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NUMERICAL SIMULATION OF INFLUENCE OF CHOSEN PARAMETERS ON TENSILE STRESSES IN BONE CEMENT LAYER IN TOTAL HIP ARTHOPLASTRY

ABSTRACT

In this paper authors present numerical-geometrical models of cemented artificial bone replacements which consist of stem with head, layer of bone cement and femur bone all created in ABAQUS CAE 6.4 environment. Results of principal stresses analysis in bone cement layer under static load are computed using FE method. The influence of eccentricity between stem and femur, as well as influence of elastic constants are discussed. The direction of stress vector leading to maximal tensile stress has been estimated.

Key words: *Artificial hip replacement, bone cement, numerical simulation*

INTRODUCTION

Joints replacements for destructive joint diseases have become a widely accepted treatment in orthopedics surgery for recent time. They are based on total or partial replacement of damaged elements of the joint. According to the new technologies of manufacturing, they remain on good survival rate for about ten years, fig.1, [1]. Among the reasons of their application there are: arthritis, dysplasia, various mechanical injures that lead to fracture both distal and proximal parts of the femur. According to statistics the most liable group contributes people after their sixties with a weakened bone structure caused by osteoporosis in addition. So that various kinds of prosthesis are applied due to life activity, patient's age, type of dysfunction.

Among various types of prosthesis, cemented prosthesis takes first place with respect to number of application. The amalgamation between bone and stem is made of bone cement (PMMA polimetylmatacrylate). Material constants dealing with bone cement like Young modulus (E) and Poisson's ratio (ν) are very distinct. For example E for bone cement according to different researchers [2-12] varies from 0,6 to 2,7 GPa. These values and others affect the stress maximum values and their position. Other factors that play important role in stress distribution are settlement mistakes of stem in femur.

According to very specific environment of working of such fixation there are a little possibilities of investigation, considering for example principal maximum values. Finite element method as kind of numerical calculations let one to investigate that assembly in vitro. Precision of calculations depends on geometry accuracy, boundary conditions and applied load. On the other hand it depends on type of finite element calculations and shape function.

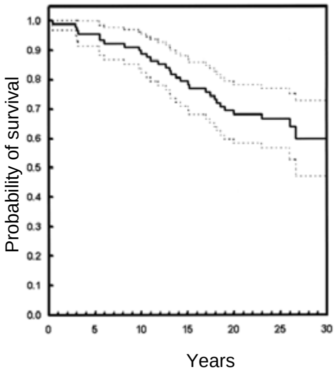

Fig. 1. Survival rate of prosthesis, [1].

The elementary hip prosthesis consists of: stem, head, acetabulum settled in a pelvic bone. Prosthesis differs in shape, dimension and type of fixation to bone (cemented, cementless press-fit, cementesless-ingrowthable). Various kinds of material for prosthesis are used. For example stems are made of stainless steal, chrome, cobalt, titanium and molybdenum alloys. Acetabulums are made of polyethylene, politethraethylene and seldom alumina powders are used.

MATERIALS AND METHODS

Spatial, virtual objects of femur, bone cement layer and stem of prosthesis with head which were created in CAD design environment using translation operations. Modeling of objects was based upon literature's investigation and on a group of prosthesis from Clinic of Orthopedic 10th Military Hospital in Bydgoszcz. Main dimensions were: length: 160 mm, head diameter: 28 mm and the angle between the head of prosthesis and the femur axis: 120 °, fig. 2. Stem's material consisted of titanium and nickel. Elastic constants were estimated using ultrasonic methods and equaled: Young modulus $E = 107$ GPa and Poisson's ratio $\nu = 0{,}3$. Hardness of the alloy was about 35 HRC. Simplified bone's model was used in this calculation. In calculations, bone remains isotropic, uniform, elastic with its elastic constants: $E = 13$ GPa and $\nu = 0{,}38$, estimated as average values from given for each direction in the literature [12].

Based on the literature studies [2-12], the properties of the bone cement layer have been estimated. According to the large distinction in material constants, their assembly has been given in tab. 1 with the source of their origin. In addition the ultrasonic tests have been carried out to estimate elastic constants of this material. The investigation was based on parameters of longitudinal and transverse wave propagation, so that Young modulus was E = 4,3GPa and Poisson's ratio ν =0,38. During calculations both experimental and literature data have been used to assess the model's sensitivity for distinction in elastic constants.

In the spatial models the influence of settlements mistakes of stem in femur has been considered, fig. 3. The eccentricity is defined like stem's axis displacement upon femur's axis along x and y direction with values up to ±1,5mm. The position of coordinate system is based on the bone's hole geometry, fig.5.

Applied load consisted of o concentrated force, parallel to the femur axis. The origin of the force was at center of the prosthesis' head. The value of applied load was estimated using literature studies [12] for models of hip joints load. In calculations, it equals 810 N and yields one leg standing position. Deviations of applied load within its magnitude cause an increase in stresses. On another hand changes in direction of applied load lead to different configurations of stresses fields. This fact will be considered further.

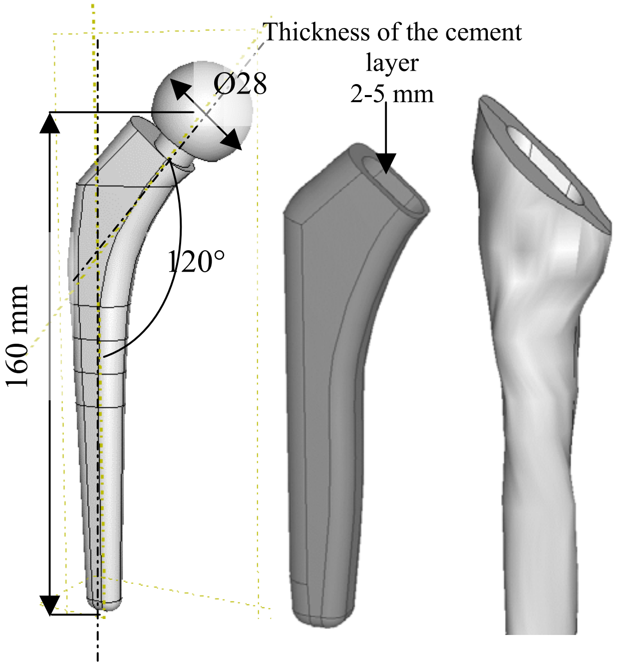

Fig. 2. Geometrical models: stem, bone cement, bone.

Table 1. *Material's constants for various groups of bone cement.*

E, [GPa]	υ, [-]	Source
2,3	0,3	3,4,5
1,8	0,35	6
2,5	0,375	6
1,8	0,4	6
2,5	0,35	6
2,5	0,375	6
2,5	0,4	6
3,1	0,35	6
3,1	0,375	6
3,1	0,4	6
0,6	0,3	7
2	0,33	8
0,75	0,3	9
1	0,3	10
2,1	0,38	11
2,1	0,42	11
2,1	0,46	11
2,4	0,38	11
2,4	0,42	11
2,4	0,46	11
2,7	0,38	11
2,7	0,42	11
2,7	0,46	11
2,65	0,45	11

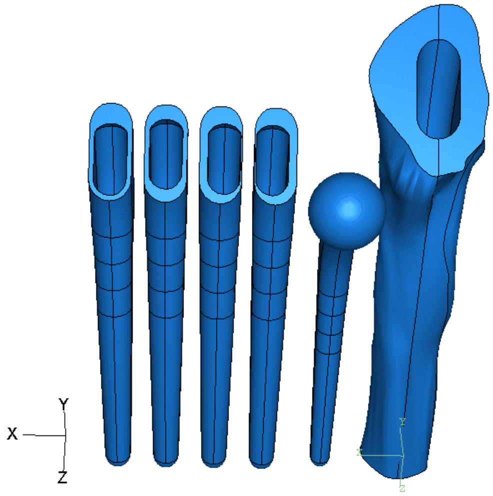

Fig. 3. Bone cements geometry modification.

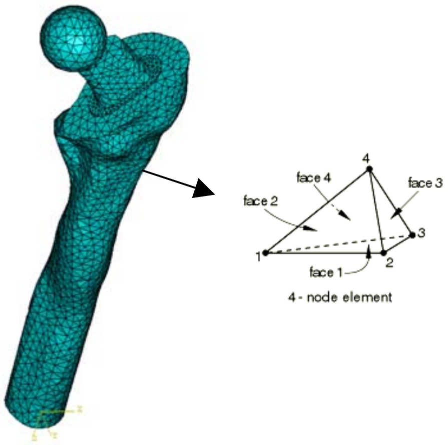

Fig. 4. Mesh structure of assembly for stem, implant and bone cement.

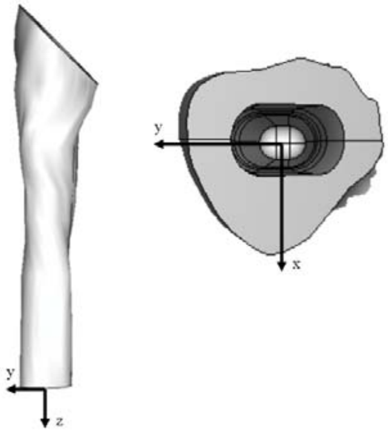

Fig. 5. Coordinate system used in geometry modification.

Abaqus 6.4/CAE environment has been used in calculations, as well as geometrical–numerical models and their assembly under special conditions. Spatial thetrahedral elements with four nodes and linear shape function have been applied to the model. Mesh structures have been generated according to the requirements of calculations for each element separately. Full constrained fixation between specific elements (bone, cement, and stem) has been applied so that parameters of good fixations are performed. The structure created of finite elements is shown in the fig. 4. The numbers of elements for stem, cement, and bone were 4122, 15904 and 10156, respectively. They vary with respect of geometry modification. Investigations [10] showed that either type or shape function of finite elements and internal bone's structure properties (cortical and trabecular) have a major influence on final outcomes.

In boundary conditions all nodes laying on the outer surface of the bone have been fixed. It is a compromise between the number of degrees of freedom and accuracy of the model. However, it is large simplification comparing to the real condition in human's body environment. In the fig. 6, 7 the applied load and boundary conditions are shown. It seems to be that those kinds of boundary conditions don't affect very much the principal stress values in the bone cement layer.

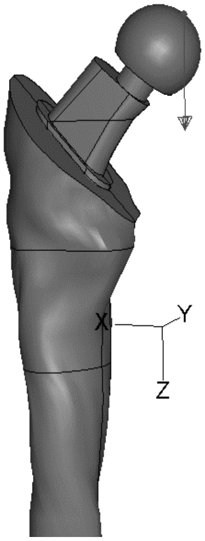

Fig. 6. Action of the force.

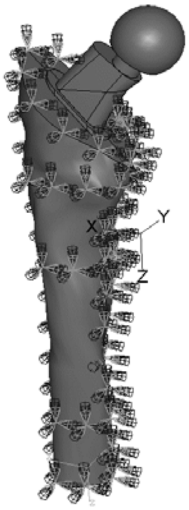

Fig. 7. Fixation of assembly.

Varieties of settlements of stem in femur bone have been investigated. This kind of calculation is called parametric study of eccentricity and allows one to assess the influence of eccentricity on the sensitivity of the model.

On the other hand parametric study of influence of bone cement's elastic constants on tensile stresses in bone cement layer has been carried out. In both cases mentioned above the load vector was parallel to the femur axis.

Moreover the identification of the most dangerous direction of load vector has been calculated. Its direction is different from the one mentioned as typical in the literature [12]. In this study and in the parametric study of eccentricity elastic constants were based on experimental data.

RESULTS

The values of maximal principal stresses have been used to estimate the influence of different parameters (settlements mistakes, elastic constants of bone cement layer, load vector direction) on tensile strength of bone cement.

Firstly, maps of maximal tensile stresses in bone cement layer have been shown. They deal with modification of geometry: displacements of stem along x axis, fig. 8, and along y axis, fig. 9, about values up to ±1,5mm according to previously defined coordinate system. Considering the influence of the eccentricity it has been noticed that either changes in maximum values of tensile stresses and location of maximum values points were observed.

In the case of no eccentricity maximum tensile stresses in bone cement layer were observed in distal part of the bone. They equaled 10 MPa, point B, fig. 8 b.

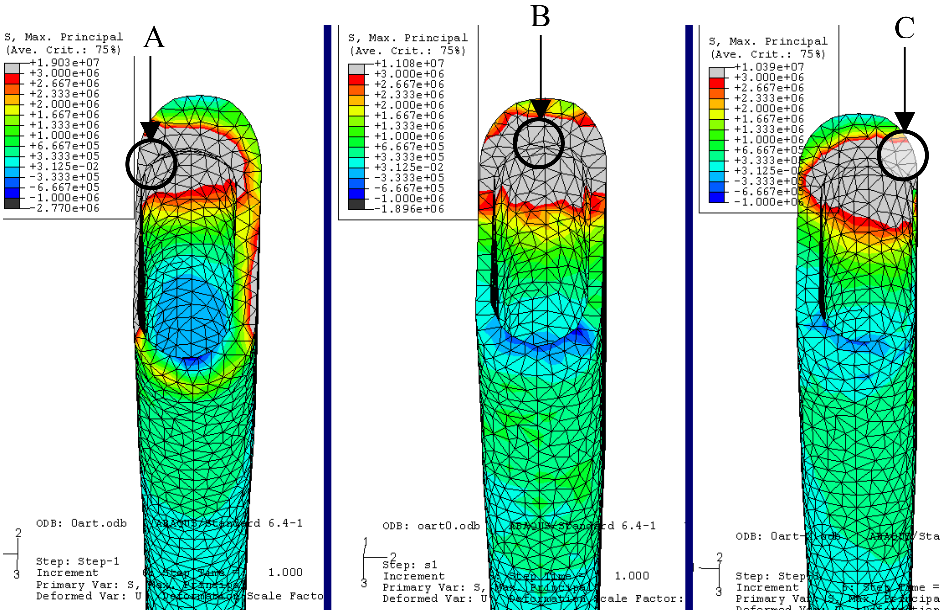

Fig. 8. Tensile stresses, max values in case of modification of geometry along x axis: a) + 1,5mm, b) 0mm, c) -1.5mm.

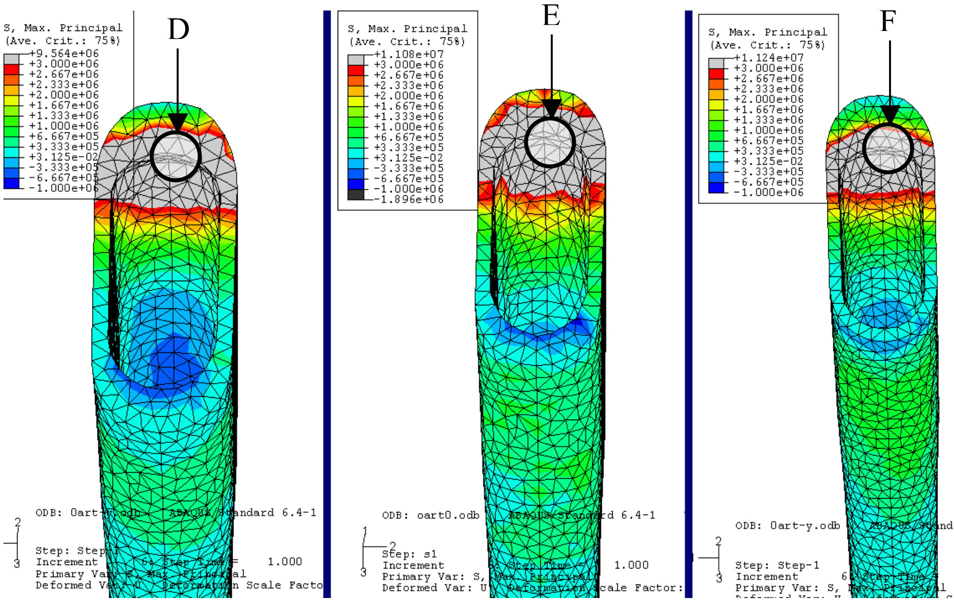

Fig. 9. Tensile stresses, max values in case of modification of geometry along y axis: a) + 1,5mm, b) 0mm, c) -1,5mm.

In case of displacement along x axis about +1,5mm a double increase in values of maximum tensile stresses is observed. The point of maximum tensile stressses is moved towards smaller thickness of the cement layer, point C, fig. 8 c. In opposite case (displacement about -1,5 along x axis) a little decrease of maximum value is noticed. Also point of maximum values is moved towards smaller thickness of the cement layer, point A, fig. 8 a.

In displacement of stem along y axis about the value -1,5 mm slight increase (10%) in maximum tensile stresses is observed, point D, fig. 9a. Displacement in opposite direction causes decrease in maximum tension stresses up to 10%, fig. 9c, comparing to no modification of geometry, point F, fig. 9b.

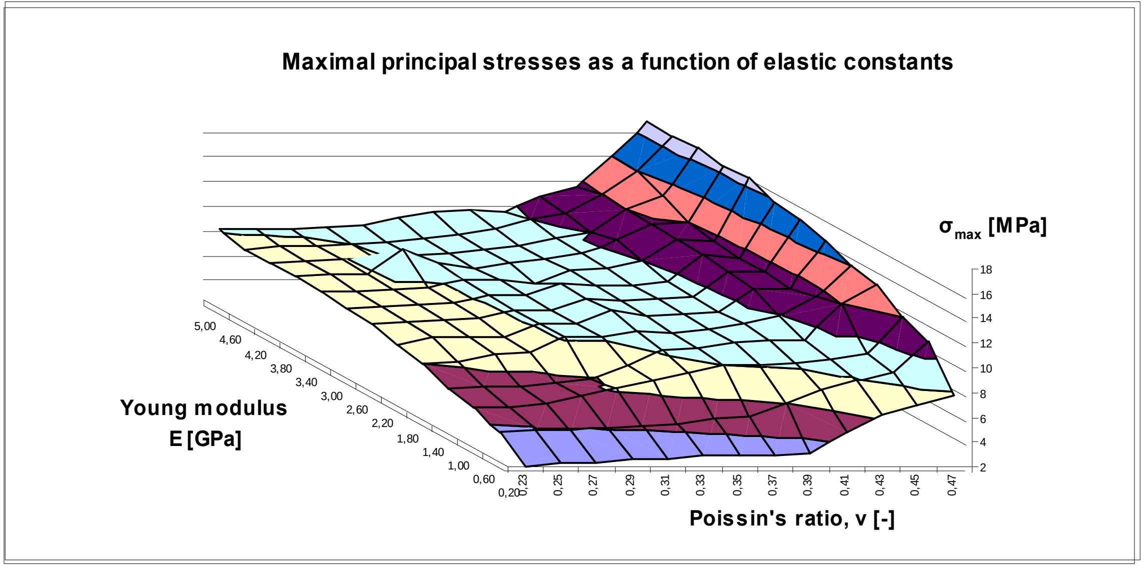

Fig. 10. Tensile stresses, max values as a function of bone cement's constants.

In assessment of influence of elastic constants of cement layer on maximum tensile stresses in that material, the maximum tensile stresses as a function of Young modulus and Poisson's ratio were ploted in the fig.10. The ranges of elastic constants have been set as: Young modulus from 0,2 to 5 GPa, Poisson's ratio from 0,23 to 0,47. They contribute both data from literature studies and experimental tests. Almost 10 times increase is observed in maximal stresses values comparing values for the lowest constants. It has to be emphasized that it is not linear tendency. The largest influence of elastic constants is observed in the ranges for Young modulus 0,2 – 3 GPa and Poison's ratio 0,39 – 47. No changes in the locations of points with maximum values of stresses are observed.

In the identification of the most dangerous load vector the influence of its direction on maximum tensile stresses was investigated. For that case elastic constants derived from experimental data and there was no geometry modification. Analysis was performed using spherical coordinate system with the origin at the middle of prosthesis' head. Axis z of this coordinate system is parallel to the axis of bone. Specific angles were described in the fig. 12. Maximal tensile stresses as a function of direction of load vector were presented in the fig. 11.

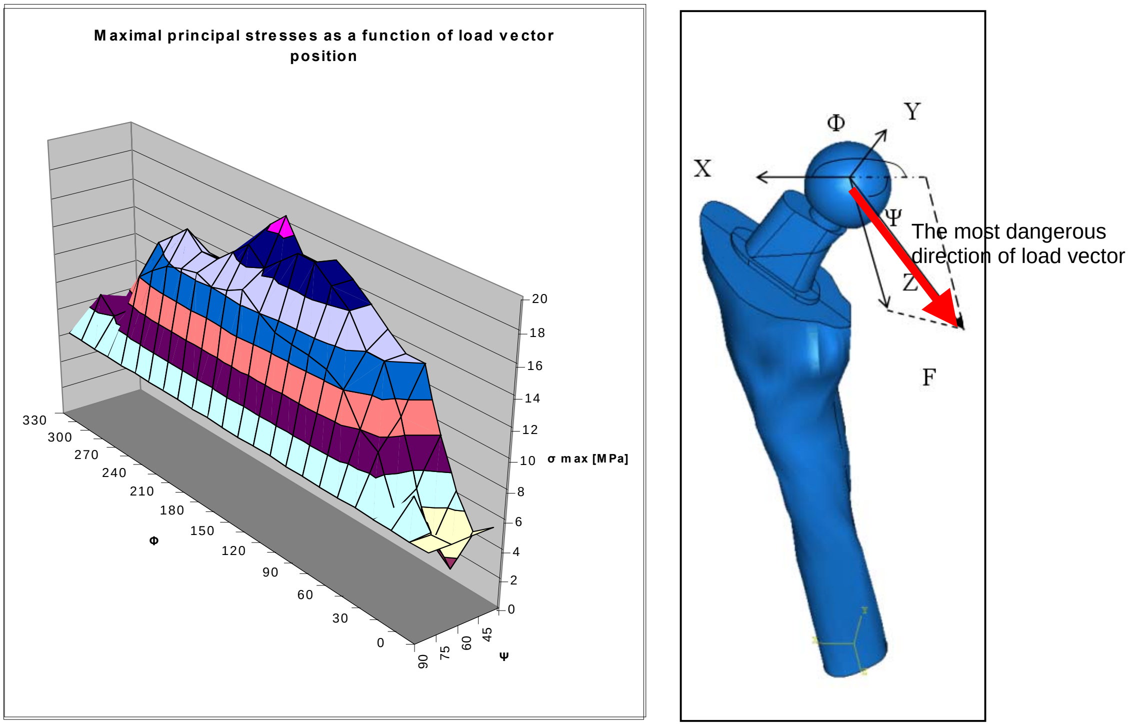

Fig. 11. Tensile stresses, max values as a function of position of stress vector.

CONCLUSIONS

Performed analysis of principal stresses have shown expectable fact that in considering geometrical-numerical models, under desired condition ultimate stresses for tension and compression, which equal according to [13] σ_t =50 MPa σ_c =89 MPa respectively were not reached. On the other hand as it has been shown that eccentricity can lead to increase in stresses.

From the parametric study of elastic constants of bone cement derives that maximal principal stresses increases with the increase of Young modulus and Poissons ratio. In investigation [7], it has been shown that the most optimal Young modulus for bone cement are values from 0,6 to 22 GPa. What also derives from this investigation is that higher E and ν increase stress intensity factor which is responsible initial cracking.

An investigation of direction of load vector shows that there is a strong dependency between direction of load and maximum tensile stresses. Following values of angles Ψ = 45 ° and Φ = 180 ° define the most dangerous direction.

All these parameters in case of acting together can lead to increase in tensile stresses up to 40 MPa. Considering in addition residual stresses in bone cement occurring during shrinkage by curing phase (changes in volume about 7%) another increase about 20 MPa can be expected, [11]. For this configuration tensile stresses reach its ultimate value. That fact deals with emergency of state for static, non-periodic loads. In the case of periodic loads especially dynamic it can indicates dangerous tendency and can lead to damage of prosthesis.

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