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INDIRECT DETERMINATION OF MATERIAL MODEL PARAMETERS FOR SINGLE TRABECULA BASED ON NANOINDENTATION AND THREE-POINT BENDING TEST

P. Zlámal*, O. Jiroušek, D. Kytýř, T. Doktor**

Abstract: *The aim of the paper is to develop a procedure for determination of elasto-visco-plastic constitutive model with damage for human single trabecula. The procedure is suited for indirect establishing of material model based on nanoindentation and three-point bending test. Constants of the material model are identified by Finite Element (FE) simulations and curve fitting using an algorithm based on least squares fitting of the experimental curves. In the case of nanoindentation, the penetration depth of tip during the FE analyses (FEA) is fitted to experimental nanoindentation curves. In the case of three-point bending, displacements of nodes are compared with displacements of markers observed during the experiment using digital image correlation.*

Keywords: ***elasto-visco-plastic-damage model, FEM, trabecular bone, three-point bending***

1. Introduction

Knowledge of mechanical properties at level of a single trabecula is important for understanding of overall deformation behaviour of bone tissue as well as for simulation of osteoporotic changes. Nanoindentation is usually used for determination of elastic properties of material, whereas yield properties as well as softening behaviour can not be directly measured. On the other hand, mechanical testing (tension test, three-point bending test etc.) is often carried out to describe nonelastic deformation behaviour. In this study an elasto-visco-plastic constitutive model with damage for human single trabecula was developed using two different procedures including experimental tests and FEA. The first procedure is based on nanoindentation and inverse FE modelling. In the second procedure a three-point bending is performed and the constants are identified from the comparison between displacement of nodes in FEA and displacements observed during the experiment using digital image correlation (DIC) technique.

2. Materials and Methods

For nanoindentation test a polished sample from human (72-year male) femoral head with average surface roughness $25\,\mathrm{nm}$ was used. The nanoindentation test with two peak forces $(10, 20\,\mathrm{mN})$, three holding times $(10, 20, 40\,\mathrm{s})$ and loading rates $(20, 120, 240\,\mathrm{mN/min})$ were performed. Young's modulus was determined directly from nanoindentation curves by Oliver-Pharr method [Oliver and Pharr (1992)]. For FE simulations of the nanoindentation test a rotationally axisymmetric plane model was created and elasto-visco-plastic material model with damage was used. For the considered model it is necessary to identify 10 material constants: (i) Young's modulus ($\mathbf{E}$) and Poisson's ratio ($\boldsymbol{\nu}$); (ii) yield point ($\boldsymbol{\sigma}_\mathbf{y}$) and tangent modulus ($\mathbf{E}_\mathbf{tan}$) for plasticity with von Mises yield criterion and bilinear isotropic hardening; (iii) $\mathbf{C_1}$, $\mathbf{C_2}$, $\mathbf{C_3}$, $\mathbf{C_3}$ for implicit creep with time hardening; (iv) $\mathbf{D_1}$, $\mathbf{D_2}$ for damage model published in Zhang (2010). Material constants (except the elastic constants which were determined directly from experiment) were identified using FEA of the nanoindentation test. For the three-point bending test samples of trabeculae were extracted from the same proximal human femur and cleaned off marrow and

*Ing. Petr Zlámal: Czech Technical University in Prague, Faculty of Transportation Sciences; Konviktská 20;110 00; Prague; CZ; e-mail: xzlamal@fd.cvut.cz
**Doc. Ing. Ondřej Jiroušek, PhD., Ing. Daniel Kytýř PhD., Ing. Tomáš Doktor: Institute of Theoretical and Applied Mechanics, v.v.i., Academy of Sciences of the Czech Republic; Prosecká 76; 190 00; Prague; CZ; e-mail: {jirousek, kytyr, doktor}@itam.cas.cz

Tab. 1: Resulting material constants identified using different techniques

	E[GPa]	μ[-]	σ_y[MPa]	E_{tan}[MPa]	C_1[-]
Exp-nano.	15.4±1.4	0.2	-	-	-
Exp-3pb.	9.3±1.3	-	185.6±42	-	-
FEM-nano.	-	-	180±43	1854±336	(3.1±4)e-18
FEM-3pb	12.1±0.7	0.2±0.05	170±4.9	1924±263	(8.6±5.1)e-18
	C_2[-]	C_3[-]	C_4[-]	D_1[-]	D_2[-]
FEM-nano	6.1±0.4	0.88±0.7	0	0.73±0.03	25.3±7.4
FEM-3pb	4.7±0.9	2.1±0.7	0	0.52±0.1	30.1±1.4

grease. A novel experimental setup was developed for the purpose of the test. Configuration of setup enables to acquire images of deformation behaviour of the single trabecula during the bending test. Groups of markers were selected in the captured image data and their position were tracked using DIC. From the identified vertical displacements of middle span markers, strain values were calculated. Young's modulus and the yield stress were established from stress-strain curve by the 0.2% offset method. For numerical simulation an accurate model of the single trabecula was developed based on inverse Radon transform. To simulate the bending test, the same material model for the single trabecula as in case of the nanoindentation was used. All ten constants were varied and resulting displacements of nodes were compared with displacements of the markers obtained during experiment.

3. Results

In case of the nanoindentation experiment, only the elastic constants were directly identified from the experiment. In the case of the three-point bending test of the single trabecula Young's modulus and yield stress were directly determined. Remaining constants were found using minimizing error based on least squares method in the optimization procedure and are shown in Tab. 1.

4. Conclusions

The visco-plastic-damage constants were assessed from inverse FE modelling in both experiments. Young's modulus and yield stress were also determined by numerical analyses but only for the three-bending test. Influence of individual constants were investigated using sensitivity analysis of the nanoindentation test. The study confirms the possibility of using the indirect determination of the numerical material model for single trabecula based on FEM and experimental methods (nanoindentation and the micromechanical testing).

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References

Oliver, W. C. and Pharr, G. M. (1992), An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. *Journal of Materials Research, Cambridge Univ Press*, Vol 7, No.6, pp 1564-1583.

Zhang, J., Michalenko, M. M., Kuhl, E., et al. (2010), Characterization of indentation response and stiffness reduction of bone using a continuum damage model. *Journal of the mechanical behavior of biomedical materials, Elsevier Ltd*, Vol 3, No.2, pp 189-202.