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CREATION OF COMPUTATIONAL MODELS OF CANCELLOUS BONE

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Abstract: *The paper deals with a creation of computational model of cancellous bone. Cancellous bone is inner porous part of bones and it is of a very complex geometry. It is composed of special trabecular architecture and the trabeculae can be less than 1 mm in diameter. In most cases, cancellous bone is modeled as a "non-trabecular" solid body with an apparent Young's modulus. The creation of a "trabecular" model of cancellous bone (which, in our opinion, is more appropriate) is quite difficult. MicroCT images are indispensable for this case as well as the software for their processing. Authors of this paper developed for this purpose a specialized software called STL Model Creator which works in Matlab platform. The software uses image processing methods in segmentation of cancellous bone images (thresholding). The paper introduces a method of creating of computational model and initial stress-strain analysis utilizing this model is presented as well.*

Keywords: ***Micro CT, bone, finite element method, stress strain analysis, image processing.***

1. Introduction

The most common problems addressing the biomechanics of the musculo-skeletal system include determining the material properties of bone tissue. There are two types of bone: Hard outer cortical bone and porous inner cancellous bone. In general, bones are inhomogeneous anisotropic biomaterials which are changing their properties and shape during the whole life. This work is focused on creating a computational model of cancellous bone which includes trabeculae and which quantity, distribution and orientation within the bone is strongly individual. A number of these trabeculae determines the density of cancellous bone. In most cases, a "non-trabecular" solid body with an apparent Young's modulus and an apparent density is used as the model of cancellous bone. A higher level of this material, specifically an inhomogeneous isotropic model of cancellous bone, can be created by using computer tomography (CT) image processing (Valášek, 2010). Nevertheless, this model is the "non-trabecular" as well. Since no trabecular architecture is included, the adequacy of these two models used for the analyses of interactions between dental implants and the bone tissue is disputable. We believe that the effect of the trabecular architecture on the mechanical interaction between the mentioned parts especially in the mandible is rather significant and it should be included in the models of cancellous bone. This is easy to do in case of 2D modeling-level as we can get the architecture from images of histological sections. The creation of the "trabecular" model of cancellous bone in 3D is much more difficult. One way how to obtain the images for 3D reconstruction of the bone is to cut thin layers of the bone embedded in dyed epoxy resin. Much more appropriate and faster is using a microCT device which directly stores series of images. By using the image processing the final 3D trabecular model can be then reconstructed. For this particular purpose, authors have developed specialized software called STL Model Creator (Konečný, 2010) which is implemented into Matlab.

2. Methods

By using the method explained below, cancellous bone specimen was modeled and stress-strain analysis was performed. The most popular numerical method – finite element method (FEM) – was used; specifically, commercial product based on this method - ANSYS 11.0 (Ansys Inc., Canonsburg,

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PA, USA). In general, computational model consists of four submodels: model of geometry, model of material, model of loads and model of boundary conditions. Model of geometry of cancellous bone specimen was obtained from microCT images series which are available for downloading online from Biomed Town database (www.biomedtown.org). Images of the bone tissue were obtained from the bone biopsy of 61-old man's femur neck by Baruffaldi and Perilli by using Skyscan microCT (see Fig. 1). Detailed description of the creation of the geometry model is given in Section 2.1.

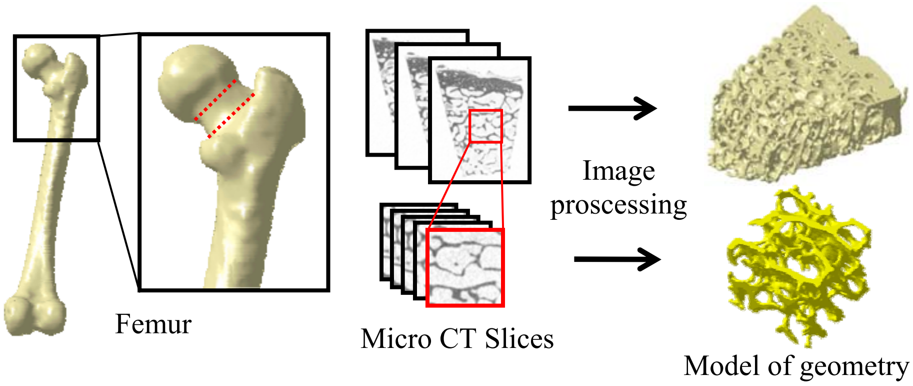

Fig. 1: MicroCT imaging procedure and the final model of geometry.

2.1. Model of geometry and FE model

The above mentioned database contains a series of microCT images of slices through the whole bone specimen and also through a specific site of the specimen. Log files containing detailed information about microCT settings are in the database available as well. In terms of geometry-modeling, the information on the number and size of pixels or voxels are the most important. In the specific case investigated in this paper, the voxel size is of 0.019479 mm, 0.019479 mm, 0.019479 mm (x, y, z). In total, 195 images with a resolution of 200x200 pixels were used. After segmentation and obtaining of a cloud of points in STL Model Creator software, a trabecular architecture specimen of approx. 4 x 4 x 4 mm in size was created (STL polygonal mesh - see Fig. 2).

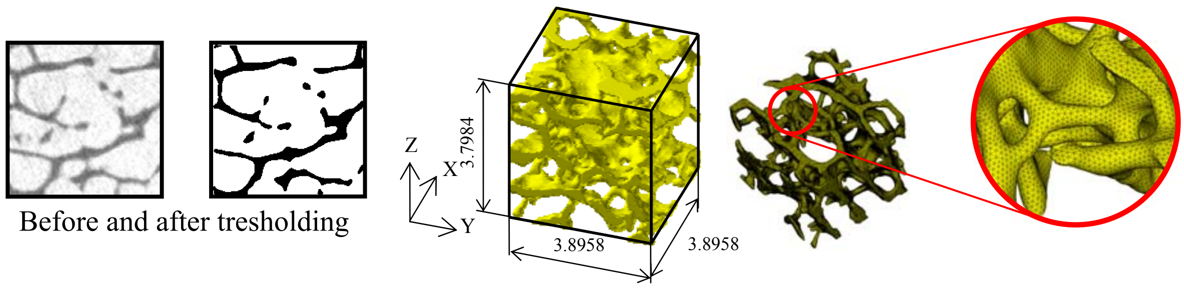

Fig. 2: Illustration of tresholding, the specimen size and the final FE mesh.

Trabecular architecture was discretized in ANSYS by using tetrahedral structural SOLID185 element (see Fig. 3). Since trabecular structures are of a very complex shape, a considerable attention should be paid to meshing of their models. A sensitivity study was performed to obtain the optimal element size. The study revealed that more than 300 000 nodes are needed for the specimen so as the results could be accurate enough.

2.2. Model of material

At micro-level, cancellous bone is of the same mechanical properties as cortical bone (Rho, 1998). The material used in the computational model is homogenous, isotropic and linearly elastic – which is defined by two independent characteristics: Young's modulus E = 13 700 MPa (Bratu, 2003) and Poisson's number $\mu = 0.3$ (Bratu, 2003).

2.3. Model of loads and boundary conditions

The specimen was loaded in Z-axis by means of pre-defined displacements of all nodes at one side of the specimen in XY-plane. The specimen was fixed on the opposite side. The specimen was loaded in tension as well as in compression so as the proportional elongation of the specimen would be 0.25%, 0.5%, 1%, 2% and 3%.

3. Results

Several testing models based on different numbers of microCT images were created in STL Model Creator software. The purpose was to asses an effect of the number of the microCT images on the quality of the model, i.e. if omitting the microCT images in the 3D reconstruction can affect the quality of the model. Therefore, computational models based on omitting one, two, three and four microCT images were created. Each image which was omitted has the voxel height of 0.097395 mm. The specimen was firstly loaded by the displacement causing the proportional elongation of 1% (in tension only). Maximum 1st and 3rd principal stresses, stress intensity and von Mises stress as well as maximum 1st and 3rd principal strains and strain intensity were plotted in the graphs below (see Fig. 4). The results show significant differences between the model based on all microCT images and the model where 4 images were omitted. The most significant differences occurred in 1st principal stress and in strain intensity which were 27.9% and 15.8%, respectively.

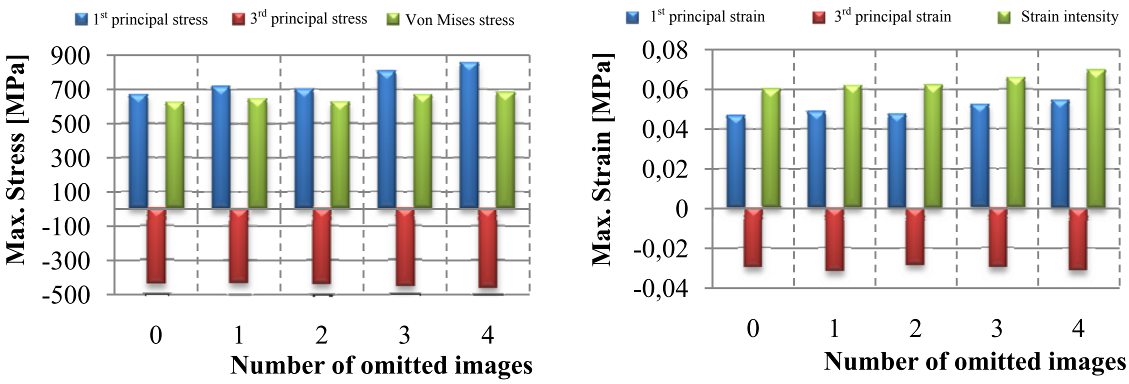

Fig. 4: Maximum stresses and strains for various models (loaded by the 1% elongation).

Omitting one and two images caused no significant difference in the monitored quantities. Omitting more images caused increase in differences. For the next analysis, model with no omitted image was used. This model was loaded again in tension and now also in compression. The representative distributions of the 1st and 3rd principal stresses are plotted in Fig. 5. The representative distributions of the 1st and 3rd principal strains are plotted in Fig. 6

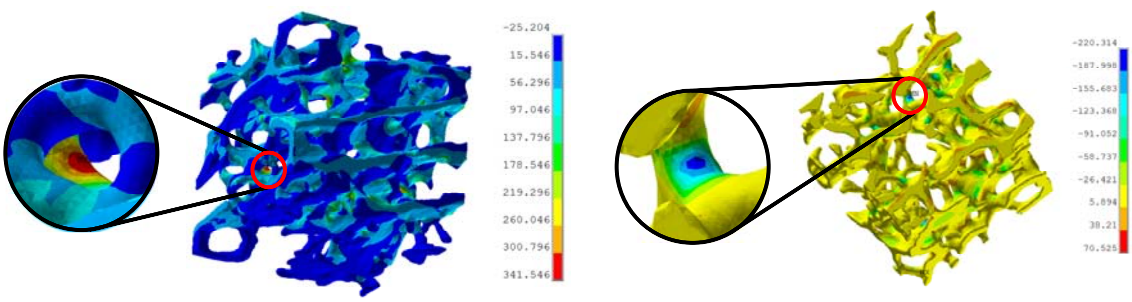

Fig. 5: 1st and 3rd principal stresses [MPa] (0.5% elongation).

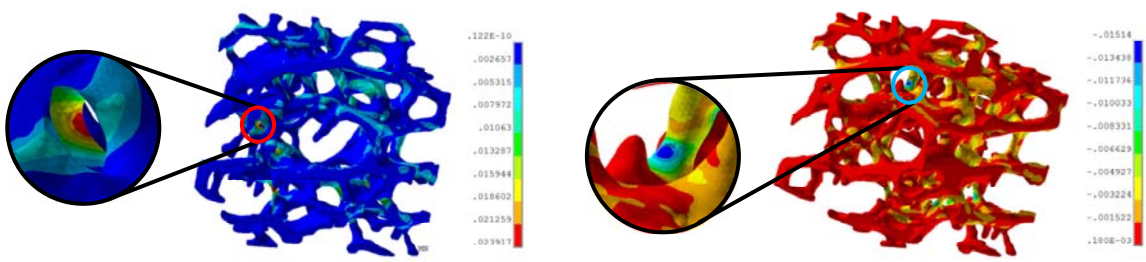

Fig. 6: 1st and 3rd principal strains [-] (0.5% elongation).

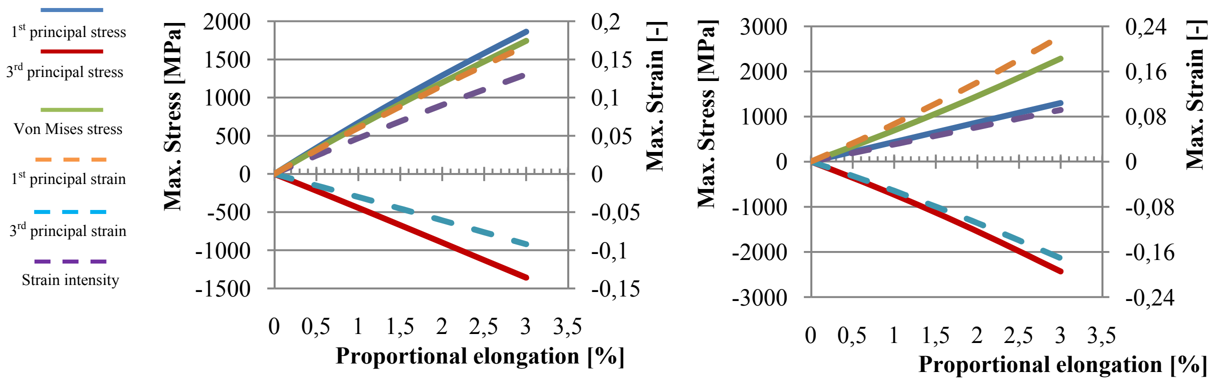

Fig. 7: Results (tension of the left, compression on the right).

When loaded by displacement causing proportional elongation of 3.5%, the monitored quantities reached extremely high values (von Mises stress = 1800 MPa, strain intensity = 0.17). The dependence of the mechanical quantities on the loading (elongation/contraction) is of a linear character (see Fig. 7). Only the inclination of the graphs changes with the changing load - significantly in case of principal stresses/strains, insignificantly in case of von Mises stress.

4. Conclusions

The aim of this paper was to create a computational model of cancellous bone specimen reflecting the trabecular architecture. For this purpose, microCT images of the real bone were processed and afterwards 3D model was reconstructed on their basis. STL Model Creator software developed by the authors was used for the reconstruction. The computational model created this way belongs to models at the highest modeling-level used up-to-date. Series of models created from lesser number of available microCT images (i.e. with omitting some images) was created and used. Stress-strain analysis revealed that sufficiently fine microCT imaging of the trabecular structures is needed, i.e. images should be at a close offset. When images are obtained from the structure embedded in a dyed epoxy resin, the specimen should be milled in thin layers of less than 0.05 mm. The results obtained from the calculation of the specimen in tension/compression revealed linear character of stresses and strains.

Acknowledgement

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