National Conference with International Participation
ENGINEERING MECHANICS 2003
Svratka, Czech Republic, May 12 – 15, 2003
paper no. 301

# PARAMETRIC STUDY OF ACETABULAR CUP MIGRATION

**J. Jírová[*], M. Micka[*], J. Jíra[#], A. Sosna[&], D. Pokorný[&]**

**Summary:** *The paper deals with loosening and migration of acetabular cup into the pelvis that belongs to the most serious therapeutic complications arising sometimes several months to years after operation. In the operation records of the Orthopaedic Clinic of the 1st Faculty of Medicine of the Charles University in Prague the implants of conical acetabular cups, which migrated across lamina in the course of several years, were retrieved and evaluated (Fig.1). By using computational model: pelvic bone – acetabular cup – endoprosthesis head we considered the geometry of acetabular cups (spherical and conical), fixation (cemented, non-cemented, by screws) and interaction with bone tissue. We concentrated on the research of contact stresses and strains. Just at the contact between bone and artificial material of the implant we can observe overloading or on the contrary insufficient loading of the trabecular bone tissue and undesirable micromotion of the acetabular implant.*

## 1. Introduction

Research in the field of human joints has advanced most in the area of the hip joint, which is for the function of the lower limb the most important one. In spite of the successful use of the total endoprostheses there are still a number of problems connected with the artificially created co-existence and interaction between the bone tissue and the technical material of the endoprosthesis. The fact, that there is still no optimal replacement is demonstrated by the every-year development of new or modified femoral components and acetabular cups. The loosening and migration of the acetabular implant into the pelvis belong to the most serious therapeutic complications that are often approved several months to years after the implantation.

To promote worldwide collaboration among organizations that try to reduce bone's and joint's diseases and to advance research and educational programs, worldwide multidisciplinary campaign was proclaimed "Ten-day period" (Avicenum, 2000). The campaign is aimed at the support prevention, treatment and research of musculoskeletal diseases and the Czech Republic has also jointed this activities. The "Ten-day period"

[*]Doc. Ing. Jitka Jírová, CSc., Doc. Ing. Michal Micka, CSc.: Ústav teoretické a aplikované mechaniky AV ČR; Prosecká 76, 190 00 Praha 9; phone/fax: +420-286 89 25 09; e-mail: {jirova, micka}@itam.cas.cz
[#]Prof. Ing. Josef Jíra, CSc.: Fakuta dopravní ČVUT v Praze, Konviktská 20, 110 00 Praha 1; phone/fax: +420-22421 3369; e-mail: jira@fd.cvut.cz
[&]Prof. MUDr. Antonín Sosna, DrSc., MUDr. David Pokorný, CSc.: Ortopedická klinika 1.LF UK v Praze, V úvalu 84, 150 06 Praha 5; e-mail: {antonin.sosna, david.pokorny}@lf1.cuni.cz

proceeds in the years 2000 to 2010 under the patronage of UNO and WHO. More than 400 national and international organizations of scientific and professional workers and patient's organizations are jointed in so far.

Recently in the Czech Republic approximately 18 thousands of femoral neck fractures have occurred every year. According to the news of International Osteoporosis Foundation (IOF) risk of osteoporosis fracture at woman is worldwide from 30 to 40 % and at man 13 %. The judgment of a number of these fractures is 414 thousands in the EU for this year and about 972 thousands in 50 years according WHO. At advanced countries more people are dieing owing to complications connecting to hip joint fracture every year than owing to cancer of stomach or pancreas.

In the framework of the press conference organized by the Department of Rheumatology of the 1st Medical Faculty of the Charles University in Prague as an one of events connected with proclaimed "Ten-day period", Professor Antonín Sosna drew participants' attention to the urgent problem of joint replacements. Recently in the Czech Republic 10 thousands joint replacements (it means 1/1000 inhabits) have been applied per year. More over necessity of reoperations grows every year. In the course of years a number of patients, who use the endoprostheses for years and very often inadequate overload them, increases (Sosna & Pokorný, 2000). A great problems, which orthopaedic surgery will have to solve, come into being, the problems of reimplantation and even more problems of filling of bone defects arisen from osteoagressive granuloma or when bone tissue has been mechanically destroyed little by little during implant migration. Unfortunately first tragic complications have appeared, that is migration of artificial cup into the pelvis. At the Orthopaedic Clinic of the 1st Faculty of Medicine of the Charles University in Prague, where endoprostheses are applied for more than 30 years, 25 - 30 % reimplantations are carried on in the last years, it means that one reimplantation comes to three primoimplantations. These operations are both very expensive and demanding to orthopaedist experiences. Above all in the cases when the loosening of implants is connected with infect, the therapy is immensely difficult and demanding. Financial limit, which restricts number of operations in hospitals, naturally tends preferring reimplantations that endanger patients to primoimplantations. Thus waiting time for implantation of artificial joints has been expressively enlarged. Especially great hospitals mention waiting time between 1.5 and 4 years. In this way chances for new patients are again limited. This restriction of number of operations is very unfavourable and not in the conformity with the contemporary trend in advanced countries where patients are indicated to be operated substantially earlier and where patients are operated with better diagnosis than patients in our country.

This question is very consequential social problem that we have been interested from the medical and technical point of views for some years. Using Finite Element Method (FEM) we have investigated the change of stress state that would be caused by implantation of different designs of acetabular cups of total hip replacements (THR). The acebular cup can have a shape (i) spherical, (ii) conical. In the period of 1990 - 1996 some two thousands conical acetabular cups of three different types were implanted. In the operation records of the Orthopaedic Clinic of the 1st Faculty of Medicine, the implants of conical acetabular cups that migrated across lamina interna in the course of several years were retrieved and evaluated. In the set of implants some 20 migrating acetabular cups were found, complying with the following criteria: technically correct implantation, defectfree bone matrix, unproved infect (Richtr & Sosna, 1998), (Libánský at al., 1996).

Total hip endoprostheses can be divided by the method of implantation into **cemented and non-cemented.** Surgeons have longest experiences with the cemented endoprostheses, which are today commonly used. A classical **cemented endoprosthesis** consists of the **polyethylene cup**, which is fixed into adjusted acetabulum by the means of polymetylmetacrylate bone cement. The acetabulum is deprived of destructed articular cartilage and marginal osteocytes. It is of high importance to keep the right direction and the angle of the acetabular cup, because after the implantation the joint is stabilised against the luxation only by the surrounding muscles. The stem of the endoprosthesis is also fixed by the bone cement into the proximal femur.

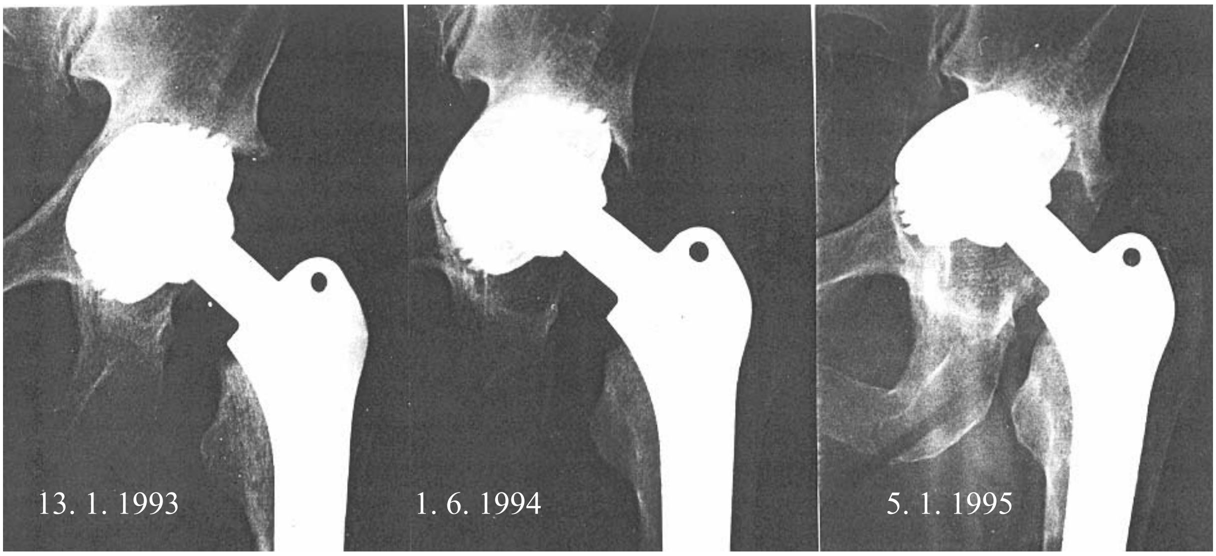


Fig. 1 Migration of cementless conical acetabular cup

**Non-cemented endoprosthesis** uses for its fixation perfect contact of the exactly shaped bone surface with the prosthesis surface. The acetabular cups are made of titan, exceptionally of Comochrome. They are either spherical or conical. Spherical acetabular cups are always equipped with distinctly coarsen surface or especially macroporous surface, occasionally with hydroxyapatite layer. These cups are fixed into the exactly prepared bone socket. Conical acetabular components are either threaded and screwed into the bone or after the insertion into the acetabulum they are expanded against the bone surface by the means of a special impactor. These implants are stabilized by material design and bone ingrowth. Good initial implant stability is needed to maximize in-growth of bone tissue. In addition to the anchoring part, both the spherical and conical components also have an articulating core. This core is fixed into the anchoring part after its implantation into the bone. It is made either out of high-molecular polyethylene or ceramics. Metal or alloyed articulating parts are quite exceptionally and those have extremely smooth surface.

The purpose of the paper is the investigation of the deformation processes and the stress state in the system comprising pelvic bone – acetabular cup – endoprosthesis head and the discovery of stress concentrations. The research deals with the two possible causes of acetabular cup migration:

1. **Micromotions** at the contact of artificial cup and trabecular bone can cause migration. Moreover abrasion particles of polyethylene caused by the cyclic loading of hip joint during gait induce formation of osteoagresive granuloma and consecutive osteolysis. This process can initiate loosening of acetabular cup. Achieving stability in the immediate postoperative

period is a prerequisite for allowing bone to grow into the porous surface of non-cemented acetabular cups.

2. The important role in the process of cup migration can play remodeling of bone tissue. Living bone tissue is continuously in the process of growing, strengthening and resorption, a process called **"bone remodeling".** Cancellous bone adapts its internal structure by trabecular surface remodeling to accomplish its mechanical function as a load bearing structure (Spears at al., 2001). Considering that a local mechanical stimulus plays an important role in cellular activities in bone remodeling, local stress nonuniformity was assumed to drive trabecular structural change to seek a uniform stress state (Fig. 2). The typical example: the initial structure of trabeculera changed from isotropic to anisotropic due to trabecular microstructural changes caused by surface remodeling according to the mechanical environment in the proximal femur. Using a hypothesis that remodeling is driven to obtained the reference value of stress / strain, trabecular structural changes by surface remodeling were predicted at a single trabecular level (Sadegh et al., 1993) and at a trabecular structural level (Huiskes et al., 2000). The results were consistent with experimental observations explained as Wolff's law of bone adaptation (Wolff, 1869; Cowin, 1986). However, a cellular-level mechanism to obtain the reference value of stress / strain by remodelling is still an open question.

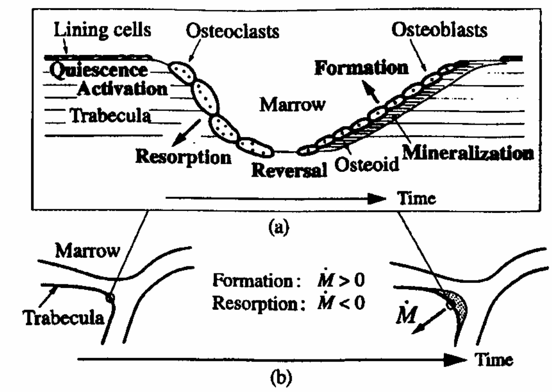


Fig. 2 Trabecular surface remodeling by cellular activities leading to morphological changes in trabecular architecture of cancellous bone:
(a) Osteoclastic resorption and osteoblastic formation on trabecular surface
(b) Surface movement by trabecular surface remodelling (Tsubota et al., 2002)

In our paper we have concentrated on the research of contact stresses and strains, as it is on the very contact between bone and the artificial material of the prosthesis that overloading or, on the other hand, insufficient loading of the bone tissue and undesirable micromotions. In the preliminary stage we have constructed 2D FE model. It's easier and more visual to start studying such complex problem in this way than constructing 3D structure (Jiroušek, 2002)

## 2. Methods

### *2.1. Mesh generation*

The two-dimensional finite element model (Fig. 3) is based on X-ray view of pelvis with implanted artificial acetabular cup in frontal plane. Three models with different acetabular cups were created in order to study the effect of shape and fixation technique and local stress state in surrounding bone tissue:

- spherical cup;
- exact-fit and screw-fixed conical cups.

Spherical and conical cups were both perfectly implanted without possibility of micromotions and with contact elements that enable micromotions between bone tissue and cups. **Boundary conditions**: Along both distal and proximal edges of the segment of pelvis, displacements in the perpendicular directions were removed. Basic element used in the 2D computational model was PLANE82, 8-node isoparametric solid element that is suitable for irregular shapes and nonlinear materials.

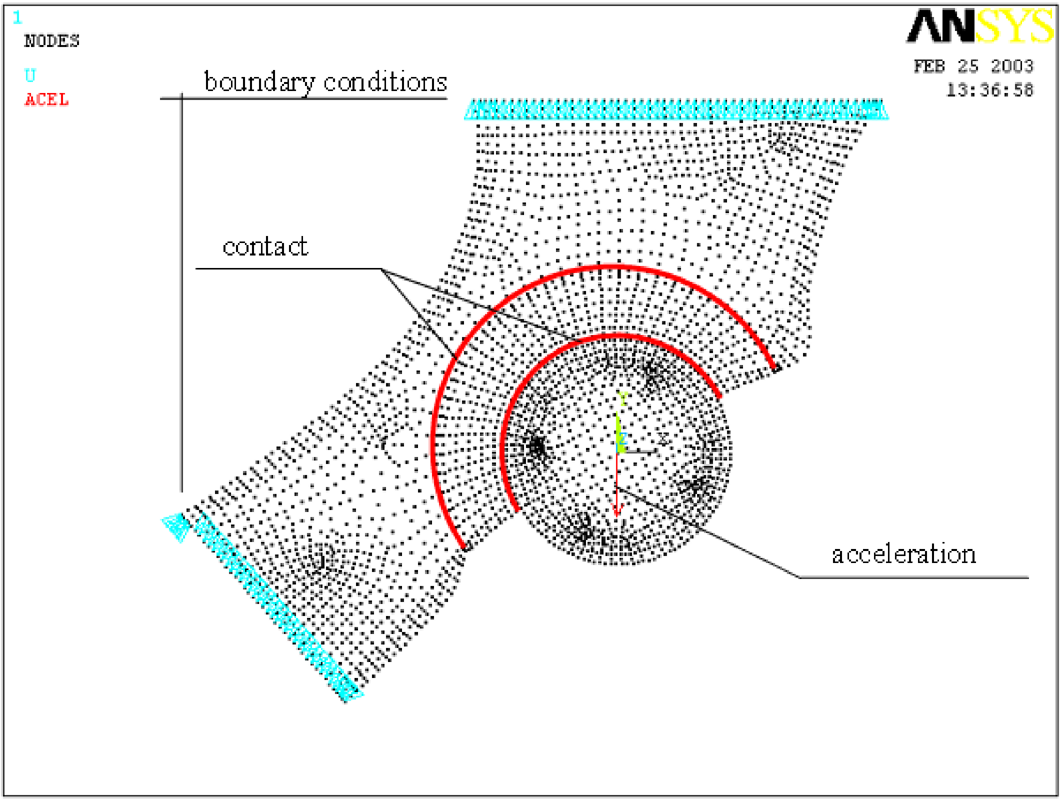


Fig. 3 Boundary conditions and contact elements

### *2.2. Material properties*

The material properties assigned in the model are shown in Table 1. For the present purpose, subchondral bone is considered to be removed during the reaming process. The stiffness of the pelvis trabecular bone is assumed to have a homogeneous modulus of 184 MPa: this value being within the range recorded by Dalstra (1993).

Table 1: The material properties assigned to the model

| **Material** | **E (MPa)** | **μ** |
|---|---|---|
| Trabecular bone | 183 | 0,3 |
| Titanium alloy | 110 000 | 0,3 |
| Polyethylene | 700 | 0,3 |
| Cortical bone | 17 000 | 0,3 |

The values of modulus of elasticity given in literature are very different that is why we carried out our experiments. In this way we obtained not only stress strain relation in the elastic region but also plastic behaviour. Thus we could introduce elasto-plastic stress/strain relation into our computational model (Fig. 4). Computational programme ANSYS contains elements that enable describing of multilinear kinematic hardening material. Non-linear behaviour of spongy bone was introduced and we could find out plastic deformation arising in the course of loading.

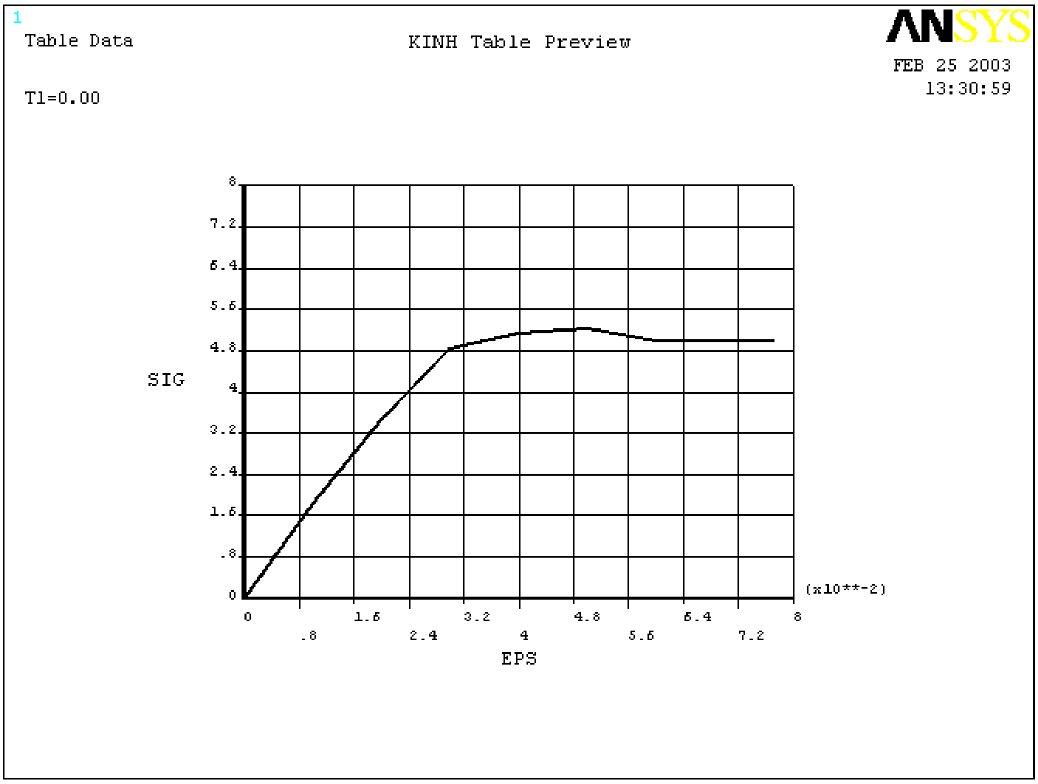


Fig. 4 Stress strain diagram for multilinear kinematic hardening material

### *2.3. Contact behaviour*

Elements representing both the outer surface of cup and inner surface of trabecular bone and the surface of femoral head and inner surface of cup are assigned contact behaviour (CONTACT172 and TARGET169). Surface element TARGET169 covers the surface part of the model with higher stiffness, element CONTACT172 covers the opposite more deformable surface. By the change of the surface elements constants slipping of the surfaces can be modelled. Two possible contacts have been solved for the cup – bone interface:

- perfect fixation – the same displacement of the opposite nodes;
- imperfect fixation – the friction value was used to enable displacement of opposite nodes.

### *2.4. Loading*

By the joint-loading is meant the resulting force and moment that one joint component exerts on the other and vice versa, by means of their articulating contacts. The kind of loading depends on the kind and intensity of the activity. The loading is caused by gravity forces, acceleration forces, muscle forces and forces due to ligament constraints (Huiskes, 1979). The loading on the artificial joint is not necessarily equal to the loading on the natural joint. Even if the same level of activity were assumed, differences may be due to the positioning of the joint relative to the bone, the rigidity of the prosthesis in comparison to those of the natural joint, and the incidence of friction. The loading also depends on the geometry of the implant. In the case of the hip joint, the neck length and the varus-valgus angle of the neck are important parameters.

Unique data based of hip contact forces with instrumented implants and synchronous analyses of gait patterns and ground reaction forces were performed in four patients during the most frequent activities of daily living (Bergmann et al., 2001). Two kinds of instrumented total hip implants with telemetric data transmission were used to measure the hip contact forces. The titanium implants had an alumina ceramic head and a polyethylene cup. An implant of type 1 was cemented in one patient; the other three patients got non-cemented prostheses of type 2. The patient images and implant signals from all measurements were stored on video tape for detailed analyses. The research contains complete gait and hip contact force data as well as calculated muscle activities during walking and stair climbing and the frequencies of daily activities observed in hip patients.

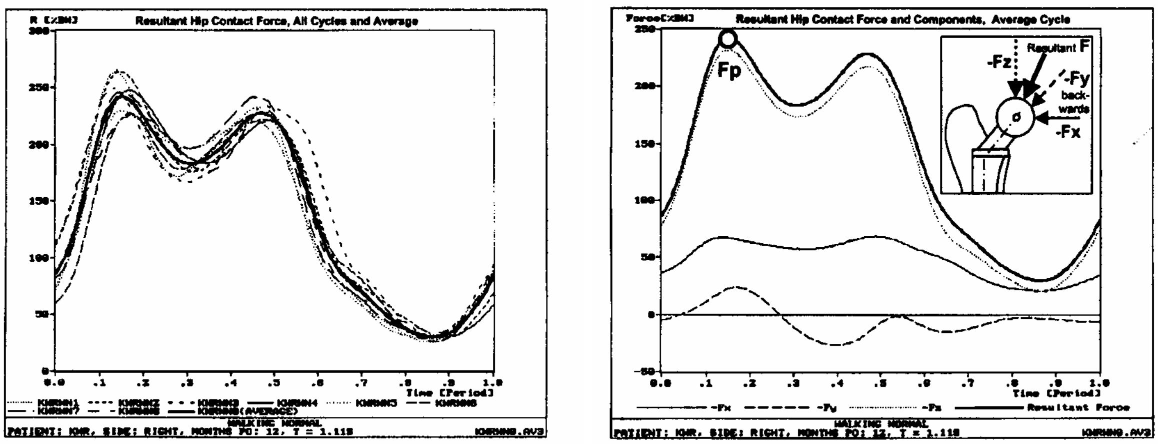


Fig. 5 Contact force $F$ of single trials and individual patient during normal walking. *Left:* Hip contact force $F$ in % BW from eight trials of one patient (thin lines) and the individual average of this patient (thick line). *Right:* Individual average of $F$ from left diagram and its components $-F_x$, $-F_y$, $-F_z$,. The highest value is the peak force $F_p$. (Bergmann at al., 2001)

In our computational model quasi-static joint contact forces, representative of the stance phase of gait, were applied for the patient (body weight BW = 84 kg) during normal walking

4 km/h. The loading was converted to the unit thickness of our model and introduced for calculation using acceleration in given direction.

## 3. Results and conclusions

The slip model of friction is used to represent the cup – bone interface. The friction value used φ = 0.5 represents an intermediate value determined for wet femoral bone and titanium implant (Sherazi-Adl et al., 1993), but could vary according to surface roughness of cup and bone or even the presence of an effective lubricant (e.g. blood).

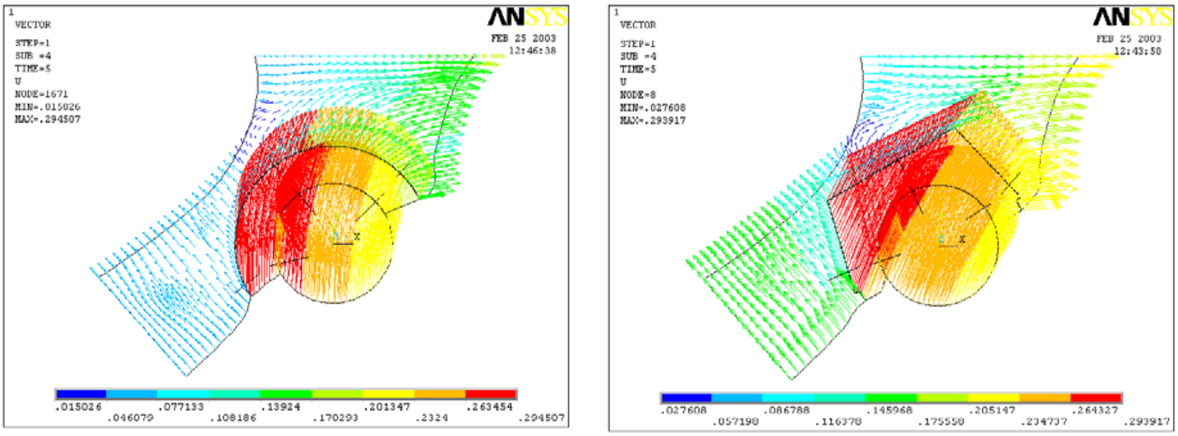


Fig. 6 Values of micromotions

The values of displacements and stresses for the calculated case of perfect fixation were much more less than values given in the Fig. 6 - 9 for imperfect fixation.

1. Micromotions at the contact of artificial cup and bone tissue are displayed in the Fig. 6. The displacement values are for both designs of acetabular cups very similar and arrows in the pictures indicate the possible direction of migration into the pelvis. The values of displacements along the proximal edge of the conical cup are higher than in the case of spherical one.

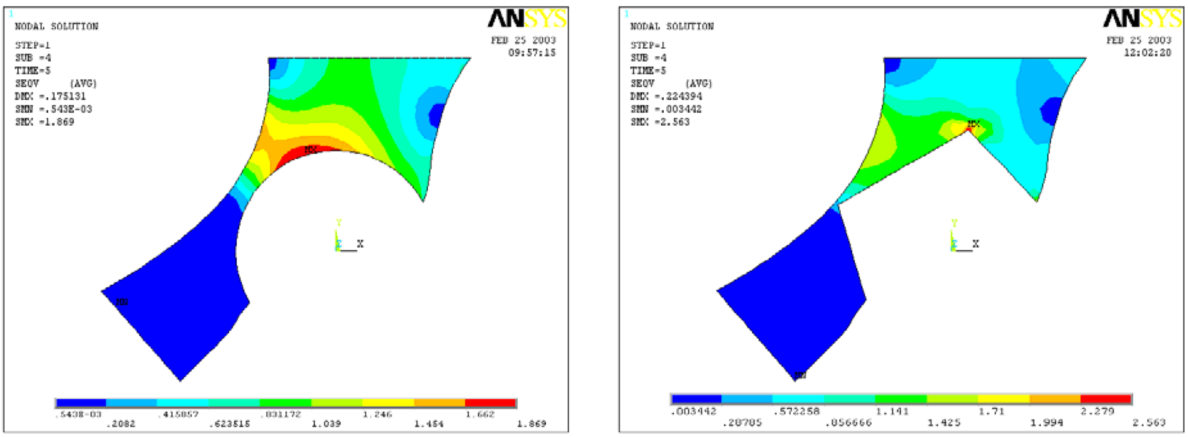


Fig. 7 Equivalent stresses (Failure Criteria HMH)

2. The stress values given in the Figures 7 – 9 are significantly different for both acetabular cups. We have found out more than twice higher values for conical cup in the places of stress concentrations. Especially tensile stress values (Fig. 8) are very unfavourable because tensile stresses are unphysiological phenomena in this place. Local stress concentrations can be assumed to drive trabecular structural change to seek a uniform stress state. The overloading of cancellous bone tissue can play the role of mechanical stimulus for bone resorption and successive turning of the acetabular implant and its migration.

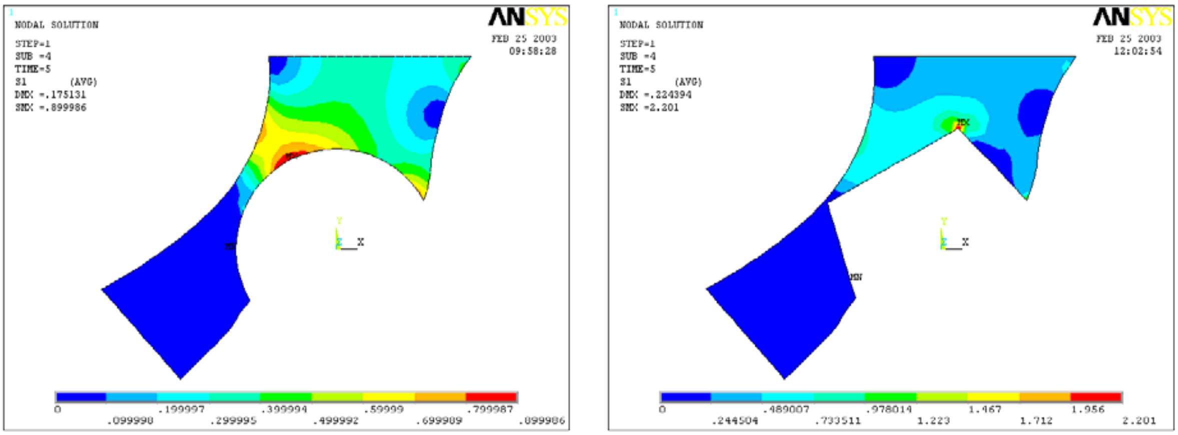

Fig. 8 Principle tensile stress

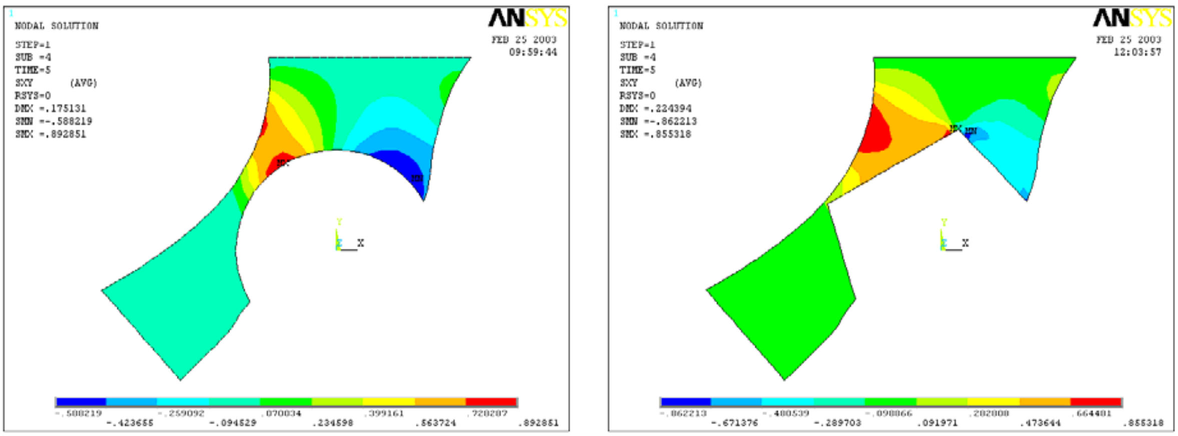

Fig. 9 Shear stresses

In this preliminary study is obvious, if the stress values are too large, they can cause excessive micromotions at the cup – bone interface. Also in the case of newly implanted prostheses, when mechanical connection by bone in-growth originates, patient must be very careful in the immediate postoperative period and it's one of the most important question faced in the rehabilitation program. Relative micromotions during daily activities are widely believed to restrict the bone in-growth process of non-cemented acetabular cups (Spears et al., 2000).

*Acknowledgement: The research was supported by the project No. 103/00/0831 and has been supported by the project No. 106/01/0535 of the Grant Agency of the Czech Republic and by research fund MSM 212600025 of the Ministry of Education, Youth and Sports of the Czech Republic.*

## References

AVICENA (Zdravotnický informační portál pro každého): Týden Dekády kostí a kloubů 12.-20. října 2000. Internet

Bergmann, G., Deuretzbacher, G., Heller, M., Greichen, F., Rohlmann, A., Strauss, J., & Duda, G.N., (2001) Hip contact forces and gait patterns from routine activities. *Journal of Biomechanics,* 34, 7, pp.859-871.

Cowin S.C. (1986) Wolff's law of trabecular architecture at remodeling equilibrium. *Transactions of the ASME, Journal of Biomechanical Engineering*, 108, 1, pp.83-88.

Dalstra, M. (1993) *Biomechanical aspects of the pelvic bone and design criteria for acetabular prostheses.* Druk: Drukkerij Leijn, Nijmegen

Huiskes, R. (1979) *Some Fundamental Aspects of Human Join Replacement.* Acta Orthopaedica Scandinavica. Supplementum No. 185

Huiskes R., Ruimerman R., van Lenthe G.H. & Janssen J.D. (2000) Effects of mechanical forces on maintenance and adaptation of form in trabecular bone. *Nature*, 405, pp.704-706.

Jiroušek O. (2002) Computational simulation of cementless acetabular cup migration. in: *Proc. The Finite Element Method in Biomedical Engineering, Biomechanics and Related Fields* (C. Dorow M. & Geiger, eds), University dental clinic of Ulm, Polyclinic of Orthodontics, Ulm, pp.95-101.

Libánský, P., Sosna, A. & Beznoska, J. (1996) Implantation Technique of a Non-cemented Conical Expansion Socket of the Balgrist Type. *Acta Chir.orthop. Traum. cech.,* 5, pp.783-786.

Richtr, M. & Sosna, A. (1998) Profylakticka osteotomie panve u dysplastickeho acetabula. *Acta Chir.orthop. Traum. cech.,* 65, 6, pp.331-335.

Sosna, A. & Pokorný, D. (2000) Změny v ortopedii za posledních 50 let. *Sanquis*, č. 8

Sadegh, A.M., Luo, G.M. & Cowin, S.C. (1993) Bone ingrowth: an application of the boundary element method to bone remodeling at the implant interface. *Journal of Biomechanics*, 26, 2, pp.167-182.

Shirazi-Adl, A., Dammak, M. & Paiement G. (1993) Experimental determination of friction characteristics at the trabecular bone/porous coated metal interface in cementless implants. *Journal of Biomedical Materials Research*, 27, pp.167-175.

Spears, I.R., Pfleiderer, M., Schneider, E., Hille, E.,Bergmann, G. & Morlock, M.M. (2000) Interfacial conditions between a press-fit acetabular cup and bone during daily activities: implications for achieving bone in-growth. *Journal of Biomechanics*, 33, 11, pp.1471-1477

Spears, I.R., Pfleiderer, M., Schneider, E., Hille, E. & Morlock, M.M. (2001) The effect of interfacial parameters on cup-bone relative micromotions. A finite element investigation. *Journal of Biomechanics,* 34, 1, pp.113-120.

Tsubota K., Adachi T. & Tomita, Y. (2002) Functional adaptation of cancellous bone in human proximal femur predicted by trabecular surface remodelling simulation toward uniform stress state. *Journal of Biomechanics*, 35, 12, pp.1541-1551.

Wolff, J. (1869) Ueber die bedeutung der architectur der spongiösen substanz für die frage vom knochenwachsthum. *Zentralblatt für die Medizinischen Wissenschaften*, pp.223–234.