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Photoelastic investigation of mechanical problems in applying acetabulum cups to hip prosthesis

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Acetabulum cups are the counterparts of endoprostheses, which are mounted in the pelvis. There are different designs of such cups. They differ in their form and in the way of mounting. This paper deals with the threaded acetabulum cups with conical shape mounted in the pelvis. In general, one has to distinguish between stresses caused by the mounting process and lifetime stresses of the mounted cup. Stresses remaining of the mounting must ensure the so-called primary stability; however, they will disappear to some degree due to rheological properties of bone.

The question arises whether the mounting stresses are responsible for local plastic deformations and the corresponding residual stresses or not. In this paper, mostly loading stresses and their dependence on the contact properties between pelvis and cup or between cup and polyurethane inlay are considered.

Key words: biomechanics, hip joint endoprosthesis, threaded acetabulum cup, photoelasticity

1. Introduction

From a common experience with conical threaded acetabulum cups it can be learnt that the problems are caused by a remaining state of stress due to their mounting procedure. In some experimental studies, LERF [1] and ROHR [2] have shown that the contact areas of the cup may be plastically deformed due to the mounting tool and the torsion moment applied. In the papers cited, two different mounting procedures are described. In the first one, the torsion moment is applied by means of four notches at the free edge of the cup. In the second procedure, the torsion moment is applied at three openings in the bottom of the cup. Figures 1 and 2 show the mounting openings in the bottom of a real cup and of the respective photoelastic model. The results of the in vitro studies using artificial bone showed that the zone and amount of plastic deformation in the second case are larger than in the first case. This is due to the fact that the lever arm in the second case is smaller than in the first case. From this the authors have concluded that the second solution is more supposed to failure than the

Fig. 1. Acetabulum cup

Fig. 2. Photoelastic model of the cup

first one. Our own numerical investigations have shown the same results. However, both numerical and experimental investigations proved that the lifetime stresses at the bottom of the cup are negligibly small compared to these in the area of the upper edge of the cup, which is true especially for azimuthal stresses. That means that plastic damage on the upper edge is much more influenced by the lifetime loading than that at the bottom and may cause cracks in this area and even failure of the cup. These results fit very well to practical experience.

2. Methods

Finite element (FE) analyses (Algor Inc.) as well as three-dimensional photoelastic model were used to investigate the mounting as well as the loading stresses in the cup. The photoelastic model was cast from partially polarized Araldite B, the isochromatic patterns were fixed using the method of gamma irradiation [3], [4].

3. Numerical investigation

There was no available information about the usual mounting moment during surgery. Therefore, two values taken from the literature were used in the numerical investigation. In [5], M_t = 60 Nm and in [1], [2], M_t = 150 Nm are mentioned. The latter reports deal with in vitro investigations using a model of artificial bone in order to study the plasticized zones and their influence on the material parameters and on the lifetime estimation.

In the first case [5], the mounting forces were applied to four notches on the upper edge of the cup, whereas in the second one [1], [2], a special mounting tool was used for three holes at the bottom of the cup (see figures 1 and 2). With respect to the most interesting questions the numerical as well as the experimental investigations are restricted to the second case only and to a given geometry of the cup. In both types of investigation, the pelvis was simulated by a quadratic block.

Keeping in mind that there are always some imperfections in the geometry of the tool and the notches of the cup, the calculation was performed for the worst case where only one tooth of the tool is in contact with the cup. The parameters of elastic material of the cup (Young's modulus $E = 110$ GPa, Poisson's ratio $\nu = 0.3$) as well as of the artificial bone ($E = 15$ GPa, $\nu = 0.3$) are taken from the literature [6], [7].

Figure 3 shows the results of FEM calculation of this kind of loading at $M_{\max} = 150$ Nm.

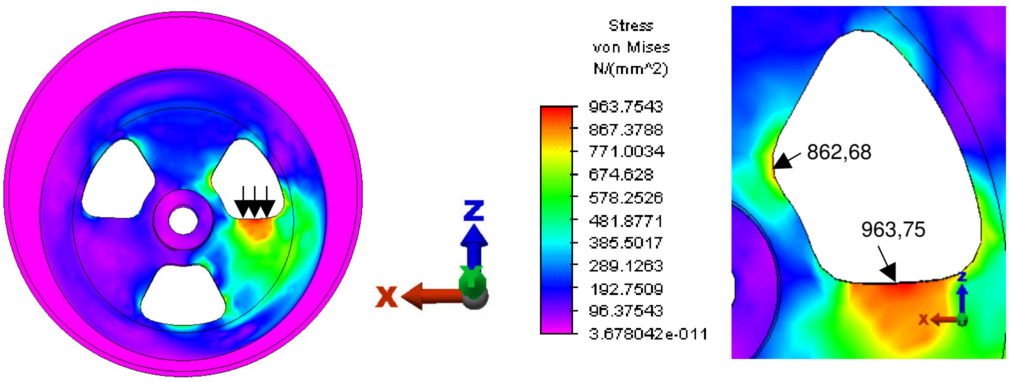


Fig. 3. Equivalent von Mises stresses in the zone of load transfer

Figure 4 shows the residual stresses after unloading caused by a partially plastic deformation of the contact area. It can be gathered from the respective analysis that plastic deformations of the contact area occur only for an unrealistic torsion moment of $M_t \geq 0.9\, M_{\max} \approx 135$ Nm.

The displacements and the stresses in the loading centre with respect to a local coordinate system as functions of the torsion moment applied are presented in figures 5 and 6.

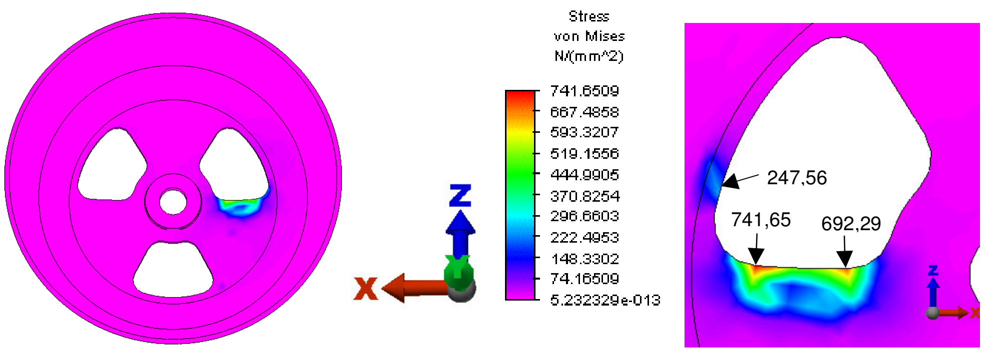


Fig. 4. Von Mises stresses after unloading due to plastic deformation of the loaded zone

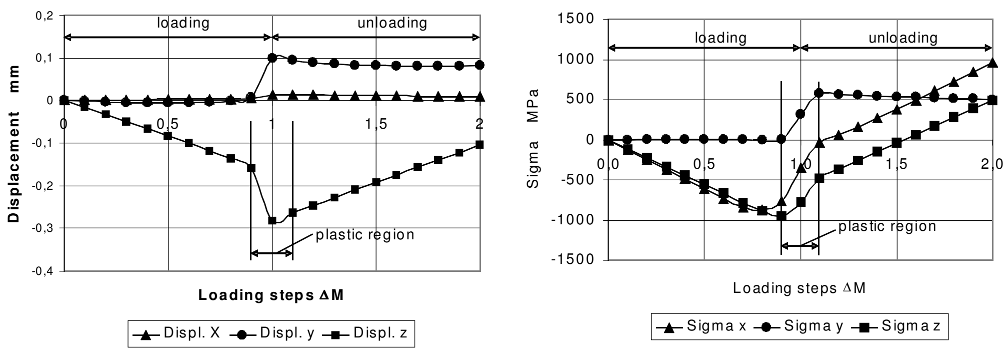
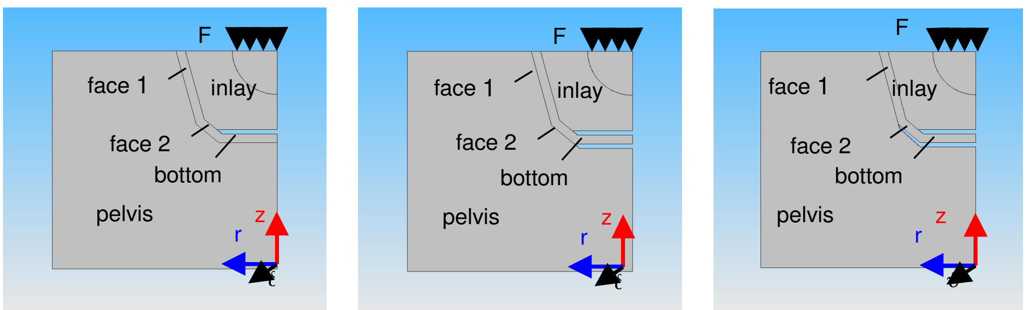
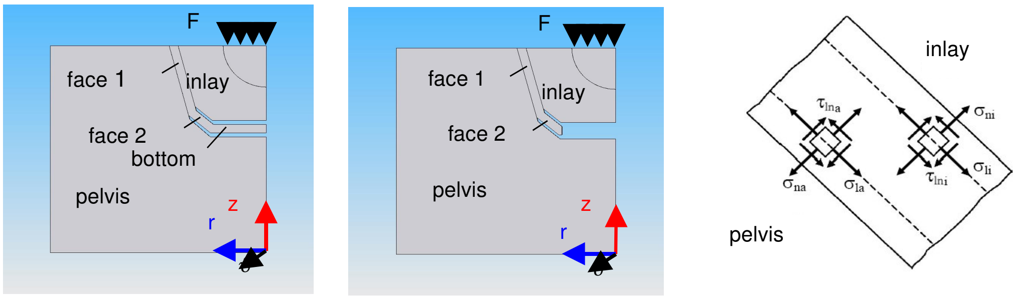


Fig. 5. Displacement components

Fig. 6. Normal stress components

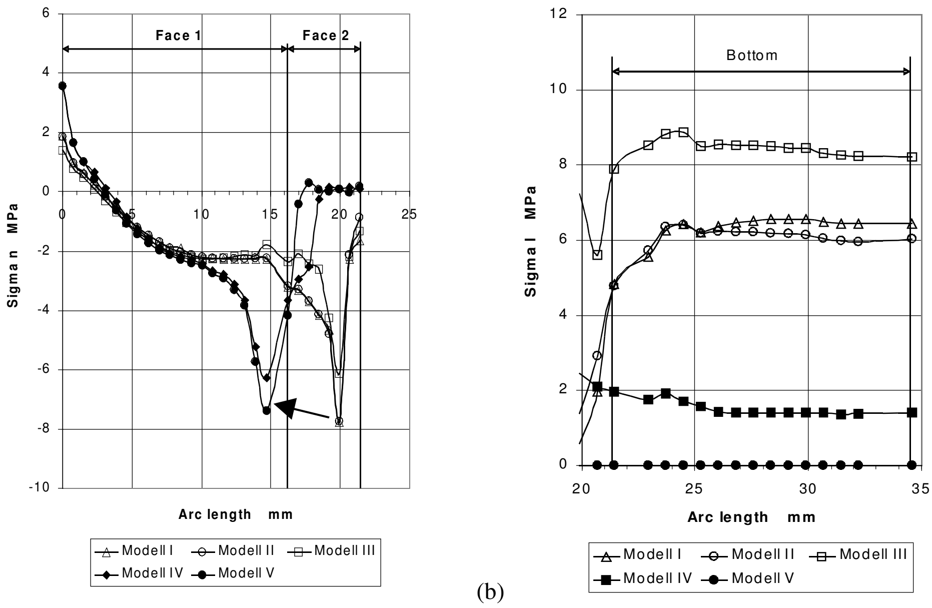


model 1 model 2 model 3



model 4 model 5 stresses according to the cup coordinates

Fig. 7. Models allowing determination of the stresses in the cup
and their dependence on the contact areas between inlay, cup and pelvis



(a) (b)

Fig. 8. Normal stresses in the cup and their dependence on the contact areas between inlay,
cup and pelvis: (a) σ_n across the cup, (b) σ_l at the bottom of the cup

The stress analysis of the cup showed that the amount of stresses and the kind of the load transfer mechanism depend strongly on the contact between pelvis and cup and between cup and inlay, respectively. The stresses in the cup were calculated for five different contact areas. The respective models are given in figure 7. Model 1 shows a full contact between the three parts of the model except those between the inlay and the bottom of the cup. This usually refers to the situation after inserting the cup into the bone. In model 2, the bottom of the cup has no contact, neither with the inlay nor with the pelvis. In model 3, the cup has no contact with the pelvis, either. In model 4, three parts are in contact only along face 1 of the cup. And in model 5, it is assumed that the bottom of the cup is missing, e.g., due to the failure during lifetime. It is assumed that all kinds of contact can be realised by a proper preparation of the pelvis before mounting the cup.

Figure 8(a) shows the results for the normal stresses σ_n across the cup for faces 1 and 2, and figure 8(b) refers to the corresponding results for the normal stresses σ_l parallel to the haunch of the bottom. These results show that there is no significant difference between the models 1, 2 and 3. However, the results for model 4 indicate that the maximum load transfer takes place at the end of face 1. This seems to be an advantage compared to the load transfer mechanisms across face 2 in the first three models. Moreover, in model 4, σ_n is distributed smoother compared to the other ones. However, a very small difference between the results for model 4 and 5 is a proof that the bottom of the cup has practically no mechanical function during lifetime.

4. Experimental investigation

The experimental investigation was carried out using three-dimensional photoelasticity by fixing the photoelastic information by gamma irradiation. For this purpose the photoelastic model of the cup (figure 2) was made of partially polymerised Araldit B [6], [7]. Figure 9(a) shows the part simulating the pelvis made of plexiglass in which the model of the cup is inserted. This figure shows also the claws for applying the torsion moment by means of a pneumatic device. Figure 9(b) shows the setup, which was put to a gamma chamber.

(a) (b)

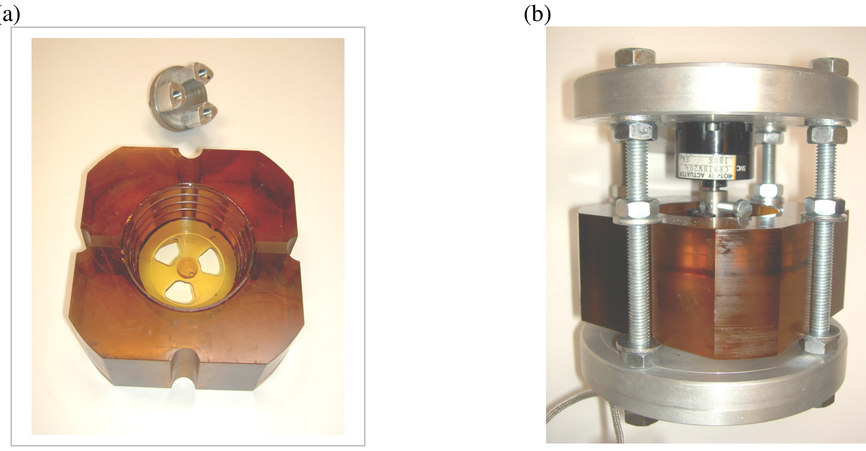


Fig. 9. Device for the experimental procedure: (a) bed for the cup with claw for applying the torsion moment, (b) cage for the bed and the pneumatic device

In order to determine the torsion moment for the experiment, the theoretical solution of the Boussinesq problem [8] was used with the goal to get fringe number 1 at the same distance from the loaded edge as in the numerical solution. Figures 10(a) and 10(b) show the results for dark-field and light-field arrangement, respectively, of the optical setup.

Keeping in mind that the thickness is 1.2 mm only, it can be seen that this method of fixing the photoelastic information is a powerful method. For the analysis of the photoelastic information the stress-optical coefficient f_σ has to be determined by a suitable calibration method using the same fixing procedure.

For a complete analysis a sufficient information about isoclines is needed, though the determination of the isoclinic distribution in the vicinity of the loaded edge is very difficult. In addition, determining the isochromatic distribution using the numerical solution gives usually a different result compared to the experimental one. The reason for this fact is simply the difference between the real unknown load distribution and the load distribution assumed in the numerical simulation. However, using the powerful tool of FE method allows superposition of suitable numerical solutions in order to simulate the real one, which is important for understanding the real load transfer mechanism between the mounting tool and the cup as used in the experiment discussed. This method can also be employed for optimising the shape of the mounting openings at the bottom of the cup and the mounting tool in order to minimise the stress concentrations in the corners of the mounting openings.

(a) (b)

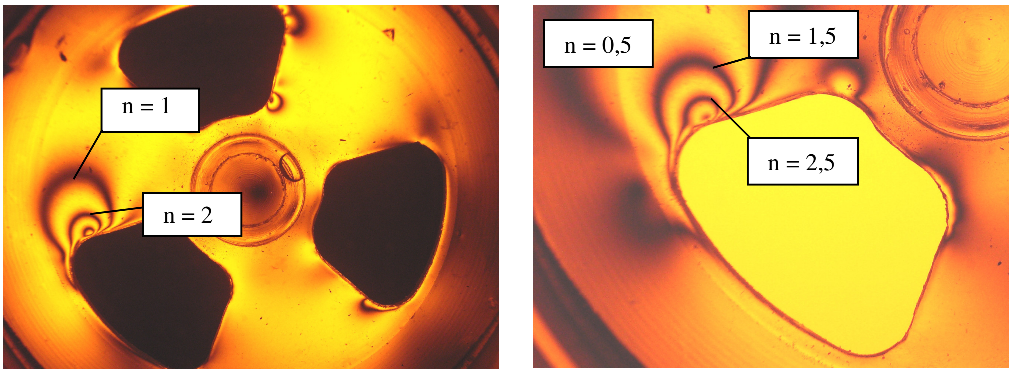


Fig. 10. Fringe distribution due to real loading:
(a) dark-field, (b) light-field polariscope

5. Conclusion

The analyses of the stresses in an acetabulum cup showed that the tangential hoop stresses on the upper border of the cup during lifetime loading, for instance, due to walking, are significantly higher compared to those at the bottom of the cup. Therefore, residual stresses caused by a mounting tool acting on the upper border of the cup yield a higher risk of failure compared to those at the bottom of the cup. This enables a clear decision which kind of the mounting torsion moment should be preferred. However, even in the case of applying the mounting tool to three openings at the bottom of the cup, the analysis methods, the numerical FE simulation as well as the experimental method, in this case the photoelasticity, showed some stress concentrations in the corners of the openings for the mounting tool. A comparison of these, at first, different results needs in any case reliable information about the boundary conditions, i.e., about the real load distribution in the contact area between the mounting tool and the cup. However, it is evident that the experimental result can be used for determining the necessary boundary conditions for the numerical calculations.

This opens also the way for the necessary calibration steps, that means for determining the stress optical coefficient f_σ even in the case of fixing the photoelastic information by gamma irradiation.

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