NUMERICAL MODELING OF ACETABULAR RECONSTRUCTION CAGES MADE OF CFRP AND ESTIMATION OF MECHANICAL BEHAVIOR FOR BONE AND CAGE

Sho Okazaki[a*], Tetsusei Kurashiki[a], Nobuhiko Sugano[b], Keisuke Uemura[b],
Shunichi Bandoh[c]

[a]*Graduate School of Eng., Osaka Univ., 2-1 Yamadaoka, Suita, Osaka, 5650871, Japan*
[b]*Graduate School of Medicine, Osaka Univ., 2-1 Yamadaoka, Suita, Osaka, 5650871, Japan*
[c]*B.I.TEC Co. Ltd., 2-28 Kagamihara, Gifu, 5090109, Japan*
**Corresponding author: okazaki-s@mit.eng.osaka-u.ac.jp*

Keywords: Medical Equipment, Artifical Joint, Modeling, FEM

Abstract

Acetabular reconstruction cage is applied to patients with bone defect because of long-term use. The metal materials are used for the conventional cage, however, the lack of mechanical biocompatibility of metal is a serious problem, because the high rigidity causes the phenomenon of stress shielding which suppresses bone remodeling. Therefore, we aimed to develop the acetabular reconstruction cages made of CFRP. We investigated the superiority of CFRP cage by estimation of mechanical behavior of bone and cage.

1. Introduction

A hip joint is a part of human body which has a role of weight support, and the largest load is provided. Therefore, the disease at hip joint causes serious problems at social activity and daily life. Owing to the aging of population, it is expected that the increase in bone and joint disease, and the number of patients in the world which was about 1.5 million in 1990 will be over 3 million by 2025[1]. A total hip arthroplasty (THA) is one of the medical treatments for serious disease of a hip joint. THA is to replace diseased hip joint by artificial hip joint.

An artificial hip joint is usually composed of cup, liner, head and stem. In the situation of huge acetabular bone loss such as revision surgery, an acetabular reconstruction cage is additionally needed to reconstruct the hip joint. In this study, we focus on an acetabular reconstruction cage which is replaced between a cup and bone. The metal materials like titanium alloy or cobalt-chromium alloy are used as the conventional cage mainly. The conventional cage as ‘Burch-Schneider Cage’ is shown in Fig.1. However, the lack of mechanical biocompatibility[2,3] of metal is a serious problem because the high rigidity[4] causes the phenomenon of stress shielding which suppresses bone remodeling.

We aim to develop the acetabular reconstruction cage made of Carbon Fiber Reinforced Plastic (CFRP). Poly Ether Ether Ketone (PEEK) is applied as one of the super engineering plastic for matrix. PEEK has already been used in a clinical manner with carbon fiber. Therefore, it is convenient to use CF/PEEK, because its excellent performance on chemical resistance and corrosion resistance [5,6]. In addition, the CFRP has the mechanical properties of high fatigue strength. Furthermore, in order to develop the tailor-made artificial hip joint that is optimum for each patient, the effects of various design parameter, such as the shape of cage and stacking sequence on the mechanical behaviors of the cage and bone have to be investigated. To consider the effects of the design parameters of acetabular reconstruction cage on the mechanical behaviors at hip joint are very important in designing acetabular reconstruction cage.

The purpose of this study is to develop the numerical modeling method for acetabular reconstruction cage, and to estimate the mechanical behaviors for bone and cage with the developed numerical model.

Figure 1. Burch-Schneider Cage (ready-made).

2. Numerical modeling of cage and bone

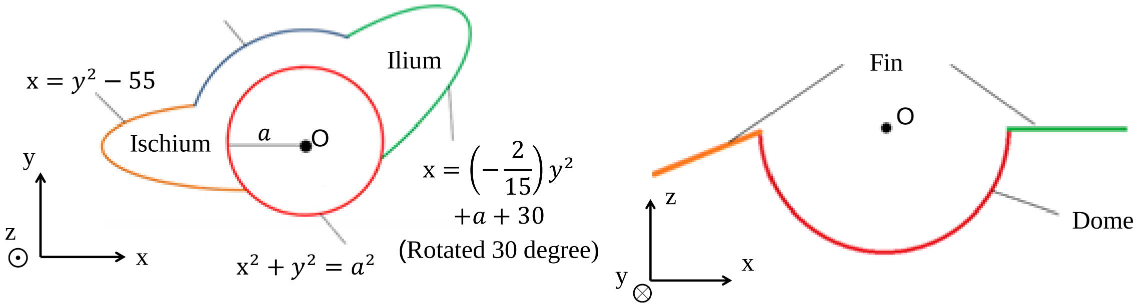
2.1. Cage and bone parts

It's possible to design the artificial hip joint that is optimum for each patient by using CFRP which can provide various design parameters. However, the numerical analysis with three dimensional model of real geometry demands an enormous amount of time. Therefore, we develop a numerical modeling method of the basic design model for quick medical supply for patients. When the Burch-Schneider Cage is applied, the protrusion is inserted in the ischium, and cage is fixed to the pelvis with screws and the application of bone cement depends on the situation of the patient. The cage is inserted to the ischium and fixed to the bone with the use of cement. The numerical model consists of two parts which are the cage and the bone.

2.2. The part of acetabular reconstruction cage

The external form of acetabular reconstruction cage is shown in Fig.2. The cage is constituted by dome part at the center and fin part at the outside. The fin part is constituted by four quadratic curve. Figure 3 shows the numerical model, which is created by setting nodes radially from center O. At the ischium side, the cage is fixed by inserting in the ischium, and the situation of inserting was simulated by replacing bone elements.

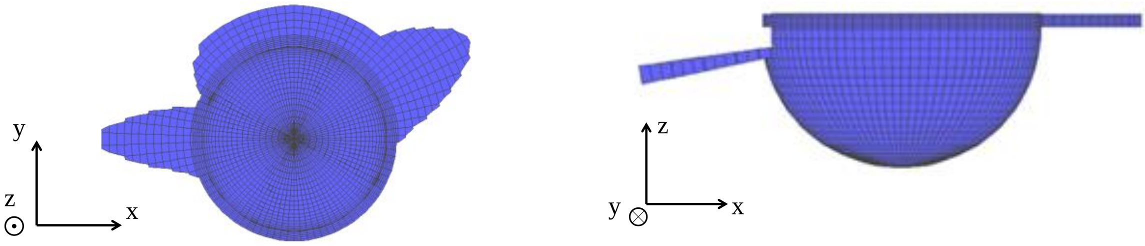
The elements between cage and bone is regarded as bone cement at dome part. At the ischium side, the interfacial elements are not used. At the other part, the cage isn't fixed to bone, and the interfacial elements with very low elastic modulus is used. Figure 4 shows the cross section of the numerical model that is constituted by these parts.



(a) Front view

(b) Cross section

Figure 2. External form line of acetabular reconstruction cage.



(a) Front view

(b) Side view

Figure 3. Numerical model of acetabular reconstruction cage.

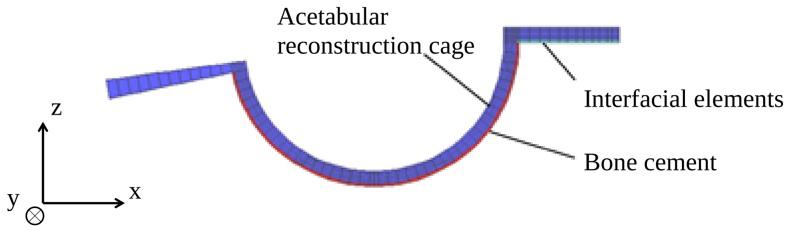
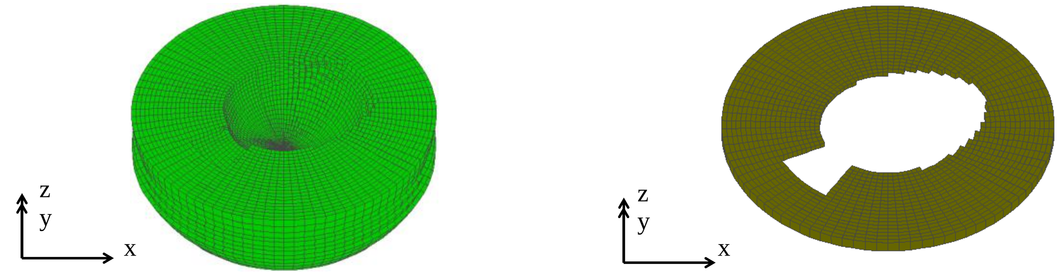


Figure 4. The part of acetabular reconstruction cage (cross section).

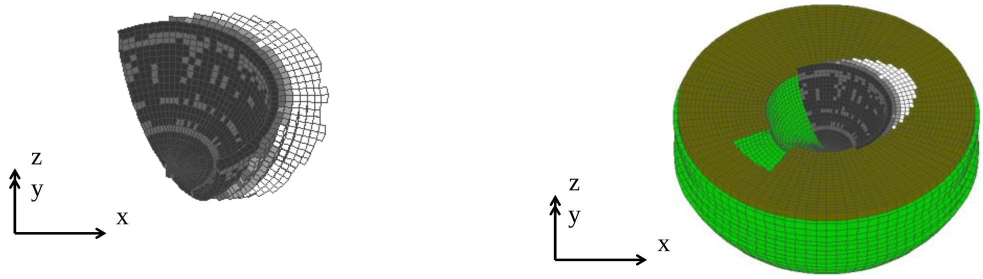
2.3. The part of bone

The numerical model of bone has the shape of the cylinder 50[mm] long, 70[mm] radius. The acetabulum is simulated by the depression of the hemispherical at the center the size of which is the same as the cage. In order to simulate the actual pelvis, different material properties are applied to the model: the cortical bone at the surface, bone graft at the bone defect, and the sponge bone at the other part. Figure 5 shows the numerical model of the bone part by setting nodes radially from center as the cage. At the bone defect, the pour bone cement after filling up bone graft is considered, and the elastic modulus is changed as mixture of bone graft and bone cement.



(a) Sponge bone

(b) Cortical bone



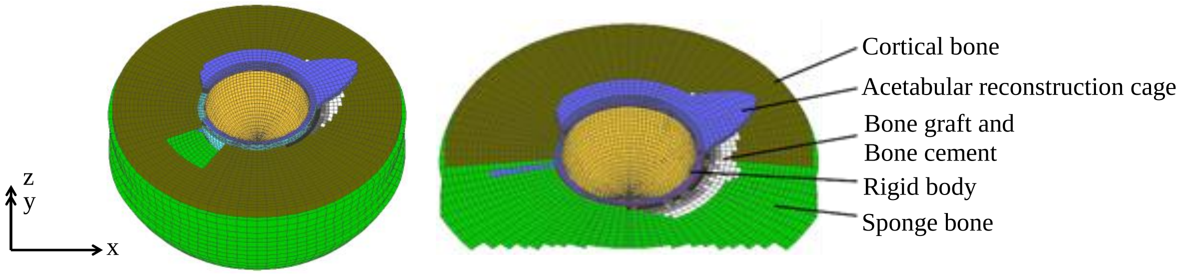
(c) Bone graft

(d) Whole bone

Figure 5. Numerical model of bone.

2.4 The numerical model

In this study, the load transfers to the cage as the contact pressure through the thighbone and the cup. Therefore, in the numerical model, the rigid body element is created in the cage, and the load is applied to the cage, in the directions of counterforce of weight, by the rigid body which is controlled by the node.
Figure 6 shows the proposed numerical model.



(a) Bird view (b) Cross section

Figure 6. The numerical model.

3. Estimation of the mechanical behaviors for bone and cage

3.1 The purpose of numerical analysis

This section evaluates the mechanical behavior of bone and cage due to difference in material property. Two estimation is made. One is the deformation of the cage, second is strain energy density (SED) at the sponge bone. These are the indexes for restraint of bone growth and restraint of bone atrophy, respectively.
First, the deformation of the cage is treated as index that evaluates the micro-movement occurrence. The micro-movement is the distance between implant and bone, which should be controlled under 0.05[mm].[7,8]
Next, the strain energy density at sponge bone is treated as the index for restraint of bone atrophy. Huiskes's and others study, it was treated as influence factor for relief of stress shielding and promotion of bone remodeling[9]. The strain energy density at elastic deformation is given by equation (1), which is the sum of the product of strain and stress in each direction.

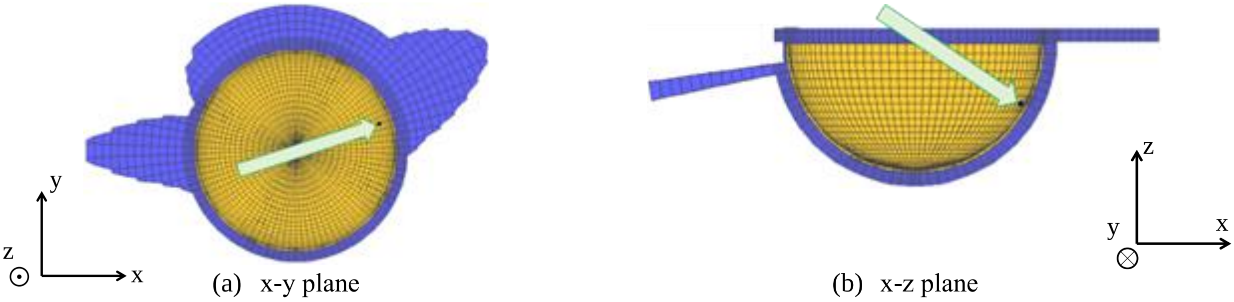
$$U = \sum_{i,j} \frac{1}{2} \sigma_{ij} \varepsilon_{ij} \tag{1}$$

As the strain energy density is numerical value of per unit volume, so it is possible to estimate not to depend on the element volume. In this study, it is used as the index for estimation. And the design for more strain energy density at sponge bone with the basis is investigated under the conditions that the stress of sponge bone is within the limits of elastic deformation.

3.2 Numerical conditions

For the load condition, the rigid body element is created in the cage, and the load is applied to the cage, in the directions of counterforce of weight, by the rigid body which is controlled by the node. Figure 7 shows the relation of the cage and the load direction. Table 1 shows load value of weight (BW) ratio, x direction is moving direction, y direction is transverse direction and z direction is vertical direction under the condition of walking[10]. As restriction condition, the full restraint is applied to the nodes of side and bottom of bone model.

Table 2 shows material properties. Three materials are used in this study: Ti-6Al-4V is widely used. CF/PEEK(Quasi-Isotropic) is composed by Quasi-Isotropic carbon fiber and PEEK. CF/PEEK(Short fiber) is composed of short fiber by carbon fiber and PEEK. As the bone defect part is filled by the mixture of bone graft and bone cement is surgery, the elastic modulus in simulation is changed accordingly. The shape of the cage is 50[mm] in inside diameter and 2.5[mm] of board thickness.



(a) x-y plane (b) x-z plane

Figure 7. The relation of the cage and load direction.

	Fx[%BW]	Fy[%BW]	Fz[%BW]
Load value	120	25	300

Table 1. Load value of weight ratio[12].

		CF/PEEK (Quasi-Isotropic)	CF/PEEK (Short fiber)	Ti-6Al-4V
Young's modulus [GPa]	**L**	4.71E+1	7.50	1.08E+2
	T	4.71E+1		
	Z	8.40		
Shear modulus [GPa]	**LT**	1.79E+1	2.68	4.18E+1
	TZ	4.10		
	ZL	4.10		
Poison's ratio	**LT**	3.17E-1	4.00E-1	2.90E-1
	TZ	3.40E-1		
	ZL	6.06E-2		

(a) Material properties of cage

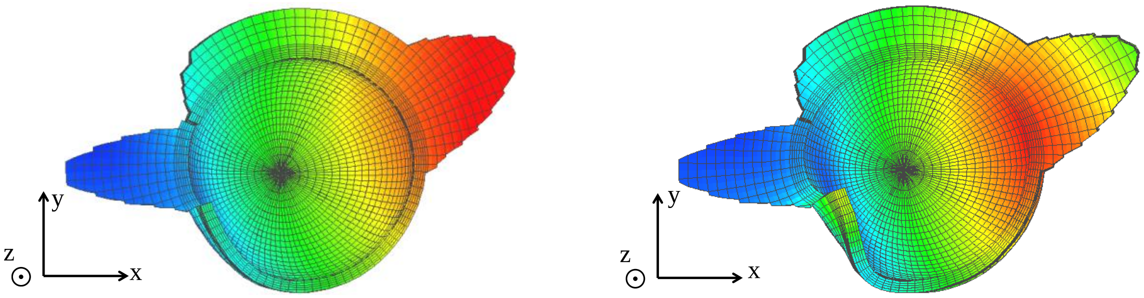
	Sponge bone	Cortical bone	Bone cement	Bone graft	Contact part
Young's modulus [GPa]	1.33E-1	1.80E+1	2.00	1.50 ~ 1.50E-1	1.00E-4
Shear modulus [GPa]	5.10E-2	1.70E+1	7.40E-1	5.56E-1 ~ 5.56E-2	3.80E-5
Poison's ratio	3.00E-1	3.00E-1	3.00E-1	3.00E-1	3.00E-1

(b) Material properties of the other parts

Table 2. Material properties

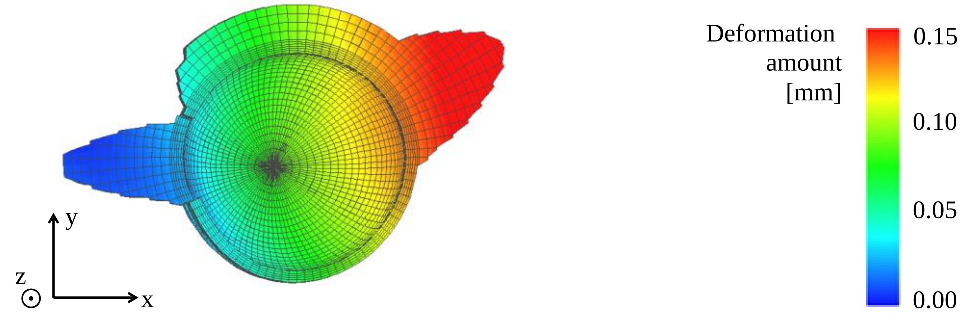
3.3 Deformation of the cage

Figure 8 shows the distribution of deformation of the cage. In spite of the difference of materials, the deformation amount at the ischium side is small, because of the connection of sponge bone, but the deformation amount at the ilium side is large because of the load influence. However, at fin of the ilium side, CF/PEEK(Quasi-Isotropic) and Ti-6Al-4V of elastic modulus is higher than cortical bone, so they are hard to be affected from cortical bone and their deformation amount are large. On the other hand, CF/PEEK(Short fiber) of elastic modulus is smaller than cortical bone, and the deformation is restrained and the deformation amount is smaller than the others.



(a) CF/PEEK(Quasi-Isotropic)

(b) CF/PEEK(Short fiber)



(c) Ti-6Al-4V

Figure 8. Distribution of deformation of the cage.

The deformation of the cage shown in Figure 10 is evaluated by two ways: the deformation of path A which is the boundary of fin and dome, and the path B-C along the load direction as shown in Figure 9.

The deformation of CF/PEEK(Quasi-Isotropic) with high in-plane rigidity was comparable as Ti-6Al-4V. The deformation of CF/PEEK(Short fiber) is a little different from the others because the lower rigidity.

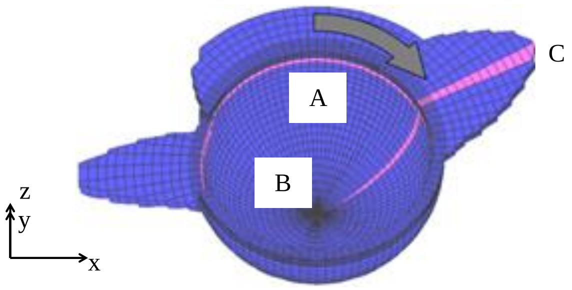
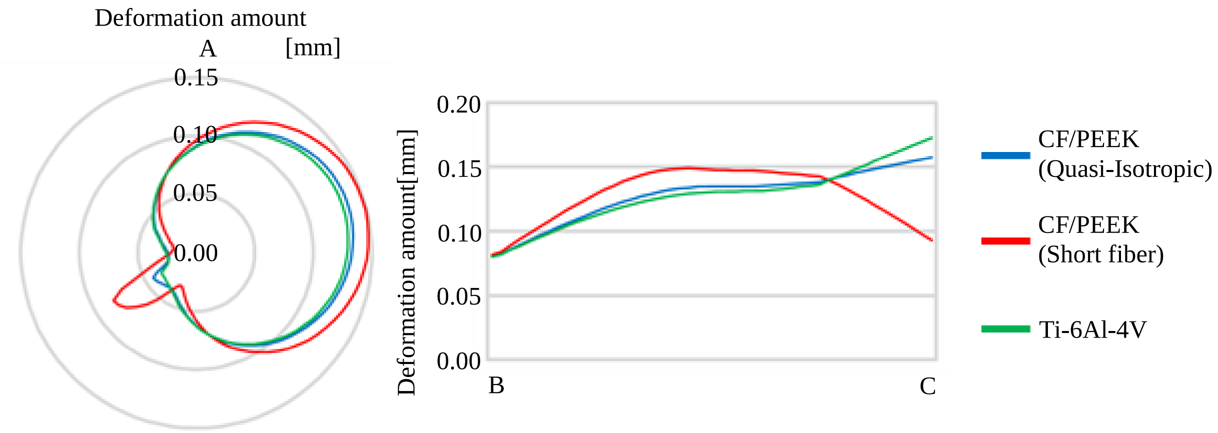


Figure 9. Elements for estimation

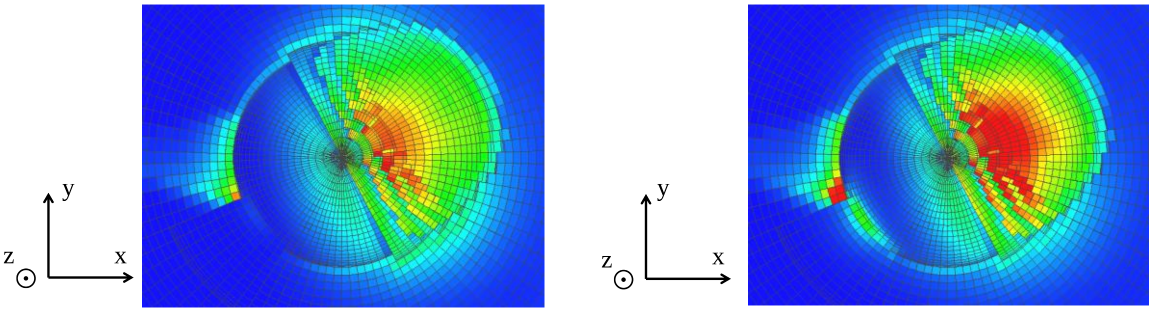


(a) At boundary of fin and dome (b) At load direction

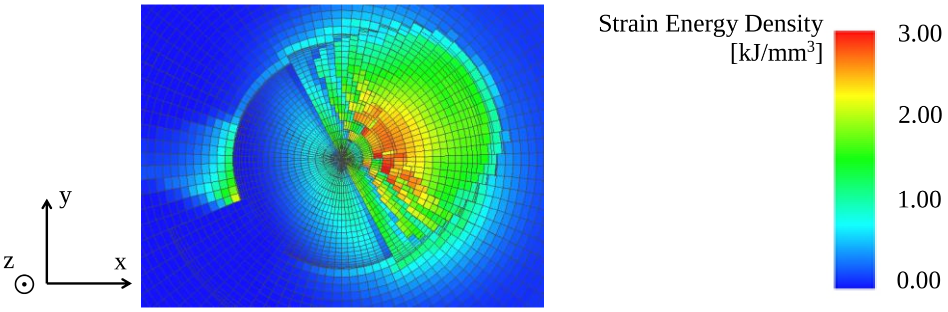
Figure 10. Deformation amount of acetabular reconstruction cage.

3.4 Strain energy density of sponge bone

Figure 11 shows the distribution of strain energy density of sponge bone. The difference in the materials was also caused of the difference in load transfer.The load transfer decreases with the increasing of elastic modulus of sponge bone. As a result, the strain energy density in case of CF/PEEK(Short fiber) was the highest, and CF/PEEK(Quasi-Isotropic) was the same as Ti-6Al-4V. Finally, CF/PEEK has more strain energy density than Ti-6Al-4V widespread, CF/PEEK is more excellent for restraint of bone atrophy and promotion of bone remodeling.



(a) CF/PEEK(Quasi-Isotropic) (b) CF/PEEK(Short fiber)



(c) Ti-6Al-4V

Figure 11. Distribution of strain energy density at peri-acetabulum

4. Summary

In this study, we aimed to develop acetabular reconstruction cage made of CF/PEEK, the numerical modeling method and estimation of mechanical behavior for bone and cage are described. CF/PEEK(Quasi-Isotropic) was comparable as Ti-6Al-4V with each index. The strain energy density of CF/PEEK(Short fiber) is higher than Ti-6Al-4V, however the deformation of CF/PEEK(Short fiber) was larger than Ti-6Al-4V, therefore CF/PEEK(Short fiber) is not the most excellent for acetabular reconstruction cages. As the results, it was concluded that the demands for development of acetabular reconstruction cage trade-off relationship, which means the optimization exists is needed which will be evaluated in the future.

References

[1]Cooper C., et al., “Hip fractures in the elderly: a worldwide projection”, Osteoporosis International, Vol.2, p.285-289, 1992
[2]C. Delaunaya, et al., “Metal-onmetal bearings total hip arthroplasty: The cobalt and chromium ions release concern”, Orthopaedics & Traumatology: Surgery & Research 96, p.894-904, 2010
[3]P.Paavolainen, et al., “Cancer Incidence in Finish Hip Replacement Patients From 1980 to 1995”, The Journal of Arthroplasty, Vol.14, p.272-280, 1999
[4]M. Higa, et al., “Shape optimization of artificial hip prosthesis with 3D FEM”, Journal of Japan Society for Precision Engineering, Vol.68-7, p.948-952, 2002
[5]Tayton K., et al., “The use of semi-rigid carbon fiber-reinforced plastic plates for fixation of human fractures: results of preliminary trials”, The Journal of Bone and Joint Surgery. British, Vol64-1, p.105-111, 1982
[6]K. Fujiwara, et al., “Feasibility of knitted carbon/PEEK composites for orthopedic bone plates”, Biomaterials, Vol.25, p.3877-3885, 2004
[7]Burke DW, et al., “Dynamic measurement of interface mechanics in vivo and the effect of micromotion on bone ingrowth into a porous surface device under controlled loads in vivo.”, Trans Orthop Res Soc 16, p.103, 1991
[8]Justy M,et al., “In vivo skeletal responses to porous-surfaced implants subjected to small induced motions.”, J Bone Joint Surgery Am 79, p.707-714, 1997
[9]Huiskes R., et al., “Adaptive bone-remodeling theory applied to prosthetic-design analysis”, Journal of Biomechanics, Vol.20, p.1135-1150, 1987
[10]G. Bergmanna, et al., “Hip joint loading during walking and running, measured in two patients”, Journal of Biomechanics, Vol.26, p.969-990,1993