Comparison of Heterogeneous Modeling Based Different Patterns of Hip Prosthesis Design

Sudhir Kumar Singh, and Puneet Tandon, *Member, IAENG*

***Abstract*—This work proposes the development of Heterogeneous modeling based bio-implant with varying material properties to reduce the stress shielding of the implant. Comparison of different design pattern, i.e. radially, axially and mixed model is done. To measure the stress shielding effect, volume average of equivalent stress is used as a parameter. It was found that radially varying prosthesis design was best suitable among the developed models.**

***Index Terms*—Heterogeneous modeling and stress shielding**

I. INTRODUCTION

HETEROGENEOUS objects are objects composed of different constituent materials and could exhibit continuously varying composition and/or microstructure, thus, producing gradation in their properties [1]. Heterogeneous objects are believed to possess superior properties in the applications where multifold functional requirements are simultaneously expected. By incorporating material heterogeneities into the design domain, anisotropic properties could be obtained. These different properties and advantages of various materials could be fully exploited and traditional limitations due to materials incompatibilities can be alleviated with gradual material variation [2]. Due to unique features and advantages, heterogeneous objects have gained great popularity in numerous applications, like design of mechanical components, e.g., turbine blades, flywheel, crank hook and stepped pulley; design of high-efficiency engine components, biomaterials used artificial human implant; drug delivery devices with release rate control; armor and armament components, etc. [3]-[5]. Fig. 1 represents the examples of the heterogeneous modeling.

The integration of computer aided design (CAD) and medical technology is referred as bio-CAD. CAD based virtual environment not only helps to ease the design and analysis of the implant but also greatly reduced the effort in pre-surgical planning and training. Bio-CAD is widely used in many applications such as computer aided surgery, structural modeling of tissue, in designing of orthopedic devices and implants, in designing of tissue scaffolds and freeform fabrication, and bio-manufacturing [6].

Natural materials such as bone could be considered as heterogeneous objects [7]. Bones is a composite structure consisting of hydroxyapatite and collagen as organic and inorganic components [8], with variation in densities, porosities, stiffness and strength in cortical and trabecular bones [9]. Like other materials, bone accumulates damage from loading, but unlike engineering materials, bone is capable of self-repair [10], by a process called bone remodeling which involves sequential osteoclast-mediated bone resorption and osteoblast-mediated bone formation at the same location [11].

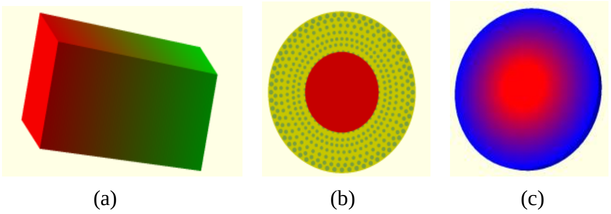


Fig. 1. Examples of heterogeneous objects

Use of computer aided design/computer aided manufacturing (CAD/CAM) and rapid prototyping (RP) technologies to fabricate physical models of hard tissues, tissue scaffolds, and custom made tissue implant prosthesis has provided advancements and opened new avenues in the domain of medical technology [12]. With the shift in both lifestyle and technology, people are more prone to suffer from bone related diseases, due to increase in accidents, osteoporosis, osteolysis and fracture. So, demands for bio-implants with long-term stability and performances have become significant. Besides infection, aseptic loosening between bone and implant is the major post-surgery concern. Stress shielding is one of the major causes of aseptic loosening [13]. The implant stem can be optimized using a stiffness optimization involving elastic modulus distribution with an aim to reduce the stress shielding [14].

The objective of this work is to model and analyze different heterogeneous models of the total hip prosthesis with various patterns of material variations with some simplification in the geometrical design. The developed models are compared based on stress shielding effect to identify the optimum model.

II. METHODOLOGY

To avoid aseptic loosening between bone and implant, stress-shielding phenomenon must be minimized. Stress shielding in femur occurs when majority of the load is taken by prosthesis and bones are spared, which may cause a decrease in bone mass due to the applicability of Wolff's law

Manuscript received May 29, 2017; revised June 07, 2017.

Sudhir Kumar Singh is with PDPM Indian Institute of Information Technology, Design and Manufacturing, Jabalpur, M.P. 482005 India. (e-mail: sudhirksingh@iiitdmj.ac.in)
Puneet Tandon is with PDPM Indian Institute of Information Technology, Design and Manufacturing, Jabalpur, M.P. 482005 India, Jabalpur, India. (corresponding author phone +91-761-2794411; fax: +91-761-2794411, e-mail: ptandon@iiitdmj.ac.in)

[15], this is also known as bone resorption, which may lead to the loosening of the implants. The effect of stress shielding is calculated by the following formula

$$\text{Stress shielding effect} = \frac{(\sigma_{vms}^{pre-THA}) - (\sigma_{vms}^{THA})}{(\sigma_{vms}^{pre-THA})} \quad (1)$$

Where, $\sigma_{vms}^{pre-THA}$ is the average volume von Mises stress in the intact femur, i.e., before Total Hip Arthroplasty (THA) and σ_{vms}^{THA} is the average volume von Mises stress in the femur where the implant was introduced, i.e., after the THA. Average volume equivalent stress is given by

$$\text{Average volume equivalent stress} = \frac{\Sigma(\text{Volume of each element}) * (\text{Equivalent stress on each element})}{\Sigma(\text{Volumeofeachelement})} \quad (2)$$

Since the von Mises stress is strictly non-negative, positive stress difference value indicates decrease of stress in post-THA situation, i.e., stress shielding. On the contrary negative value of the stress shielding effect indicates an increase in stress when the prosthesis is present and thus, it can be interpreted as a measure of stress concentration, especially if the actual stress in the bone exceeds yield strength or physiological based threshold [16].

The main cause of the stress shielding phenomenon is the large difference between the stiffness of the bone and the implant [17]. If the two materials are bonded and equal forces applied to both, then by applying the strain equality and Hooke's law in both bars, the load shared in each part of the composite will be [18].

$$F_i = \frac{A_i E_i F}{A_i E_i + A_b E_b} \qquad F_i = \frac{A_b E_b F}{A_i E_i + A_b E_b} \quad (3)$$

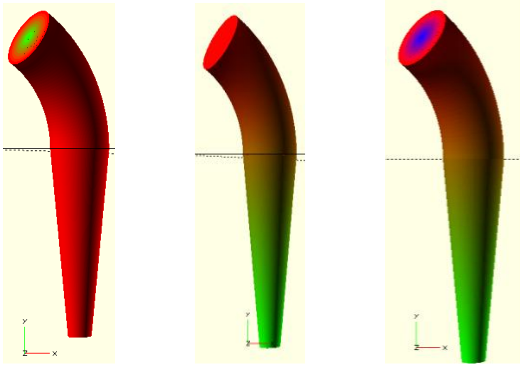
Where, the subscript *i* denotes the implant and *b* denotes the bone.

Further,

$$\frac{F_i}{F_{normal}} = \frac{A_i E_i}{A_i E_i + A_b E_b}; \quad \frac{M_i}{M_{bending}} = \frac{I_i E_i}{I_i E_i + I_b E_b} \quad (4)$$

Where, $\frac{F_i}{F_{normal}}$ is the normal load shared by implant under axial load and $\frac{M_i}{M_{bending}}$ is the transverse load shared by implant under bending loads. From equations (3) and (4), it is observed that the load shared by the prosthesis and the bone in composite loadings depends upon the respective stiffness. Higher stiffness of the prosthesis will lead to more load being shared by the prosthesis and will eventually cause more stress shielding.

Thus, by reducing the overall stiffness of the implant by varying the stiffness using two or more materials according to the distribution of the load on the implant, one can reduce the stress shielding effect. The portion of the implant where the stresses are higher would have higher stiffness values compared to low stress zone. For this purpose, stem hip prosthesis has been modeled heterogeneously. Some design simplification has been considered and the model is generated in open source, OpenSCAD. Three variants of implant model had been developed with radial, axial and mixed (simultaneous radial and axial) material variations. In these models, the properties like stiffness, density and Poisson's ratio are varied. Fig. 2 represents the radial, axial and mixed models of hip prosthesis.



(a) (b) (c)

Fig. 2. Heterogeneous modeling of prosthesis with (a) radial, (b) axial and (c) mixed (combined radial and axial) models

For radial variation of the materials, regions along the periosteal surface are more loaded due to bending and torsion in combined loading, so the stiffness in the models decreases as we move towards the center. For axial variation of the materials the stiffness decreases as one moves from proximal end to distal end [18]. The stiffness decreases as one moves towards distal end. While varying the material one need to take care that the too low stiffness of the stem increases stress concentration at the interface between the implant and the femur, which decrease the stability of the implant [19].

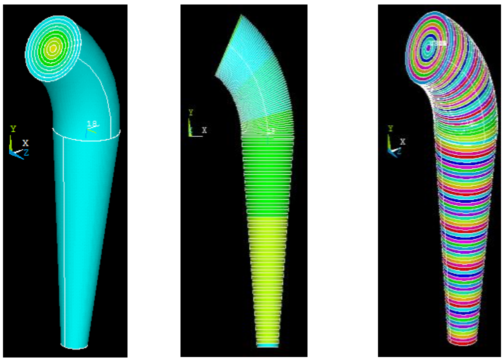
The implant should possess material properties like it should be non-toxic, inert, high corrosion resistance, non-magnetic, biocompatible, have suitable mechanical properties and promotes osseo-integration [20]. The choice of materials that are considered in this study and their approximate properties [21] are given in Table I.

TABLE I
MATERIALS AND ITS PROPERTIES

Material	Young's Modulus (GPa)	Tensile Strength (MPa)	Poisson's Ratio	Density (kg/m^3)
Ti64	110	900	0.32	4500
TMZF	75-85	1030	032	5000
TNZTO	66	1010	034	5600

The loading on the femur is complex which in include bending and torsion besides normal and shear loads at various position and movement of the body. In this study, static analysis of the model is carried out, for which a load of 3 kN (F_{static}) at an angle of 20° is applied on the surface of the implant. An abductor muscle load of 1.25 kN (F_{abdm}) is applied at an angle of 20° representing the equivalent weight of 70 kg [18]. To simplify the analysis only implant is considered rather than bone implant composite. The distal end of the implant has been fixed.

For analysis of the models, coding was done in ANSYS Mechanical APDL and SOLID 187, 3D 10 nodes tetrahedral structural solid element was used. Fig. 3 represents the color and pattern variation along radial and axial direction of model.



(a) (b) (c)

Fig. 3. ANSYS APDL models with color and pattern variations in (a) radial, (b) axial (c) mixed models

III. RESULTS AND DISCUSSIONS

The major objective of the work was to compare different heterogeneous prosthesis to minimize stress-shielding phenomenon. Through heterogeneous modeling the stiffness of the prosthesis was optimized by varying the material stiffness according to load distribution. Average volume von Mises stress in each of the models was calculated using APDL coding in ANSYS. The intact femur volume stress varies at different locations in the femur and variation of stress also depend upon the weight, age, gender, health status of the individuals and current body positioning. This work assumes the intact femur average volume von Mises stress as 8 MPa, as the stress in femur varies between 1-17 MPa at various location during various actions [22]. Results of stress variation for different models are presented with the help of Fig. 4.

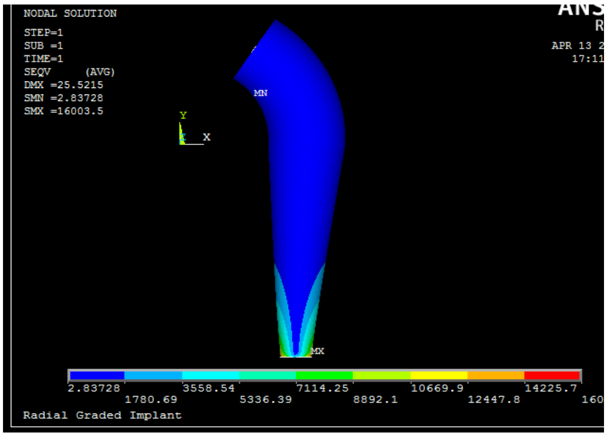


Fig. 4(a). Stress variation in radial model

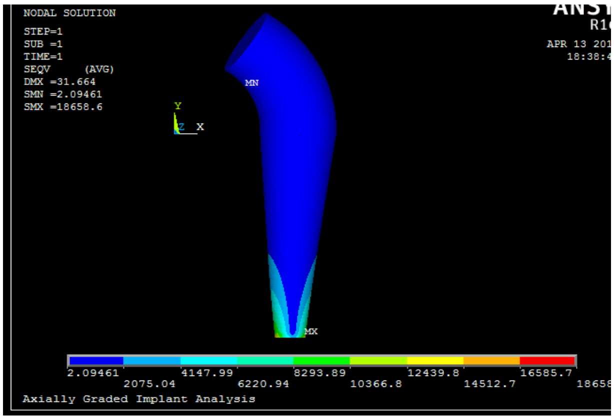


Fig. 4(b). Stress variation in axial model

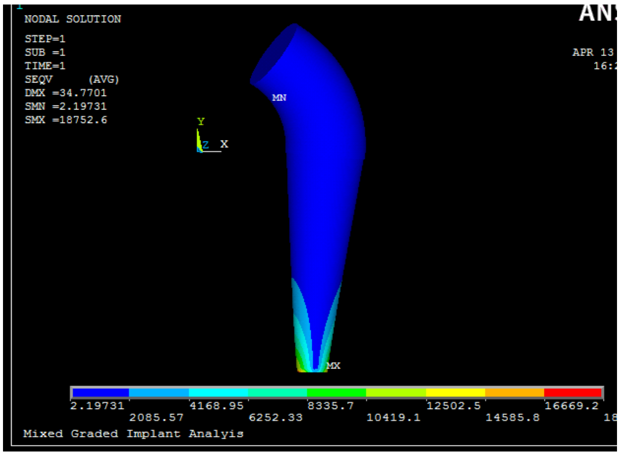


Fig. 4(c). Stress variation in mixed model

Although the stress variation in all the three models shows similar behavior but quantitatively they differ under the state of loading. The distal end of the prosthesis has highest stresses. Similar stress distribution is observed in [23]. It can be observed that there is symmetry in stress distribution. This may be because the prosthesis behaves like a cantilever beam as the distal end of the prosthesis is fixed. Fig. 5 represents the average stress variation in different models. Fig. 6 represents the stress shielding effect in each model, which is calculated with the help of equation (1).

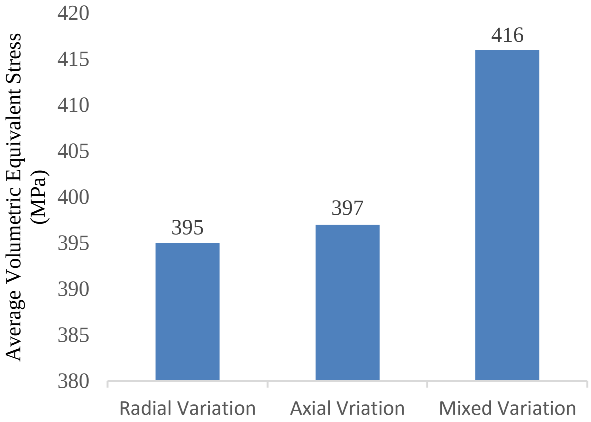


Fig. 5. Average volume equivalent stress values for different models

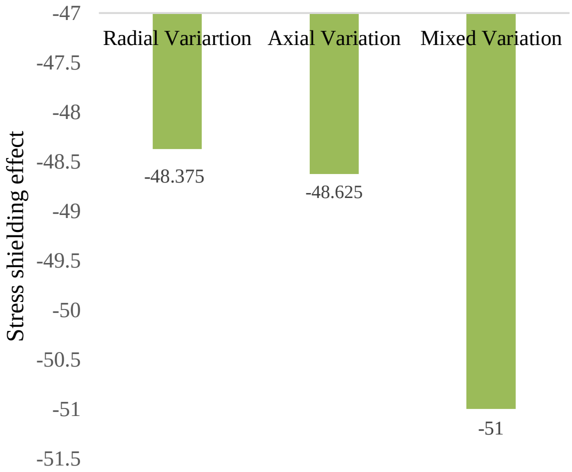


Fig. 6. Stress shielding effect in different models.

It is observed that that the radial variation implant has the least average volumetric equivalent stress and mixed variation implant has the highest. These variations in the stresses indicate that the stress concentration was highest for the mixed implant. From the results, it could be observed that difference in average volume equivalent stresses between radial and axial heterogeneous prosthesis are negligible compared to that of the mixed heterogeneous prosthesis. This difference could be due to the fact that for mixed heterogeneous prosthesis meshing might be improper due to sudden and large variation in element properties. This work would help the engineers and medical practitioners to improve the design of prosthesis.

IV. CONCLUSION

By comparing the radial, axial and mixed heterogeneous prosthesis from the point of stress shielding by taking average volume equivalent stress as a decision-making parameter, radial variation prosthesis was observed to be the most suitable among the three models. Further, merely comparing the models based on stress shielding effect is not sufficient to select the prosthesis model. If fatigue loading and frictional contact between the bone and prosthesis is included, the design would be further improved. Further, by comparing it with experimental results and including factors like micro-motion, interface-stress and bone ingrowth would add value to the work. Manufacturing of heterogeneous prosthesis possesses a new challenge and opens possibility for evolving processes such as additive manufacturing to utilize its full potential. Economic viability is another area that needs to be studied while selecting the process, material and the design parameters.

REFERENCES

[1] Kumar, V., Burns, D., Dutta, D., Hoffmann, C., "A framework for object modeling." *Computer-Aided Design*, *31*(9), 541-556, 1999.

[2] Kou, X. Y., Tan, S. T., "Heterogeneous object modeling: A review." *Computer-Aided Design*, *39*(4), 284-301, 2007.

[3] Ozbolat, I. T., Koc, B., "Multi-directional blending for heterogeneous objects." *Computer-Aided Design*, *43*(8), 863-875, 2011.

[4] Gupta, V., Tandon, P., "Heterogeneous object modeling with material convolution surfaces." *Computer-Aided Design*, *62*, 236-247, 2015.

[5] Shin, K. H., Natu, H., Dutta, D., Mazumder, J., "A method for the design and fabrication of heterogeneous objects." *Materials & Design*, *24*(5), 339-353.

[6] Yoo, D. J., "Three-dimensional human body model reconstruction and manufacturing from CT medical image data using a heterogeneous implicit solid based approach." *International Journal of Precision Engineering and Manufacturing*, *12*(2), 293, 2011.

[7] Cheng, J., Lin, F., "Approach of heterogeneous bio-modeling based on material features." *Computer-Aided Design*, *37*(11), 1115-1126, 2005.

[8] Pan, M., Kong, X., Cai, Y., Yao, J., "Hydroxyapatite coating on the titanium substrate modulated by a recombinant collagen-like protein." *Materials Chemistry and Physics*, *126*(3), 811-817, 2011.

[9] Osterhoff, G., Morgan, E. F., Shefelbine, S. J., Karim, L., McNamara, L. M., Augat, P., "Bone mechanical properties and changes with osteoporosis." *Injury*, *47*, S11-S20, 2016.

[10] Robling, A. G., Castillo, A. B., Turner, C. H. "Biomechanical and molecular regulation of bone remodeling." *Annu. Rev. Biomed. Eng.*, *8*, 455-498, 2006.

[11] Allen, M. R., Burr, D. B., "Bone modeling and remodeling. In *Basic and Applied Bone Biology*." Elsevier Inc., 2013

[12] Sun, W., Lal, P., "Recent development on computer aided tissue engineering—a review." *Computer methods and programs in biomedicine*, *67*(2), 85-103, 2002.

[13] Joshi, M. G., Advani, S. G., Miller, F., Santare, M. H., "Analysis of a femoral hip prosthesis designed to reduce stress shielding." *Journal of Biomechanics*, *33*(12), 1655-1662, 2000.

[14] Saravana Kumar, G., George, S. P. "Optimization of custom cementless stem using finite element analysis and elastic modulus distribution for reducing stress-shielding effect." *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, 0954411916686125, 2017.

[15] Ridzwan, M. I. Z., Shuib, S., Hassan, A. Y., Shokri, A. A., Ibrahim, M. M., "Problem of stress shielding and improvement to the hip implant designs: a review." *J. Med. Sci*, *7*(3), 460-467, 2007

[16] Fraldi, M., Esposito, L., Perrella, G., Cutolo, A., Cowin, S. C., "Topological optimization in hip prosthesis design." *Biomechanics and modeling in mechanobiology*, *9*(4), 389-402, 2010.

[17] Xie, F., He, X., Ji, X., Wu, M., He, X., Qu, X., "Structural characterisation and mechanical behaviour of porous Ti-7.5 Mo alloy fabricated by selective laser sintering for biomedical applications." *Materials Technology*, *32*(4), 219-224, 2017.

[18] Oshkour, A. A., Osman, N. A., Bayat, M., Afshar, R., Berto, F., "Three-dimensional finite element analyses of functionally graded femoral prostheses with different geometrical configurations." *Materials & Design*, *56*, 998-1008, 2014.

[19] Hedia, H. S., Fouda, N., "Design optimization of cementless hip prosthesis coating through functionally graded material." *Computational Materials Science*, *87*, 83-87, 2014.

[20] Chen, Q., Thouas, G. A. "Metallic implant biomaterials." *Materials Science and Engineering: R: Reports*, *87*, 1-57, (2015).

[21] Geetha, M., Singh, A. K., Asokamani, R., Gogia, A. K., "Ti based biomaterials, the ultimate choice for orthopaedic implants–a review." *Progress in materials science*, *54*(3), 397-425, 2009.

[22] Alonso-Rasgado, T., Jimenez-Cruz, D., Bailey, C. G., Mandal, P., Board, T., "Changes in the stress in the femoral head neck junction after osteochondroplasty for hip impingement: a finite element study". *Journal of Orthopaedic Research*, *30*(12), 2012.

[23] Senalp, A. Z., Kayabasi, O., Kurtaran, H., "Static, dynamic and fatigue behavior of newly designed stem shapes for hip prosthesis using finite element analysis." *Materials & design*, *28*(5), 1577-1583, 2007.