The Effect of Hollow Sphered Structure on Stress Shielding Reduction

Mohammadreza Yazdifar
Ibrahim Esat
Brunel University, UK
Mahshid Yazdifar
Coventry University, UK

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Abstract

Bone mechanics and traditional implant materials cause a frequent problem for patients of total hip arthroplasty (THA): the bone becomes shielded from the loading. This will result in loosening of the implant, pain, and therefore revision surgery will take place to correct the issue. The current study, a methodology is developed for creating an innovative structural design that extracts volume in the shape of spheres from the samples, in order to focus solely on expected behaviour within the samples and bone. The design decreases extreme stresses carried by samples and pass them onto the remaining bone. Finite element analysis was applied to various models with different complex internal structures that contain hollow spheres close to surface. Moreover, compression test was applied to solid sample and the experimental case containing hollow spheres. This approach was to investigate the effects of spherical hollow structure near the side surface and its bone-sample interface. The models containing hollow spheres have smaller young modulus and strength in comparison to the solid sample. The hollow spherical structures reduce the stress shielding and they transfer more stress onto the bone compared to the solid model. This approach also re-structures a hard material such as stainless steel to enhance osseointegration. The reduction of the young modulus and stress directly depends on the volume of the spheres in the models. However, there is a range defined for the volume that could be extracted from solid structure to achieve the most effective outcome.

Keywords: Hollowed Structure, Implant Design, Stress Shielding

Introduction

The current materials used in biomedical engineering could not compete with the material properties of the bone (Thielen, et al., 2009). The main biomedical metals used for medical applications are Stainless steel, Cobalt alloys and Titanium alloys (Niinomi, 2008) (Karanjai, Sundaresan, Rao, Mohan , & Kashyap, 2007). Titanium alloys used in femoral stems have certain problems while producing and articulating surfaces are no longer recommended for biomedical applications (Zhang, 2009).

One of the most important failure parameters that all implants face is stress shielding (Bitsakos, Kerner, Fisher, & Amis, 2005), (Sumner & Galante, 1992). However, flexible stems decrease bone resorption if the interface bond is strong. It could be concluded that flexible stems are the solution to bone resorption but it may also result in increased loosening rates (Huiskes, Weinans, & van Rietbergen , 1992) (Diegel, Daniels, & Dunn, 1989). Implant stiffness depends on implant material and its cross sections.

There are studies (Mattheck, Vorberg, & Kranz, 1990), (Schmidt & Hackenbroch, 1994), (Chang , et al., 2001) (Ridzwan, Shuib, Hassan, Shokri, & Mohamad Ibrahim, 2007) regarding factors which could lead into stress shielding reduction.

A study in 2001 focused on optimising a hollow structure stem to decrease stress shielding and also decreased the maximum stress in cement. In this study, the inner diameter was the variable and cement stress was defined as the design constraint. The obtained results were compared with a solid structure stem, but, the implant was only cylindrical with simple boundary conditions. The stem with hollow structure showed an increase in proximal bone stress about 15% and it was 32% for the case with high strength cement (Gross & Abel, 2001).

There have been two approaches about the relation between porosity and young modulus that when porosity goes up, Young's modulus will decrease. In these studies, the cellular implant has a structure like a spongy bone and it acts nearly as a solid femoral stem. The cellular implant demonstrated a rise in the load-transfer mechanism in comparison to the solid one. Therefore, metal foams may cause longer period for stress shielding to happen (Rahman & Mahamid, 2002) (Smith, Szyniszewski, Hajjar, Schafer, & Arwade, 2012).

Finally, honeycomb geometries were added to the stems design in new total hip replacement implants. These geometries were analysed using finite element method and auxetic stems showed reduction in stress shielding effect (Sanami, 2015).

As the above studies show, stress shielding is a major problem that reducing the young modulus could solve the issue. One of the ways to reduce the young modulus is to have porous structure.

The aim of this paper is to develop the idea of having hollow voids near the surface to reduce the localised stress on samples and increase the stress on the surrounding area which is bone. This paper focuses on verifying if hollow sphered structure near surface will decrease stress shielding. In addition, this paper also identifies the best configuration in terms of the sphere size and their distribution within the mass. Having reduced young modulus improves displacement, as the displacement increases; more stress will transfer onto the surrounding area which in this study is bone. The purpose of having the spheres near the surface is to transfer the stress to the surrounding areas to reduce stress shielding and at the same time having solid centre to maintain the strength of the structure. Furthermore, having empty spheres near the surface helps the stress inserted to be distributed evenly to the surrounding bone. FEA and experiments were used to investigate theses effects under specific load. This study was designed to evaluate whether these structure decreases stress shielding by altering the size and distribution of spheres. The spheres in each sample have been placed uniformly in each row close to the surface.

Method

Study of 3-dimentional designs

Cylindrical samples with radius of 30mm and the height of 20mm were created. As it is shown in figure 1, the outer layer of the cylinders contain empty spheres. The centre of the cylinders is solid with a radius of 20 mm. Cases were created based on the distance from surface, distance from each other, number and size of spheres. These parameters were defined to see the effect of them on young modulus, stress in bone and implant.

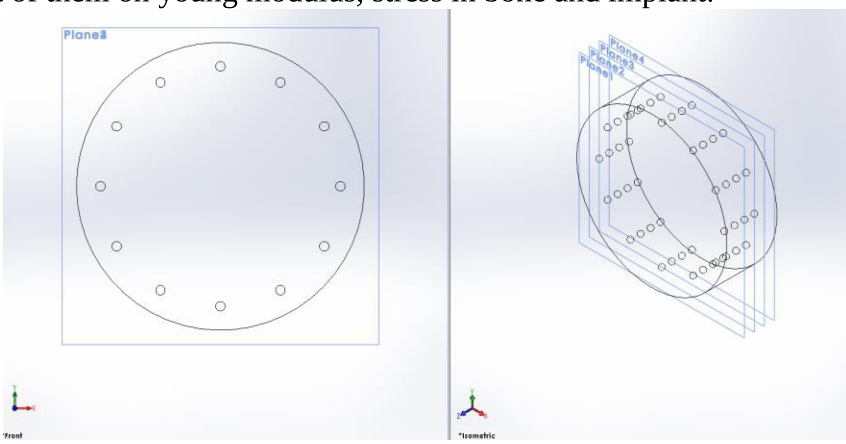

Figure 1: Schematic view of the hollow shell cylinder

There were 11 samples that were designed in this paper. Table 1 summarises different cases according to the hollow voids distribution, sizes and numbers. Samples 9 and 10 were solid samples without voids. Sample 9 is solid stainless steel and sample 10 is solid Titanium. Sample 11 is the experimental sample.

Table 1: Various designs based on distribution and sphere size

Different cases	Size of spheres (mm)	No of Spheres	Width of hollowed spheres close to surface	Distance from each other vertically	Distance from surface mm
Sample 1	1	4x24	10 mm	4 mm	3
Sample 2	1	3x24	10 mm	5 mm	3
Sample 3	1	3x24	10 mm	5 mm	2
Sample 4	1	3x24	10 mm	5 mm	5
Sample 5	1	3x24	10 mm	5 mm	3
Sample 6	1	3x12	10 mm	5 mm	3
Sample 7	1	3x24	10 mm	5 mm	5
Sample 8	2	3x24	10 mm	5 mm	5
Sample 9 (Solid Steel)	-	-	-	-	-
Sample 10 (Solid Titanium)	-	-	-	-	-
Sample 11	1	4x12	10 mm	4 mm	5

FEA Simulation

FEA simulation was carried out in Abaqus to comparison the stress distribution in bone and samples. The samples are created according to the Table 1.

Cylinder material

Three different material properties have been used in running simulations. The mechanical properties used in simulations for two cylinders and bone are listed in Table 2:

Table 2: Mechanical properties of common biomaterials (Sabatini & Goswami, 2008)

Material	Elastic modulus (GPa)	Ultimate tensile strength (Mpa)	Poisson's ratio	Density (g/cm^3)
Ti6Al4V	114	900	0.32	4.4
316L SS	200	1000	0.3	7.9
Cortical bone	20	130	0.3	2.0

Force and pin area

Figure 2 shows where the stress was inserted and where the model was pinned. The pressure inserted for cylinders was 5 MPa. The figure also demonstrates the pinned area which is at the bottom of the empty cylinder.

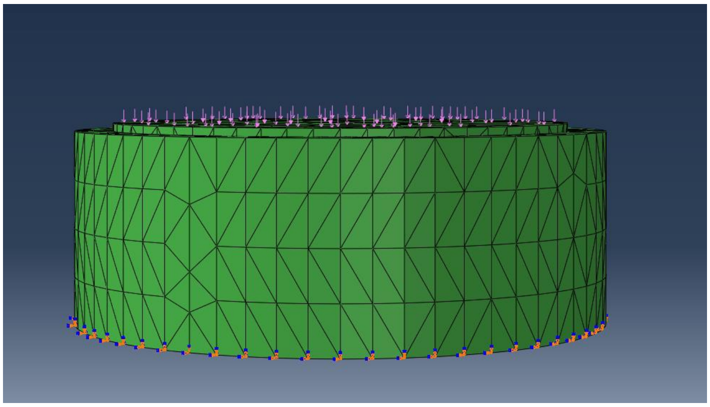

Figure2: Force and pin area

Experiment to validate the FEA results

Two cylinders were printed using in 3D printing lab. One cylinder contained hollow spheres close to the surface (sample 11) and the other one was solid. The experiment was carried out to compare stress-strain graphs of hollow shell structures with solid structure. Furthermore, these tests were carried out to justify the structure. A strain gauge was attached to each cylinder to calculate the strain and the stress inserted to the surrounding areas.

Results

Table 3 summarises the results of FEA based on von Mises stress distribution in bone and cylinders. It is shown that the von Mises stress reduces in comparison to the solid one. However, it is still higher than Titanium. In addition, the results indicate that the stress in bone-implant interface increases compared to the solid stainless steel. On the other hand, it is still lower than Titanium.

Table 3: Von Mises stress results for different study cases

Different cases	Bone (MPa)	Bone near cylinder (MPa)	Cylinder (MPa)
Sample 1	1.45-2.34	2.8-3.9	10-15
Sample 2	1.1	1.59	6-11
Sample 3	1-2.65	2.65-3.5	10-15
Sample 4	1-2	2-4	7-12
Sample 5	1	1.7	7-13
Sample 6	1	1.7	4-10
Sample 7	0.8-2	2-4	6-10
Sample 8	1.1-1.7	1.7-2.5	3-10
Sample 9	2-4	4-5.3	3.6-7
Sample 10	0.05-1	1.1-2.2	4.3-10
Experiment Sample	2-3	2.24	6-9

Figure 3 displays finite element analysis for hollow spheres in the shell (close to the surface) of cylinder and solid structure. At each node, the stress is compared and as it is shown, the stress in bone for the solid structure is less than hollow structure. This could be counted as an effect of hollow spheres structure on stress shielding.

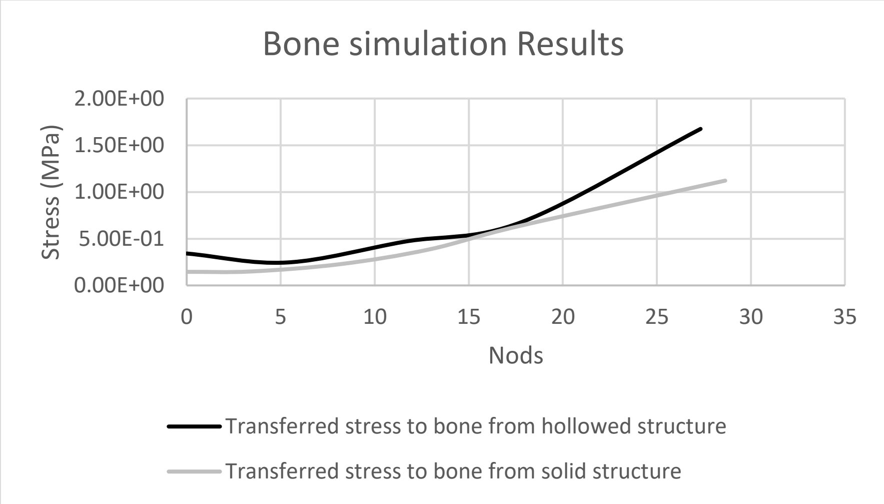

Figure 3: Transferred Stress to bone from two specimens

Figure 4 displays experimental results for hollow spheres in the shell (close to the surface) of cylinder and solid structure. The strain and stress of the samples were measured. Experimental results are confirming that having hollow spheres close to the surface reduce the young modulus compare to the completely solid model. A reduction in the young modulus was observed when hollow spheres were added to the solid mass close to the surface. Reduction of the young modulus helps higher stress to be transferred onto the bone in comparison to the solid model.

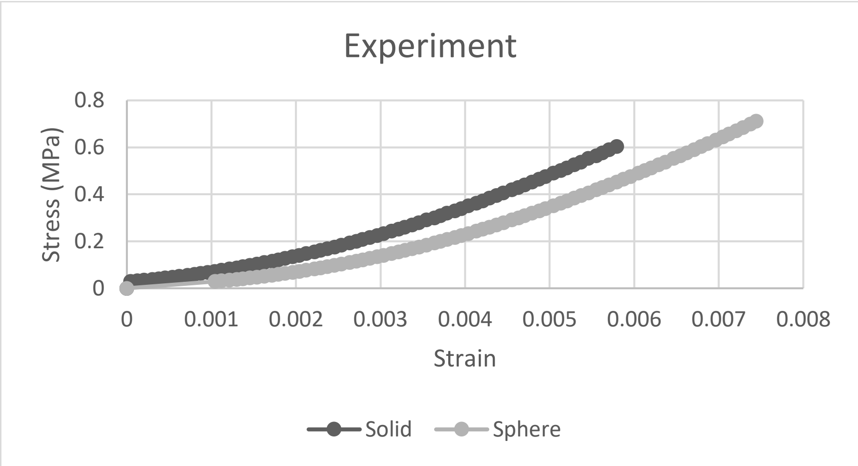

Figure 4: Stress-strain graph of solid and hollowed spheres closed to the surface structure

The results obtained from computational and experimental methods, confirms the reduction in young modulus in hollow shell cylinders. The decrease in young modulus causes higher strain at the same applied stress. Therefore, the higher the strain, the higher the stress will transfer onto the surrounding bone from cylinders.

Conclusion

In conclusion, this study has represented that having hollow spheres in a solid mass reduces Young's modulus. The limitation of this study was manufacturing process for experimental sample creation, due to the small amount of debris left inside each hollow spheres. Moreover, the hollow sphered (closed to the surface) structure improves the stress at the cylinder-bone interface. As the extracted volume is similar in all the cases, FEA results visualisation were almost similar. However, the sphered samples were not as sufficient as titanium, but better than solid stainless steel. Moreover, the samples 1 and 3 demonstrated larger stress-transfer onto the surrounding bone, the stress in sample 1 is 3.9 MPa and in sample 3 is 3.5 MPa. Whereas, the stress in solid titanium is 5.3 MPa, and in solid stainless steel is 1 MPa. To conclude, it is observed that in sample 1, the spheres are closer to each other in terms of their horizontal distance, and the spheres are closer to the surface in sample 3. Therefore, closer spheres to each other and surface result in larger stress-transfer onto the surroundings. The future work should focus on applying the structure on actual hip implant to compare the effect on stress shielding caused by titanium and hollow stainless steel structure.

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