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Effect of cavity-defects interaction on the mechanical behavior of the bone cement

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Abstract. The presence of cavities in the bone cement has a great importance for the transport of antibiotics, but its existence in this material can lead to its weakening by notch effect. The aim of this study allows providing a physical interpretation to the cavities interconnection by cracks observed experimentally. The most important stress of Von Mises is localized at the cement/bone interface near the free edge which is the seat of stress concentration. The presence and interaction of cavities in this site concentrate, by notch effect, stresses which tend to the tensile fracture stress of Bone cement.

Keywords: bone cement (PMMA); porosity; interaction; stress concentration

1. Introduction

The bone cements are composed of two components, polymer powder and liquid monomer, which can be mixed with different methods. Depending on the mixing method, this process sometimes generates air voids in the cement (Ayatollahi and Karimzadeh 2012). Another common method for mixing the bone cement components is vacuum mixing in which the polymer powder and liquid monomer are mixed with vacuum pressure. This method is expected to reduce the porosity in the bone cement (Dunne and Orr 2001). The formation and development of microvoids, usually plays a dominant role in the damage and fracture of bone cement. The major problem associated with the presence of flaws due to pores and additives is that when a critical flaw size is achieved, the flaws act as sites of stress concentration, leading to weakening of the cement. The Griffith crack criterion stipulates that there exists a critical flaw size is 70μm. Thus, porosity alone would not compromise the fracture strength of bone cement, especially if all the pores were smaller than the critical flaw size for PMMA. But the size of the pore and their distribution are expected to strongly affect the fracture strength if some of the pores exceed the critical flaw size for PMMA (John *et al*. 2007). Pores at the interface between the cement and femoral stem can also act as sites of stress concentration, with the potential for crack emanating from micropores initiation; the number of these pores can be decreased by preheating the femoral stem

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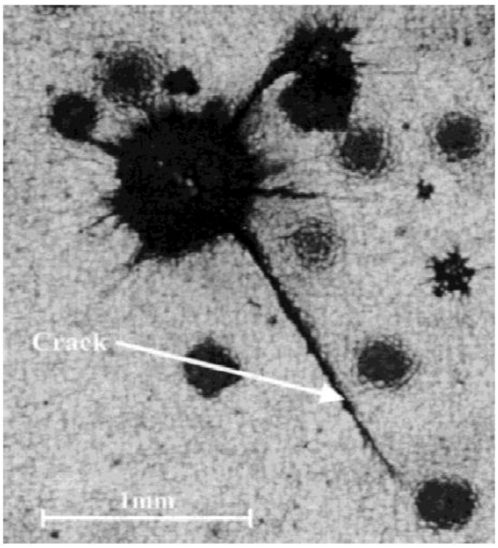


Fig. 1 Cracks in acrylic bone cement observed under transmitted light

(Bachir Bouiadjra *et al*. 2007, Benbarek *et al*. 2007, Bouziane *et al*. 2010, Spears *et al*. 2001, Katzer *et al*. 2008, Achour *et al*. 2010), but the interaction between these defects has not been studied too, which is the aim of our work. These defects can also act as sites of stress concentration which the level reaches or exceeds, locally, the tensile strength of the cement (Murphy and Prendergast 2001): see Fig. 1. This level can lead to the fracture of the joint bone/implant and therefore the loosening of the prosthesis. To do this, the finite element method was used to analyse the effect of cavities, in the cement mantle binding the cup to the bone, on the level and distribution of the normal stresses and Von Mises.

2. Materials and methods

2.1 Geometrical model

The analysed model is composed of the cortical shell of the iliac outer layer with a constant thickness of 0.9 mm (Spears *et al*. 2001). The trabecular bone was merged into the cortical bone. A polyethylene cup with an internal diameter was 28 (mm) and external diameter of 54 mm was secured by PMMA into an acetabulum with a diameter of 56 (mm). The thickness of cement bone was 2 mm (Tong and Wong 2005). Figs. 2(a)-(b) present the geometrical model of the reconstructed acetabulum.

2.2 Materials properties

The commercially available total hip acetabular components, which consisted of a titanium alloys femoral head, a polyethylene acetabular cup and acrylic cement due to their wonderful biocompatibility behaviour in clinical conditions. All the materials were assumed to be linearly

(a) (b)

(a)Latero-medial view of the solid model

(b) Antero-posterior view of the pelvis and acetabular component

Fig. 2 Composition of a reconstructed acetabulum

isotropic and homogeneous. This is a reasonable assumption since the stresses are not enough high to create a plastic deformation of the polyethylene. Table 1 (Benbarek *et al*. 2007) gives the elastic properties of the five materials: of prosthetic femoral head, cup, cement, cortical and trabecular bone.

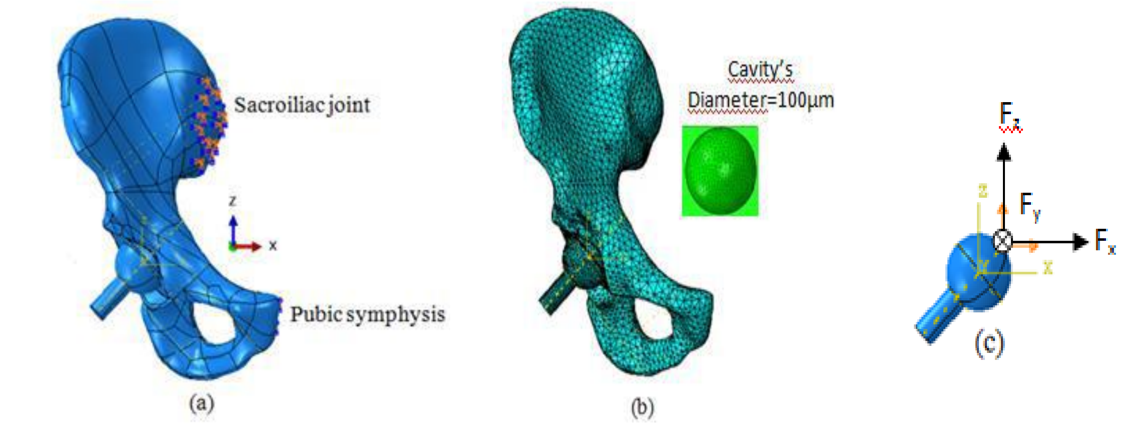
It is known that in general, cement do not resist well to tensile loading. The tensile strength of the cement is 25MPa, the compressive strength is 80MPa and the shearing strength is 40MPa (Merckx 1993).

2.3 Finite element model

Computational methods such as finite element method are widely accepted in orthopaedic biomechanics as an important tool used to design and analysis the mechanical behaviour of prosthesis (Nocollela 2001). Three-dimensional finite element model of reconstructed acetabulum was developed from the commercial FE code ABAQUS (Abaqus Ver 6-9 2008) of a right pelvic bone. The elements of 4-node tetrahedron are used to mesh the structure. In total, there were 23541 nodes and 110919 linear tetrahedral elements of type C3D4 in the mesh models without cavities and 28801 nodes and 132390 elements with cavity: see Fig. 3b. A special mesh refinement is used around the cavity with the aim of increasing the precision of calculations.

2.4 Loading conditions

The hip contact force with the amplitude F is applied to the centre of the femoral head: see Fig. 3a. The three force components medial (F_x)-ventral (F_y)-proximal (F_z), in static analysis, were measured in the “femur coordinate system” X; Y; Z of the femur right: see Fig. 3c. It is transmitted by the femoral head to the cement across the acetabular cup. The z-axis is the idealized straight midline of the femur; x is perpendicular to z and parallel to the transverse plane, the y-axis points in the Antero-posterior direction. The average body weight (BW) was F = 233%BW with F_x = 52%BW; F_y = 32%BW and F_z = 225%BW (Bergmann *et al*. 2001).



(a)Boundary condition and directions of forces applied to the center of femoral head

(b)Meshed model of the pelvis and acetabular component

(c) The three force components (F_x, F_y, F_z)

Fig. 3 Antero-posterior view of the model

Table 1 Material properties

Materials	Young's modulus (MPa)	Poisson's ratio (ν)
Cortical bone	17000	0.3
Spongious bone	1 to 132	0.2
Subchondral bone	2 000	0.3
PMMA	2 300	0.3
UHMWPE	690	0.3
Titanium alloy	210 000	0.3

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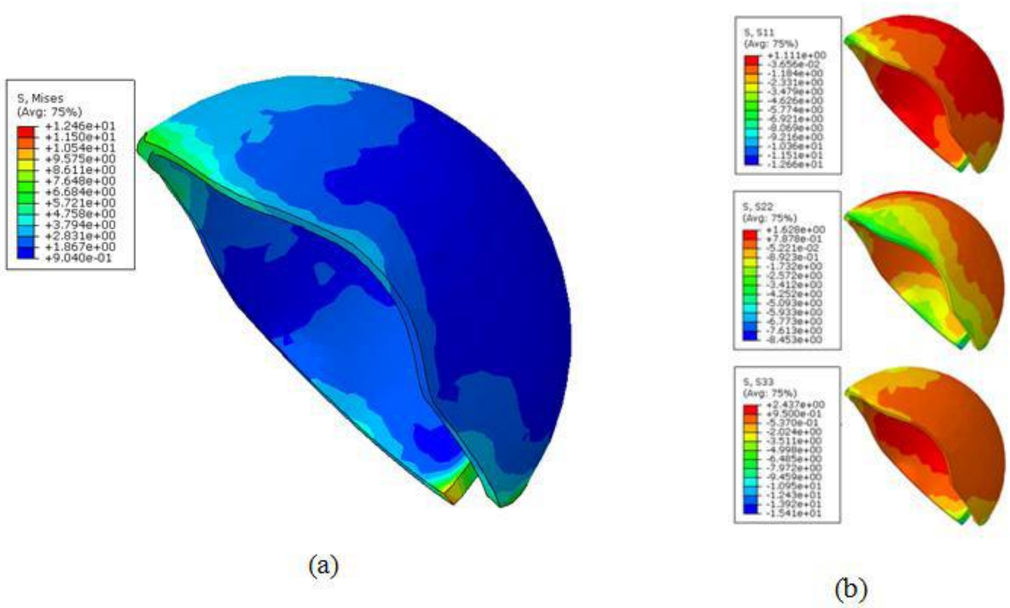
We opted for the orientation 0° of the neck femoral head compared to the cup axis that reflects the standing position of the human body. Nodes at the sacroiliac joint and the pubic symphysis were fixed in all degrees of freedom as the boundary condition (Spears *et al*. 2001, Bergmann *et al*. 2001). The contacts bone/cement and cement/cup were fully tied. That of femoral head (metal)/cup (UHMWPE) having a friction coefficient of 0.25 (Kusaba 2004). This contact was assumed to be the tangential and normal behaviour.

3. Results

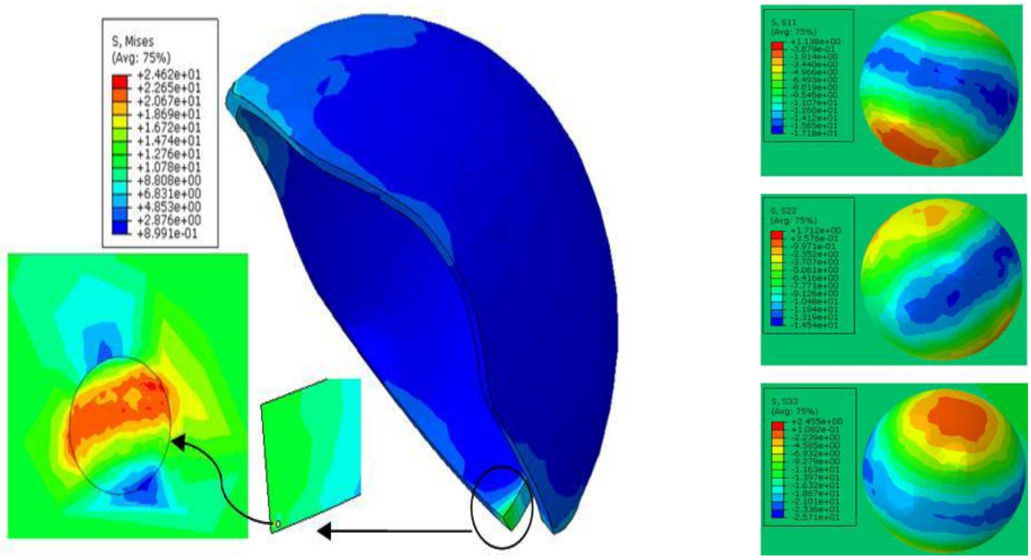
The aim of this study is to analyse, by the finite element method, the level and distribution of Von Mises stress in the bone cement between the cavities based on their inter-distance and their location. To illustrate this effect, the distribution and the intensity of the stress generated in perfect and porous cement are analysed.

3.1 Stress distribution in the cement

Figs. 4(a) and (b) illustrate that this stress is not distributed homogenously in the cement. There are areas located close to the edge at the interface with the bone, are strongly mechanically stressed. They are the seat of stress concentration. The cement is subject to both the normal



(a)Von Mises stress (b) Normal stresses
Fig.4 Stress level and distribution in the cement



(a)Von mises stress

(b) Normal stresses (S11, S22 and S33)

Fig. 5 Stress level and distribution in the cement around the cavity

stresses of tensile and compression. The low amplitudes of tensile stress pose no risk of damaging of this binding. The compressive stress is much more intense. It is strongly soliciting the cement along the *z* axis: see Fig. 4(b).

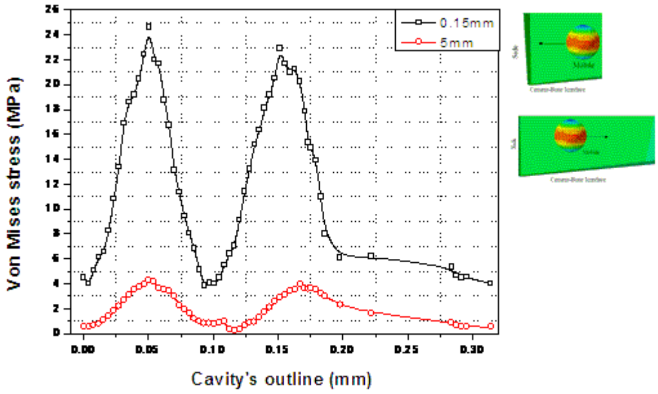
The Von Mises stress Induced in the compact cement: see Fig. 4a is more intense near the edge and at the interface with the bone. Far from this site of the structure, the level of this stress falls considerably. This shows that the edge of the structure is a seat of the stress concentration. It is in this area where is located the cavity with 100μm of diameter. Such localization allows analysing its effect on the mechanical behaviour of the bone cement. The results, in Fig. 5, show that the normal stresses, intensively localized around the porosity put much cement in compression. In the presence of the cavity, the stresses on the cement almost doubled of intensity: see Fig. 5(a)-(b). The tensile strength of bone cement is reached.

3.2 Interaction effect

3.2.1 Edge-cavity

The Von Mises stress, in Fig. 6, shows two maxima whose level increases strongly with the rapprochement of the cavity to the edge of the structure. Compared to the fracture stress in compression of the cement, this high stress is not a risk of damage. A cavity location, away from the edge, generates low stress amplitudes.

The edge resulting from the joining of the cup to the bone plays an important role on the mechanical behaviour of the cement. Indeed, the geometric defect is a source of stress concentration by notch effect. Fig. 7 shows a location of the cavity in the cement closer to the edge, along the thickness of the cement in the cement/bone and cement/cup interfaces and in the inside cement, generates stresses increasingly strong whose the intensity tends to its tensile fracture.



(a)Von mises stress (b) Normal stresses (S11, S22 and S33)

Fig. 6 Stress level and distribution in the cement around the cavity

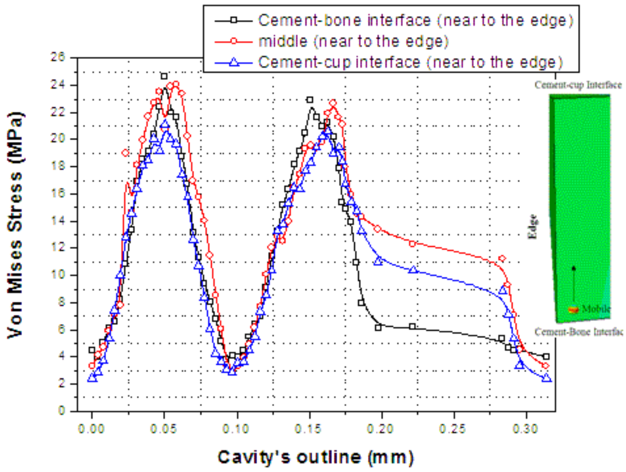


Fig. 7 Variation of the stress in the cement around the cavity according to its position along the thickness of the cement close to the edge

3.2.2 Cavity-cavity interaction

The density of cavity facilitates the transport of antibiotics across the cement but this, weakens the material by notch effect. It can be simulated by the distance between the cavities. The objective of this study is to analyse the interaction effect of stress fields in the cement between two cavities located near and away from the edge and at the cement/bone interface.

Cavity-cavity interaction near the edge

The stresses have been analysed in the cement around a fixed cavity which is located near the edge and other mobile moving away from the edge, according on the distance between them. Fig. 8 shows the location of two cavities in the vicinity very close to each other in cement generates stress which exceeds that of its tensile fracture. Such a position can lead to damage to the cement so the loosening of the prosthesis. The interaction between the stress fields in the cement around the first cavity effect disappears when the second is located far enough: see Fig. 10. This location generates significantly lower stresses around the second cavity: see Fig 9.

Cavity-cavity interaction far from the edge

In this section, we analyse the effect of a mobile cavity located at the cement/bone interface and near the edge moving to another fix situated far from the edge of the structure. The level of the equivalent stress around the first mobile cavity fell about five times when it migrates to the fixed defect (Fig. 11). This behaviour shows that the equivalent stress is much lower than the mobile cavity come closer that fixed.

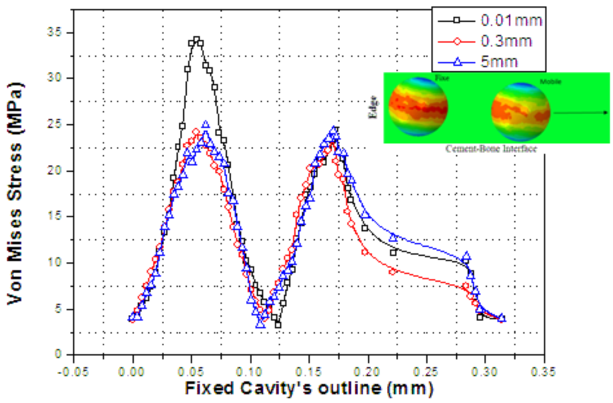


Fig. 8 Variation of the stress in the cement around the fixed cavity at the free edge according to the distance separating it to that mobile both to the interface cement/bone

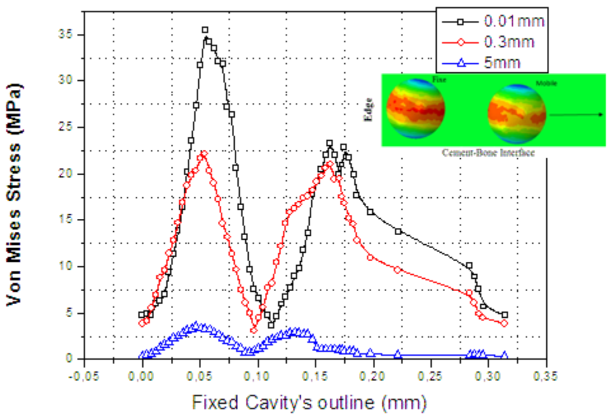


Fig. 9. Variation of the stress in cement around the mobile cavity according to the distance separating it to that fixed at the free edge both to the interface cement/bone

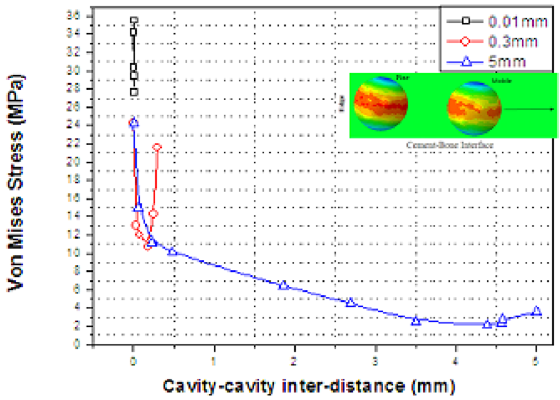


Fig. 10 Variation of the stress according to the fixed cavity- mobile cavity interdistance

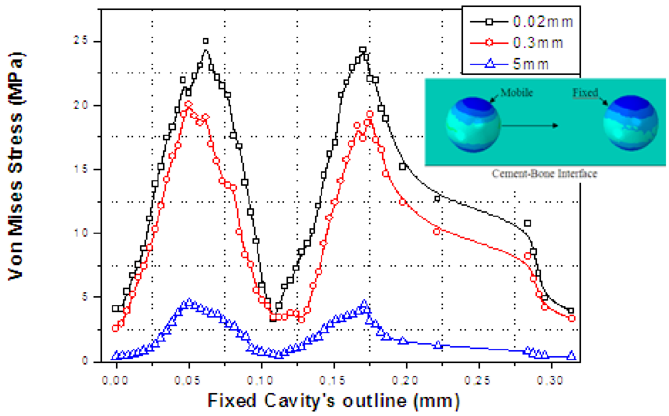


Fig. 11 Variation of the stress around the mobile cavity according to the distance separating it to that fixed both at the interface cement/bone

4. Discussion

The results obtained in this work clearly show that if the presence of cavities in the cement is beneficial for reducing the risk of infection, it presents a risk of tensile fracture of the material. Indeed, the level of Von Mises stresses induced locally in the material around the cavity exceeds the fracture threshold tensile which promotes priming and propagation of cracks originating from porosity. This behaviour is exacerbated by the presence of two cavities situated near the free edge of the cement at the interface with the bone in close proximity to one another. From this location resulting, in the cement, equivalent stress largely surpassing the limits of damage by cracking in tension.

High stress in the cement between two cavities can cause the initiation and propagation of cracks. This seems to explain the interconnection of pores through cracks in the bone cement (PMMA) observed experimentally (Murphy and Prendergast 2001).

5. Conclusions

This study showed that:

– Cement is subjected under the effect of human posture at normal tensile and compression. These last are highly concentrated at the free edge of the structure, are much higher than the tensile stress level;

– The most important equivalent stress of Von Mises is located at the cement/bone interface near the free edge. This is the seat of stress concentration;

– The presence of another cavity in the bone cement in close proximity to the first concentrated, by notch effect , the normal stresses and Von Mises in this material which that of von Mises tends to the tensile fracture stress of PMMA;

– The level of the von Mises stress is much higher than the cavity is located in close proximity to the free edge. This interaction is a risk of loosening of the prosthesis by tensile fracture of the cement;

– The intensity of the Von Mises stress in the cement between two cavities depends not only on their inter-distance but also their position in this material. Their locations in vicinity close to one another, near the free edge and at the cement/bone interface, induced stresses much higher than the tensile fracture stress. This risk decreases significantly when these defects are located far from the free edge.

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