11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
E. Oñate, J. Oliver and A. Huerta (Eds)

HOMOGENIZATION OF TRABECULAR BONE MICROSTRUCTURE BASED ON FINITE ELEMENT METHOD AND MICRO COMPUTED TOMOGRAPHY

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Key words: Trabecular Bone, Homogenization, Mechanical Properties, MicroCT, FEM

Abstract. The prediction of the mechanical properties of trabecular bone is usually based on in vitro measurements of real samples via Micro Computed Tomography (MicroCT) combined with Finite Element Method (FEM). The aim of this study was to compare such an approach with the homogenization techniques: Mori-Tanaka, Self-Consistent and Incremental Scheme, well established for composite materials, to determine the full elastic constant tensor of the trabecular bone.

1 INTRODUCTION

Trabecular bone is a three-dimensional porous structure consisting of a characteristic network of trabeculae. Although density of trabecular bone is a important parameter in determining its properties, it cannot fully reflect the mechanical behavior on its own. Trabecular bone architecture, characterized by thickness, number and distance between individual trabeculae and their 3D network, plays an important role in its mechanical behaviour. Therefore, high-resolution images, such as microCT scans, of trabecular bone samples are used as inputs for FEM analysis to predict elastic moduli of bone based on its geometry [1]. Alternatively, some analyses use idealized periodic geometry of trabecular bone, composed of networks of beams and plates, instead of its actual geometry [2].

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2 MATERIALS AND METHODS

Using the homogenization techniques for the trabecular bone with the composite material approach, the structure consists of the matrix (trabecular part of the bone tissue) and ellipsoidal inclusions (corresponding to the voids) to obtain versatile method of determining the elastic constants. Therefore a complicated geometrical structure of trabecular bone can be substituted by a simpler material with several interacting ellipsoidal inclusions of different shapes, sizes and relative positions. The determination of these geometrical parameters was treated as a following inverse problem.

Based on the real samples of animal origin, binarized and segmented using previously developed approach [3], three-dimensional parallelepiped models can be automatically meshed with the usage of hexahedral elements. Calculations of the apparent mechanical properties of the trabecular bone structure is next performed attributing any a priori selected elastic properties of the trabeculae. The models are virtually tested under traction (compression) and shear loads in three orthogonal directions. From elongations and reactions obtained, the apparent elastic properties of the sample can be deduced. The knowledge of these apparent properties of the bone sample allows finding parameters of the composite material model. The Genetic Algorithm (GA) was used in order to set up the best geometric properties of inclusions. For simplicity, in this work, the mechanical properties of bone trabeculae were assumed to be isotropic.

3 TESTS AND RESULTS

A series of homogenization techniques for the calculation of the average mechanical properties of composite materials based on the concept of Eshelby's inclusion [4] was implemented and tested, namely: Mori-Tanaka (M-T) [5], Self-Consistent (S-C) [6] and Incremental Scheme (IS) [7]. Ultimately, for determining the elastic properties, the incremental approach of averaging the mechanical properties (IS) was used, and the utilized approach is illustrated in figure 1. This scheme proved to be well suited for the materials of high porosity.

In order to set up the proper distribution, sizes and orientations of the ellipsoids that are consistent with the measured or simulated results, GA was used. The results obtained by averaging composite material properties were compared with the FEM. Visualization of a typical Representative Volume Element (RVE) in composite material representation and corresponding FEM hexaedral mesh in are illustrated in figure 2. Supposing that the local elastic properties of the bone tissue are known and constituting the input data of this problem, the global apparent properties of the bone volume were calculated using 6 linear simulations, namely 3 compression and 3 shear tests in orthogonal directions. The applied procedure is illustrated in figure 3. It has to be underlined that the elastic properties of the matrix were arbitrarily imposed by the user both in FEM calculations and the GA optimization. Comparative analysis for the FEM and GA solutions is presented in table 1. The value of fitness function error for the best individual ($\mathrm{err}_{\mathrm{best}}$) was 2.1 %.

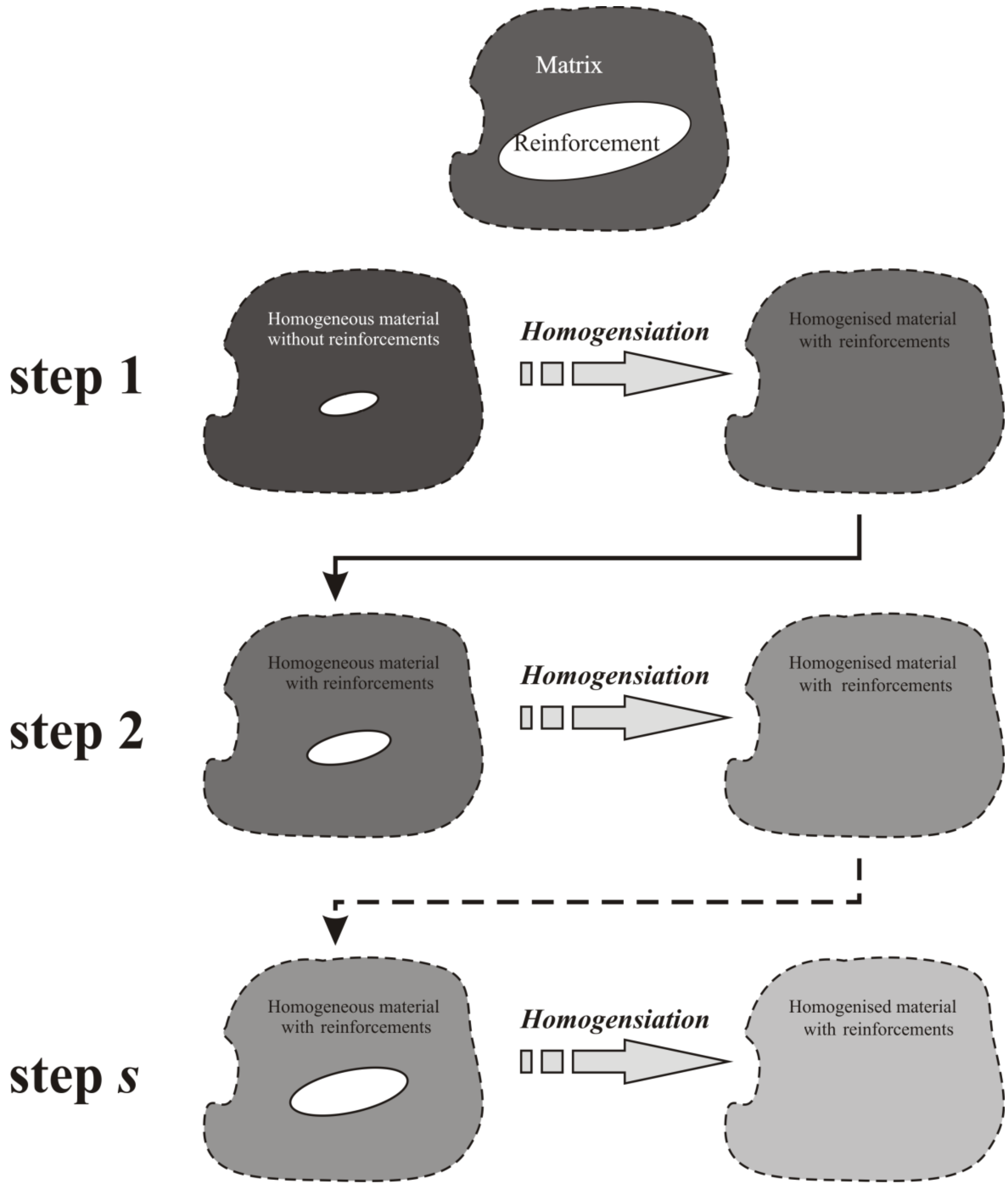

Figure 1: Construction of a homogeneous material using the Incremental Scheme idea.

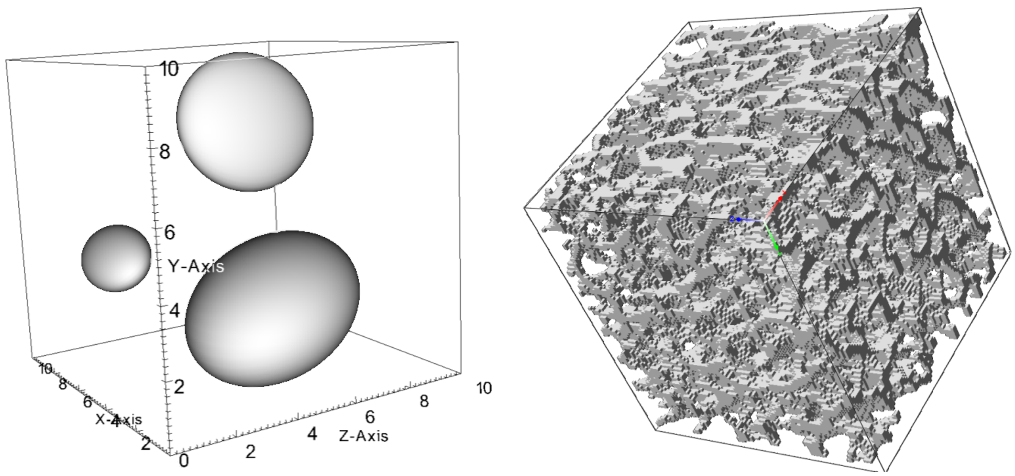

Figure 2: Visualization of a typical RVE consisting of three ellipsoids embedded in a matrix (on the left). Corresponding FEM mesh of the bone sample (on the right).

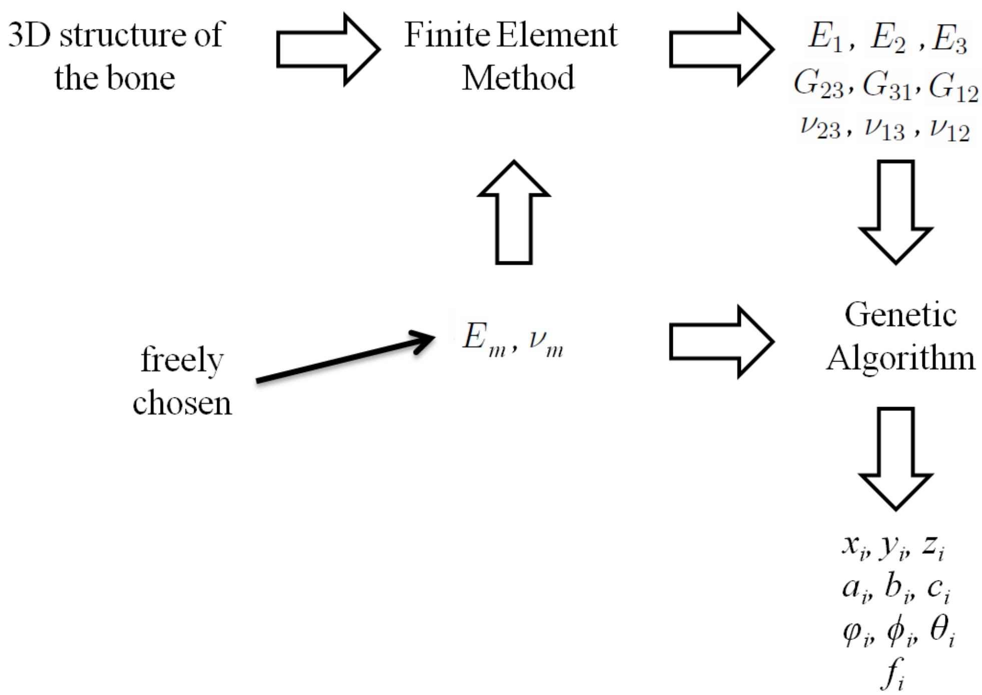

Figure 3: A scheme of optimizing the parameters of the model using the genetic algorithm.

Table 1: Statistical listing of the best solutions for which the relative average error of fitting mechanical parameters was smaller than 5%. Data from reduced set of 178 solutions.

	FEM	GA_{best}	err_{best} [%]	$GA_{average}$	$err_{average}$ [%]	deviation
Porosity	0.74	0.75	1.9	0.76	3.2	0.0083
E_1 [MPa]	104.0	104.0	0.0	104.8	0.8	2.1
E_2 [MPa]	38.0	38.5	1.3	38.1	0.3	0.57
E_3 [MPa]	37.4	39.5	5.5	38.8	3.8	1.4
G_{23} [MPa]	21.2	19.6	7.2	18.1	14.1	0.92
G_{31} [MPa]	34.8	34.3	1.3	32.7	5.9	1.5
G_{12} [MPa]	25.8	25.6	0.7	26.1	1.3	0.47
ν_{23}	0.238	0.244	1.1	0.247	0.1	0.0040
ν_{13}	0.439	0.439	0.0	0.426	2.9	0.0150
ν_{12}	0.290	0.290	0.1	0.287	0.8	0.0059

4 CONCLUSIONS

The proposed method is fast and enough accurate in comparison to the FEM calculations. Further validation is planned to be implemented soon, however the presented approach can be used at this stage in several applications, potentially also for other materials. Study of the three-dimensional structures creates possibilities to obtain the results of the mechanical properties of trabecular bone microstructure, taking into account the structural parameters.

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