architecture [13–16]. More recent models start to consider biological

* Corresponding author.

E-mail address: job@isep.ipp.pt (J. Belinha).

and mechanical factors based on bone cell activity, resulting in mechanobiological models, which allow to simulate the evolution of bone tissue considering both mechanical and biological stimuli [17–20].

Bone started to be characterized mechanically using the fabric tensor concept [21,22]. Fabric tensor is a symmetric second rank tensor that characterizes the arrangement of a multiphase material, encoding the orientation and anisotropy of the material. Back in 1985, Cowin [23] developed a relation between the elasticity tensor \mathbb{C}_{ijkl} and a fabric tensor \mathbf{A} , proving that an ellipsoid may be associated with the varieties of material symmetries observed in many natural materials. The fabric tensor can be acquired by two different techniques, the mechanical based techniques and by the morphologic-based. In morphologic-based methods the interface between phases of the material are to estimate the fabric tensor. The bone morphology is usually obtained using a micro-CT (at the microscale) or a CT (at the macroscale). Most of the available techniques, using morphologic-based methods, obtain the fabric tensor applying an orientation distribution function (ODF), which is estimated from an orientation-dependent feature of interest.

In mechanics, and in biomechanics, the accurate determination/characterization of the material's mechanical properties is a key parameter, which will allow to describe and predict numerically the behaviour of such materials for different scenarios.

Discrete numerical methods allow to study and analyze in silico the behaviour of materials and structures, being the finite element method (FEM) one of the most popular discrete numerical method [24].

2. Homogenization technique

In this section, the used homogenization technique is fully described. Firstly, 2D images (thin slices) were selected. The images correspond to the cuboid bone and describe locally the bone morphology at its microscale. Then, it was applied the fabric tensor concept in order to determine the material orientation to the selected square microscale images. Additionally, a bone tissue phenomenological law was used to obtain the homogenized material properties of the microscale patch. This homogenization allowed to define the anisotropic mechanical properties of the trabecular bone. Fig. 1 represents the algorithm describing the proposed homogenization technique.

2.1. Fabric tensor morphologic based method

By defining a relevant micro-CT slice image and then identifying a square region of interest with relevant information (the binary image represented in the left-upper image of Fig. 1), it was possible to define the morphologic based fabric tensor. This square patch, a grey scale image, was then binarized, resulting in a binary image I_s that contained the characteristic morphology of the (local) trabecular bone.

To define the fabric tensor it was used a methodology developed by Whitehouse [25], in which the number of interceptions between a parallel family line set, with direction ι , with the interface between both phases of the material was counted, $Int(\iota)$.

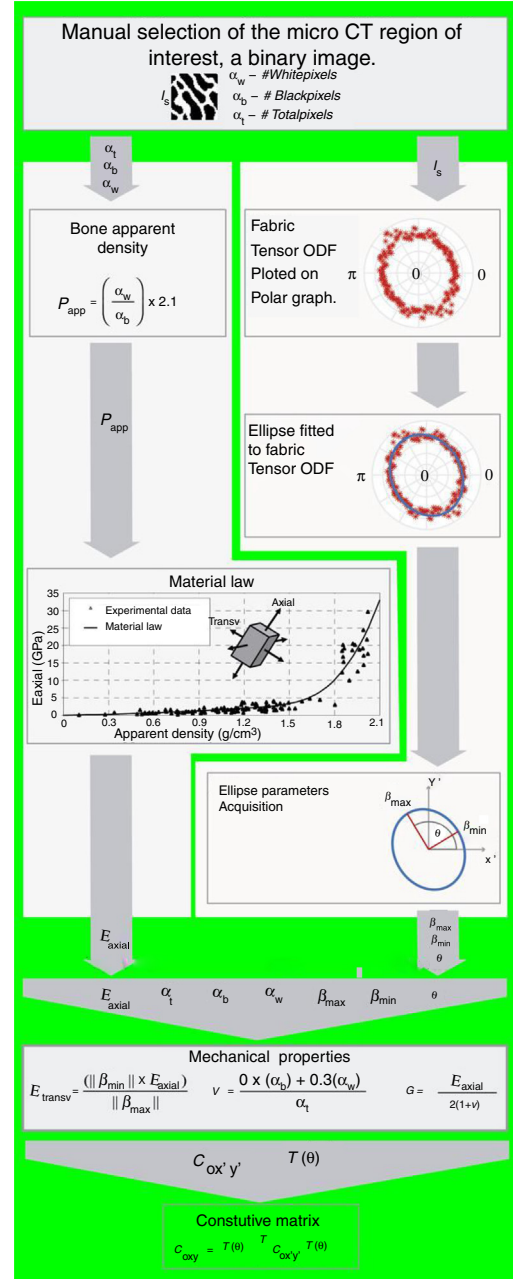


Fig. 1. Microscale homogenization technique.

The length of the parallel lines family, h , for the ι direction was also obtained. Knowing h and ι , it was possible to define the ODF, which in this case is called mean intercept length (MIL), represented in Eq. (1):

$$MIL(\iota) = \frac{h}{Int(\iota)} \quad (1)$$

Whitehouse's methodology is considered a golden standard to predict mechanical properties of trabecular bone since exists a large amount of works that sustain its appropriateness [25–29]. The literature shows that when the ODF data is disposed on a polar plot and fitted in an ellipse, the corresponding ellipse parameters can be correlated with the material orientation (its anisotropy), in particular the trabecular bone [30].

Download English Version:

<https://daneshyari.com/en/article/8941160>

Download Persian Version:

<https://daneshyari.com/article/8941160>

[Daneshyari.com](https://daneshyari.com)