Three-point bending test of cortical bone - experiment and numerical simulation

Grzegorz Kokot[1], **Marcin Binkowski**[2], **Antoni John**[1], **Tomasz Konopka**[3]

[1]*Department of Strength of Materials and Computational Mechanics, Silesian University of Technology*
ul. Konarskiego 18A 44-100 Gliwice, Poland
e-mail: grzegorz.kokot@polsl.pl
antoni.john@polsl.pl

[2]*Department of Biomedical Computer Systems, Institute of Computer Science, University of Silesia,*
ul. Będzińska 39, 41-200 Sosnowiec, Poland
e-mail: marcin.binkowski@us.edu.pl

[3] *Medical College, Jagiellonian University,*
ul. Grzegórzecka 16, 31-531 Kraków, Poland
e-mail: konopat@wp.pl

Abstract

The paper presents the results of research on obtaining the bone mechanical properties using the 3-point bending test and computational simulation. The FE numerical model is build on the base of scans from X-ray microcomputed tomography (XMT) using the specialized software. The density phantom was scanned together with the specimen to enable quantitative measurement of the bone mineral density. The non-homogenous material properties were assumed. Simulation were performed using the MSC.Nastran solver. The experimental material parameters are gathered on the base of 3-point bending performed for 8 specimen. The MTS Insight testing machine was used. Finally, the results from experiment were compared with numerical calculations.

Keywords: computational biomechanics, material parameters, 3-point bone bending test,

1. Introduction

The measurement of the mechanical parameters of the bone is a one from the standard issues in biomedical engineering. The strong anisotropic nature of the mechanical properties of bone is a subject of intensive studies. Methods from mechanics are more suitable then tomography imaging, which is as so far not sensitive for this type of anisotropy.

Patient specific (or subject specific) finite element models are usually generate based on data from medical imaging like quantitative computed tomography. In this case each voxel of data is transferred into one element [1-3]. This approach enables assignment material properties based on the images for every single element in the model.

The main aims of the describe studies were measurement of the mechanical parameters by three-point bending test, assessment of the anisotropic parameters of diaphysis of femur, numerical simulation of the experiment and validation of the material properties assigned based on X-ray microcomputed tomography imaging.

2. Materials and methods

2.1. Sample preparation

The studies have been performed using human femora dissected from cadaver body from female donor 30 years old.. The 8 specimens were dissected from femora diaphysis. The 4x4x40 mm cube shape size of each sample was mechanically machined. Each sample where measure by digital slide caliper (Mitutoyo, resolution 0.01 mm) to control the accuracy of the machining.

2.2. XMT - X-ray microcomputed tomography

The samples were scanned by X-ray microcomputed tomography (XMT) scanner (Nikon Metrology, X-tek, Tring, UK). Scanning settings (kV, µA, no filter, 2000 projections, voxel size 20 µm) were adjusted using the manufacturer software. The density phantom was scanned together with the specimen to enable quantitative measurement of the bone mineral density. After image acquisition reconstruction of cross-sectional axial images were performed. The total volume of interest contains 2000x2000x2000 voxels from about 356 000 voxels were busy with the bone friction. The reconstructed volume was stored in the single file (32-bits real, little endian) on the computer hard drive.

Known density of the phantom was linked to the grey values of the phantom imaged on the reconstructed slices. It enables estimation of the calibration curve, which was then applied to calculate calibrated bone density and then material parameters in the FE model.

2.3. Mechanical test

Specimen was tested by three-point bending test. Test was performed using the MTS Insight testing machine (max. load 10kN). Test parameters are: span 30mm, max. axial load F=220 N, load speed 5,1 mm/min, sample strain= 0.1%. Test parameters are based on the strength parameters of the specimen. The tests were performed for 8 specimen and measurements were done on each of face of the specimen. After the test on the selected face the specimen was rotated 180 degree, the second test was done and then the test was repeated for the last two faces. In this paper results from one specimen are presented (specimen was tested twice on each surface). The full set of results will be presented during the conference.

The setup of the testing machine is shown on the fig. 1.

Figure 1: The setup of the three-point bending test

2.4. Numerical simulation

The FE model with material parameters was generated automatically, based on approach described by [4] and own developed software [5]. For each voxel contained bone one element (HEXA 8-noded) was defined. Based on calibrated grey value material parameters (Young modulus *E*, ultimate strength *S*,) have been defined. Relationship which connects calibrated bone density with material properties were defined based on following equations:

$$E= 10.5 + 0.0102\rho_{QCT}; \quad (1)$$

$$S= \_63.8 + 0.184\rho_{QCT} \quad (2)$$

-where ρ_{QCT} – density calibrated based on greyscale and calibration curve.

This gives the model with non-homogenous material parameters what is closer to the reality then taking into account the model with one material with linear properties. The FE model was built using the HEXA 8-noded elements and consist of about 3 mln DOF. Specimen with material parameters is presented on Fig 2.

Boundary condition were taken from the experiment and modelled in the MSC.Patran (Fig. 3). Simulation were performed using the MSC.Nastran solver.

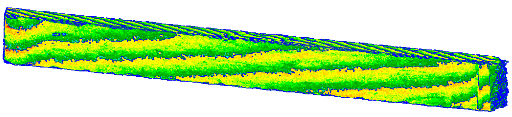

Fig. 2. The specimen FE model generated from XMT with assigned materials properties

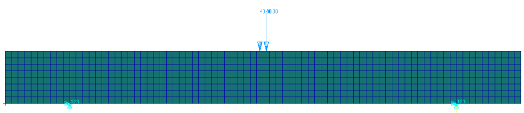

Figure 3. The FE model with boundary conditions

3. Results

Performing the mechanical tests the obtained result (the one specimen) is Young modulus E≅22200 MPa and ultimate tensile strength S=319 MPa with max. deflection y=0.69 mm. The finite element analysis gives the results presented on Fig. 4. The max. normal stress is $\sigma_x \cong 314$ MPa and deflection y≅0.73 mm . It means that stresses and deflection are comparable with results obtained from experiments.

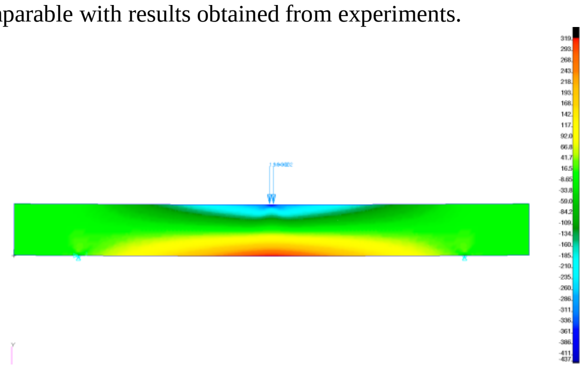

Figure 4. The stress distribution in specimen

4. Discussion and conclusions

The results from simulation matched the results from the experiment. The numerical calculations using finite element method give the deflection and stresses comparable with experimental results. It shows that the numerical analysis of models generated on the base of X-ray microcomputed tomography (XMT) scans with material parameters described based on Hounsfiled scale can be used as the tool for determining the mechanical properties of bone. The computational methods primary used in mechanics are useful for solving the biomechanics problems too.

References

[1] Les CM, Stover SM, Keyak JH, Taylor KT, Willits NH. The distribution of material properties in the equine third metacarpal bone serves to enhance sagittal bending. J Biomech 1997;30:355-61.

[2] Kaneko TS, Pejcic MR, Tehranzadeh J, Keyak JH. Relationships between material properties and CT scan data of cortical bone with and without metastatic lesions. Med Eng Phys 2003;25:445-54.

[3] Keyak JH, Kaneko TS, Rossi SA, Pejcic MR, Tehranzadeh J, Skinner HB. Predicting the strength of femoral shafts with and without metastatic lesions. Clin Orthop Relat Res 2005;439:161-70.

[4] Keyak JH, Kaneko TS, Tehranzadeh J, Skinner HB. Predicting proximal femoral strength using structural engineering models. Clin Orthop Relat Res 2005:219-28.

[5] Tanck E, van Aken JB, van der Linden YM, Schreuder HW, Binkowski M, Huizenga H, Verdonschot N. Pathological fracture prediction in patients with metastatic lesions can be improved with quantitative computed tomography based computer models. Bone 2009;45:777-83.