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USE OF X-RAY COMPUTED TOMOGRAPHY FOR CONSTRUCTION OF FE MODELS OF BONES

O. Jiroušek, J. Jírová,[*] J. Máca[†]

Summary: *The article reports on procedures used for development of FE models of bones on basis of data obtained from series of computed tomography (CT) scans. These models include mechanical properties reflecting the bone inhomogeneity through apparent density which can be easily retrieved from the CT scans. Experimental procedures used for evaluation of mechanical properties of cancellous bone using small samples of cylindrical shape were designed in such a way, which allows for determination of the viscoelastic properties of cancellous bone. Both compressive and tensile specimens are tested while for the strain measurement an optical method utilizing CCD camera of high resolution is used. Relationship between the apparent density and mechanical properties of cancellous bone in a power-law form is proposed.*

1 Introduction

Finite element method has become well established method in many fields of computer aided engineering widely used for investigation of the stress-state in different application areas. The FEM is also frequently used in biomechanics, however, the FE models here are specific, due to the fact, that the domain of interest is that of organs and therefore has very complicated shape.

Algorithms for automatic generation of finite element models on basis of the data obtained from medical imaging systems were used to detect the surface of the bones, construct the outer and inner surface of the bone using the triangular mesh, optimize its shape for the FE analysis and fill the volume of the organ with tetrahedral elements of high quality. The described algorithms work in general for any organ and any medical imaging technique, but special emphasis has been given to construction of parts of the skeletal system. It is convenient to use CT images as the source data because the hard tissues are clearly distinguishable using the X-ray radiation.

[*]Ing. Ondřej Jiroušek, Doc. Ing. Jitka Jírová, CSc.: Institute of Theoretical and Applied Mechanics, Academy of Sciences of the Czech Republic, Prosecká 76, 190 00 Prague 9, Czech Republic, phone/fax: +420-286892509, email: {jirousek, jirova}@itam.cas.cz

[†]Doc. Ing. Jiří Máca, CSc.: Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, 166 29 Praha 6 - Dejvice, Czech Republic, phone/fax: +420-22435-4500, email: maca@fsv.cvut.cz

Apart from the problem of defining the geometry in finite element modeling of the living tissues there is a problem of material properties of the selected tissue. The medical imaging systems give us not only the information about the geometry, but also some information about the density of the represented tissue is given. This information is given by the attenuation of the radiation by the respective tissue and can be different for every imaged pixel. Apparent density of the tissue is dependent on the attenuation of the radiation used. It has been shown by several authors that material properties of the bone tissue are proportional to relative density and thus information about the apparent density extracted from the CT scans can be used for material properties assessment.

2 Methods

Material properties of cancellous bone were measured experimentally using small samples of cancellous bone drilled from fresh proximal porcine femurs. Every tested bone is first scanned using Somatom Plus CT scanner to enable reconstruction of three-dimensional FE models and assessment of values of the apparent density in Hounsfield units for each individual finite element. Small cylindrical specimens for compressive testing of 10 mm in diameter and the same height are drilled out using a slow-rotation micro-drill cooled with water and cut using a low-speed, water-cooled saw. The ends of the specimen are then machined using wet sand-paper with the specimen fixed in a special device ensuring that the ends remain perfectly parallel. The surface of the specimen is then examined microscopically to identify possible cracks caused by machining. The tensile specimens are only 5 mm in diameter and $20 - 40$ mm in length. Their ends are fixed in metal tubes using either cyanoacrylate adhesive or two-component epoxy. Mechanical properties of bone depend significantly upon the storage and handling procedures used after the removal of the tissue and kept during the specimen preparation and mechanical testing. Immediately after the removal the specimens are wrapped into a towel impregnated with saline solution and put into a freezer at -20^oC. During all stages of sample preparation the bone tissue is kept hydrated in saline solution.

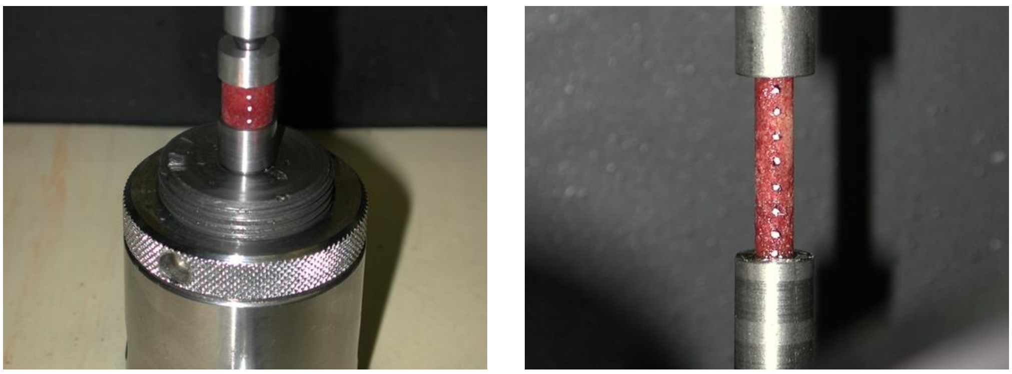

Figure 1: *Compressive and tensile specimens*

Complete stress-strain relationships were obtained for each individual sample using an optical identification method with the help of a fast CCD camera. The camera is able to process 25 images per second enabling determination of viscoelastic properties of the cancellous bone. The experimental set-up is shown in Fig. 2.

Figure 2: *Experimental set-up*

Material properties based on apparent density can be prescribed to every finite element of the model of bone. To stress the importance of material properties of cancellous bone variable according to its density a comparative FE study was performed with the help of three FE models of the same bone constructed using data from computer tomography. Material properties of the first model were considered homogeneous, isotropic and linear elastic. The second model had material properties inhomogeneous isotropic, with Young's modulus of elasticity varying for each individual element. The last model was constructed as inhomogeneous, orthotropic with directions of orthotropy reflecting the Wolff's law. More details about this model can be found in section 3.

3 Results and conclusions

To assess material properties of cancellous bone, $n = 44$ samples from 38 porcine proximal femurs were obtained. Cylindrical tensile specimens of 5 mm in diameter ($n_1 = 26$) and cylindric compressive specimens of 10 mm in diameter ($n_1 = 18$) from the femoral neck regions of 38 fresh proximal femora were used in the experiments. A great care was taken to ensure, that the physeal scar in the femoral neck was not within the measured part of the specimen during the mechanical testing. Not more than three tensile or one compressive specimens were taken from each of the porcine femurs. The specimens were drilled in the direction aligned with the principal trabecular orientation. A special care was given to specimen preparation procedure as well as the environmental conditions kept during the mechanical testing. As an example of experimental results we present a strain-stress diagram for one tensile specimen (Fig. 3).

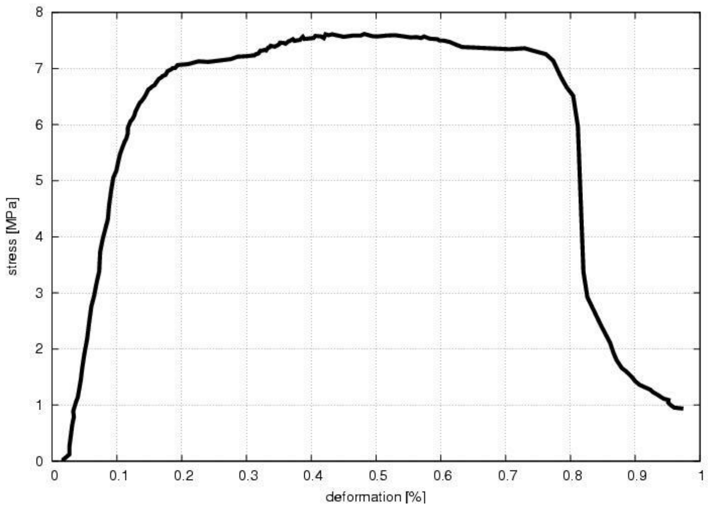

Figure 3: *Typical stress-strain diagram of cancellous bone evaluated by the optical identification method*

The yield strain was found to be dependent both on the anatomic site and strain rate applied. Mean compressive yield strains ranged from 0.91 ± 0.09%; mean tensile yield strain in the same region was found to be 0.61 ± 0.03%. The yield stresses were found to be less reliable (18.54 ± 6.30% in compression and 12.15 ± 2.80% in tension) as well as the moduli of elasticity (672 ± 110 MPa for compression and 602 ± 52 MPa for tension).

From the experimental measurement of material properties of cancellous bone using the small samples and optical identification method it is clear, that:

- yield strains could be considered *uniform within the region of proximal femur*
- better correlation between the apparent density and mechanical properties is for the *tensile* loading; however the reason for this might be explained by better experimental set-up of the tensile tests
- *power-law relationship* between the yield stress and apparent density can be formulated both for compression and tension

Our results showing strong correlation between the yield stress and apparent density are consistent with the results of previous studies [1, 2], however the yield strains were found to be of little higher values particularly in tension. This is probably caused by the small distance between the markers on the specimen surface. Strains are thus evaluated using smaller base length and because the failure of the trabecular bone is of local nature, our optical measurement gives better results.

A least squares regression analysis was used to test this power-law fit between Young's modulus and effective density. It was found, that for small strain rates ($\dot{\epsilon} \leq 0.05\ s^{-1}$) the Young's modulus of elasticity of cancellous bone of porcine proximal femurs can be expressed in terms of the effective density of the bone tissue as follows:

$$E = 2615\, \rho_{\text{eff}}^{2} \tag{1}$$

where ρ_{eff} is the effective density in $[\text{g.cm}^{-3}]$, which can be computed from the apparent density (given in Hounsfield units) obtained directly from the CT scans. The relationship between these two densities has the form:

$$\rho_{eff} = 0.523\ \text{HU} + 1000 \qquad \left[\frac{\text{kg}}{\text{m}^3}\right] \tag{2}$$

Ultimate stress of cancellous bone is determined from:

$$\sigma_{ult} = 38.2\, \rho_{\text{eff}}^{1.5} \qquad [\text{MPa}] \tag{3}$$

The power law exponent in the relationship between the modulus of elasticity and apparent density (1) is same as determined by [3]. However, our relationship gives a bit higher values of the modulus in the region of proximal femur. On the other hand, stronger correlation was found between the apparent density and yield strains, which gives a good argument for the strain-based measurements of failure. The failure criteria for the cancellous bone should also be expressed in terms of strain rather than stress. More references about the stress-based or strain-based failure criteria for cancellous bone can be found e.g. in [4].

It should be stressed, that these results are valid only for small strain rates ($\dot{\epsilon} \leq 0.05\ s^{-1}$). For greater values the strain rate influences the response of the bone and the strain rate has to be taken into account. This has been a subject of several investigations (i.e. [5, 6]), but the results differ substantially.

For the construction of finite element models of whole bones material properties based on apparent density values of individual elements appears to be the most suitable procedure to account for individual variations in bone structural properties. It has been shown that for small ranges of strain rate the material properties of cancellous bone are proportional to the apparent density of bone tissue and the strain rate to the power of 0.06 [6]. However, viscoelastic properties of cancellous bone with a correlation to apparent density for higher values of strain rate have not been described up to now. No correlation with bone density has been shown for tensile or torsional strength of cancellous bone or Poisson's ratio.
Using the described method we are able to assess the material properties of cancellous bone in relationship with the apparent density in Hounsfield units for both in compression and tension. This procedure is used to validate finite element models of whole bones used in our computational analyzes.

To highlight the importance of material properties variable with density of the cancellous bone a comparative FE study was performed. A whole bone was reconstructed and stress analyzes of the bone under different loading conditions were performed. Three models with different approach for describing the material properties were used. The objective was to compare the maximal absolute strain values determined computationally using the different FE models. First FE model with homogeneous material properties will be referred to as *I*, model with material properties assigned based on the apparent density will be marked by *II* and model with orthotropic material properties will be referred to as *III*.

The last FE model used in the study, was model with variable material properties as model *II*, but accounting for orthotropy of the cancellous bone. However, this model has one important limitation: the directions of the orthotropy were not evaluated experimentally, but described based on following idea. It is well known fact, that the bone adapts to mechanical stimuli and thus the architecture of the bone is closely related to its mechanical function (Wolff's law). Wolff observed changes in trabecular structure after fracture in proximal femur. He first described this phenomena of changes in internal structure and related them to mechanical loading. Important finding was that the directions of the principal axes of material orthotropy are aligned corresponding to the direction of the dominant load [7].

This fact was used in the FE model. Each model was first assumed to be isotropic with homogeneous material properties. The model was loaded by means of a single load in the direction of the dominant load found in [8]. From the results, the directions of the principal stresses corresponding to this dominant load were computed for several regions in the femur and the directions of material orthotropy of the influenced elements rotated. The isotropic Young's modulus computed using Eq. 1 was assumed to be in the principal direction and Young's moduli in the other directions are computed using averaged apparent densities of surrounding voxels in appropriate direction:

$$\begin{aligned} E_{1,i} &= 2615\,\frac{\sum_{i=1}^{m}\rho^2_{\text{eff},i}}{m} \\ E_{2,i} &= E_{1,i}\frac{\sum_{i=1}^{n}\rho_{2,i}}{\sum_{i=1}^{n}\rho_{1,i}} \\ E_{3,i} &= E_{1,i}\frac{\sum_{i=1}^{n}\rho_{3,i}}{\sum_{i=1}^{n}\rho_{1,i}} \end{aligned} \qquad (4)$$

where m is number of voxels contained in the i-th element and n is number of voxels in appropriate direction corresponding to the largest dimension of the element expressed in voxels. The procedure was found to give reasonable results, however, this model was used only for the demonstrative purpose to evaluate the importance of material orthotropy and was assigned number *III*.

Finite element models of four different human femurs were created using data obtained from the Institute of Forensic Medicine, 2^{nd} Faculty of Medicine, Charles University in Prague. Every femur was scanned using computer tomography device (Somatom Plus), calibrated CT images of the femurs were saved in DICOM image format and consequently converted into 16-bit raw images. The 16-bit images were used only to create the three-dimensional FE model of the bones; for the material properties computations, the DICOM data were used.

After the construction of the FE model, an automated procedure is used to assign the material properties to each of the element in the entire mesh. The procedure works separately for every finite element and can be described in the following steps:

- from the z-coordinates of the element's nodes find the corresponding DICOM slices
- identify the voxels belonging to each element by interposing the finite element and the appropriate DICOM images
- average the gray values of the voxels corresponding to the element and convert them to Hounsfield Units
- compute the bone effective density ρ_{eff} corresponding to the density in HU using Eq. 2
- compute the modulus of elasticity of the element using Eq. 1.

In this way, each element of the model *II* has a unique material property, depending on the bone density at that location, while model *I* has only one material property assigned to all of its elements.

Each of the FE models was subjected to the same load conditions. The loading and boundary conditions were prescribed to simulate these three basic cases: (i) three-point bending, (ii) compression/tension and (iii) torque.

We studied the influence of the material properties of the cancellous bone on several results obtained from the FE analyzes of the reconstructed models subjected to three-point bending, compression and torque. As the most important result, the maximal value of first principal stress in the cancellous bone is presented in Table 1.

$\sigma_{1,\text{max}}$[MPa]	bending	compression	torque
model *I*	6.7	4.3	10.8
model *II*	4.2	2.2	4.3
model *III*	3.2	1.9	3.9

Table 1: First principal stresses in cancellous bone for different loading (average values)

The results from the simple FE analyzes show that the influence of the variable material properties of the cancellous bone is extensive even in the case of the simple compression case. The greatest difference in the principal stresses is for the torque, where the simplest model *I* gives maximal value of first principal stresses three times larger than model *III*. On the other hand, for the worst loading (torque) the difference between the models *II* and *III* is not more than 25%.

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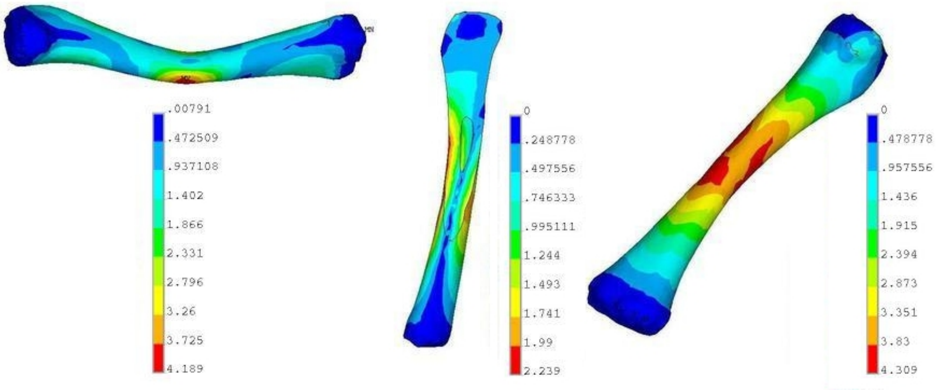

Figure 4: Example of FEA results for (a) bending (b) tension (c) torque

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