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# Effects of Interaction between Two Cavities on the Bone Cement Damage of the Total Hip Prothesis

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In orthopedic surgery and more particularly in total hip arthroplasty, the fixation of implants is usually done with surgical cement consisting essentially of polymer (PMMA). Fractures and loosening appear after a high stress gradient. The origin of this phenomenon is the presence of micro–cavity located in the volume of PMMA.

The aim of this study is to investigate the effect of the interaction between two cavities on the cement damage where the external conditions (loads and geometric forms) can cause the fracture of the cement and therefore aseptic loosening of the prosthesis. A numerical model is generated using finite element method to analyze the damage of orthopedic cement around the microcavity and estimate the length of the crack emanating from microcavity for each position of the human body.

Result show that the damaged area is influenced by the cavity shape (only elliptical cavity shape can initiate damage). The most dangerous cavity position is located in the middle of the cement socket, on the axis of the loading. The distance between two cavities has an effect if it is less than 100 $\mu$m. One can estimate the initiation of a crack of maximum length of 16$\mu$m.

*Keywords*: Total hip prosthesis, cavity, bone cement, biomechanics, damage.

## 1. Introduction

Total hip replacement has become commonplace as a form of treatment in the humans hip arthroplasty (Fig. 1) [1, 2]. Aseptic loosening of the prosthesis is still a problem in the artificial joint implant replacement. Prosthesis loosening may cause the patient severe pain which can induce cost intensive revision surgery [3].

The mechanical strength of the total hip replacement depends essentially on the strength of the cement used. The principal role of the cement is to ensure a good adhesion of implant to bone and homogenize the load transfer from the implant to the bone. The cement must be able to resist the initiation and propagation of cracks which can lead to the cement collapse and consequently the loosening of the THP [2–4]

By its brittle nature and low mechanical properties, cement is the weakest link in the chain of load's transfer implant–cement–bone, it breaks the first by presenting a split at the cement–implant interface or the initiation of microcracks, which over time becomes larger by fatigue, and cause the break of the cement and the mobility of the implant inside the bone, resulting to the fracture of the pelvis of the patient [5].

The knowledge of the areas undergoing significant rate of damage and the initiated crack length estimation from the damaged area is highly important. This work deals with this phenomenon.

Several numerical studies have modeled the orthopedic cement damage. The majority of these works has focused on particular modes of damage [6, 7], such as the propagation of cracks [7, 8], fracture [9], fatigue [10], and the debonding [11].

However, there is a lack of studies describing how the presence of porosity in the orthopedic cement can affect its damage.

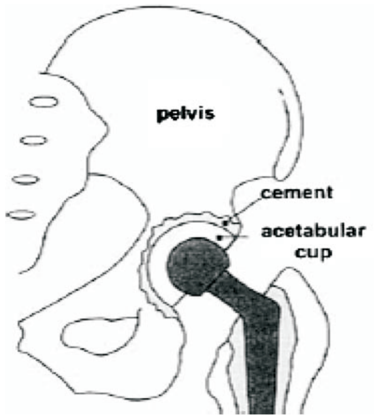


**Figure 1** Cross section of acetabulum

In this study we assumed the existence of two cavities and studied the effect of the interaction between these latters on the damage of the orthopedic cement.

Numerical modeling using the finite element method gives a better time saving, information and details on the PMMA damage phenomenon. The good knowledge of regions that undergo an important damage and the crack initiation is essential. In this study, one modeling the PMMA damage around cavities and study the effect of interaction between that cavities on this damage.

## 2. Methods and modeling

The numerical modeling of the cemented total hip prosthesis with the finite element method is used to analyze the damage of the cement mantle [12]. The model was defined in terms of geometrical, loading and material definitions.

### 2.1. *Geometrical model*

The model was generated from a roentgenogram of a 4 mm slice normal to the acetabulum through the pubic and the ilium. This model has the advantage of being closer to the real acetabulum. The elements of the total hip which are the hip bone, the cement, the implant and the cup are clearly defined in Fig. 2 [5–13].

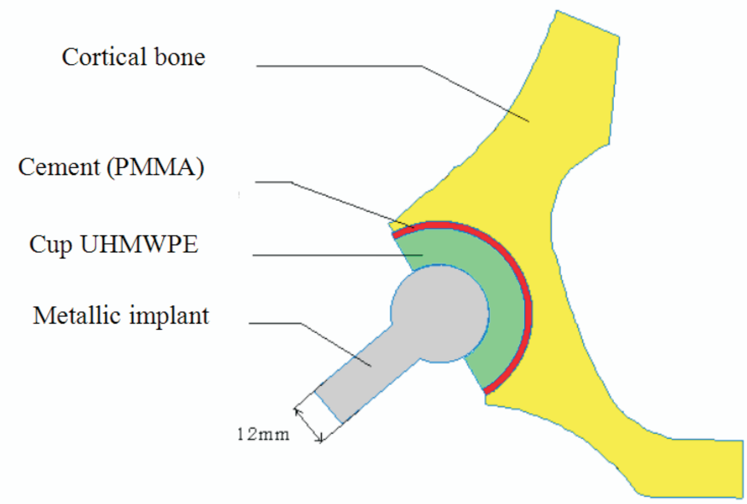


**Figure 2** Model geometry of the total hip prosthesis analysis

We have supposed the existence of two types of cavity: elliptical and circular [3] (Fig. 3).

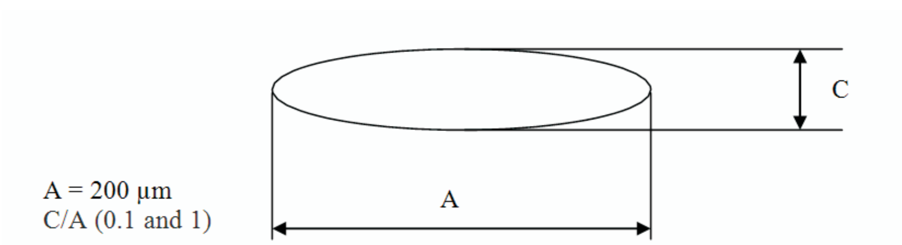


**Figure 3** Profile of the cavity

### 2.2. *The interaction analysis between cavities*

Knowing that the orthopedic cement is a porous material, the analysis of interaction between cavities in the cement is compulsory. In this study, we assumed the existence of two cavities of the same type (lliptical) or different shapes (circular, elliptical) in the cement (Fig. 4). The effect of the distance between the cavities on the orthopedic cement damage is studied.

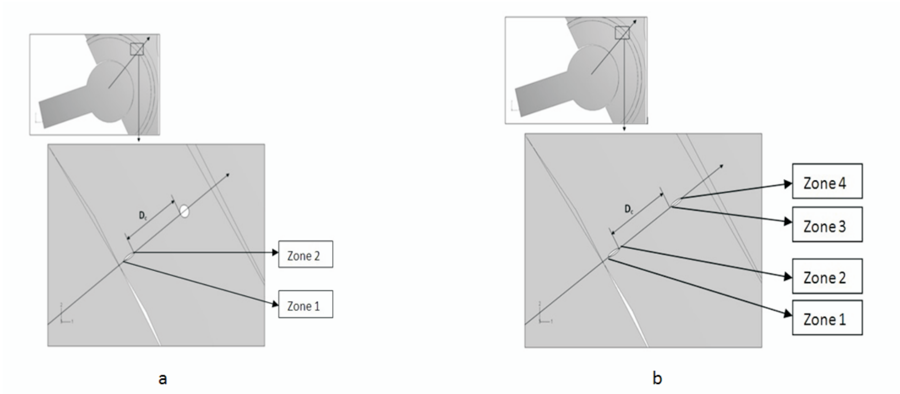


**Figure 4** The studied positions and damaged zone

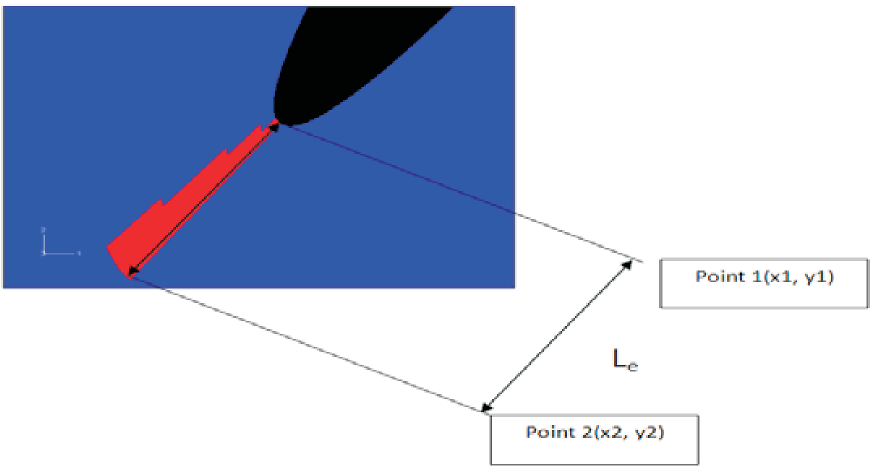


**Figure 5** Estimated length of the crack

### 2.3. *The estimation of the crack length*

Fig. 5 is a schematic representing the method of the crack length estimation. The estimated crack length is taken between two points that belong to the perimeter of the damaged area. These two points make a line unit a direction that is perpendicular to the maximum principal stress direction [14]. We took the coordinates of the two points and calculate the crack length using the following formula.

$$L_e = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

$L_e$ – estimated length of the crack [$\mu$m].

### 2.4. *Material model*

In this study, we have used a non uniform cortical bone thicknesses in the range of 1–4 mm. Therefore, the finite element model consists of a cancellous region surrounded by a uniform cortical bone. The femoral component was fixed to the femur using a uniform PMMA cement with a thickness of 2 mm [15, 16].

All the materials considered in the current study were assumed as linear elastic and isotropic [16].

Tab. 1 shows the mechanical properties of the bone, cement, implant and the cup [15, 18].

**Table 1** Material properties

| Materials | Young Modulus E (MPa) | Poisson ratio $\nu$ |
|---|---|---|
| Cortical bone | 17000 | 0.30 |
| Subchondral bone | 2000 | 0.30 |
| Spongious bone 1 | 132 | 0.20 |
| Spongious bone 2 | 70 | 0.20 |
| Spongious bone 3 | 2 | 0.20 |
| Cup UHMWPE | 690 | 0.35 |
| Ciment PMMA | 2300 | 0.30 |
| Metallic implant | 210000 | 0.30 |

### 2.5. *Damage criteria*

Numerous approaches of this phenomenon were undertaken to determinate the damage criterion of the PMMA bone cement [12, 13, 15]. We chose that of Gearing [19], since this one has the advantage to be easily implemented. The others criteria additionally requires the modeling of the crack, which is numerically expensive.

According to this criteria the damage can initiate when the following conditions are met.

$$\sigma_{p1} > 0 \tag{1}$$

$\sigma_{p1}$: The Maximum principal stresses.

$$\sigma = \frac{1}{3}(\sigma_{p1} + \sigma_{p2} + \sigma_{p3}) > 0 \tag{2}$$

$\sigma_{p1}$, $\sigma_{p2}$, $\sigma_{p3}$: Principal stresses.

$$\sigma_{1\,cr}(\sigma) > 0, \qquad \sigma_{1\,cr}(\sigma) = c_1 + \frac{c_2}{\sigma} \tag{3}$$

$c_1 = 45,60$ MPa, $c_2 + 785,560$ MPa$^2$

### 2.6. *Mesh and boundary conditions of the model:*

The refinement of the mesh is important for the analysis of the structure. Due to the importcance of the stress distribution in the cement and particularly around the micro-cavity; a very high refinement was used with an advancing front meshing strategy to get a numerical solution closer to the real solution. Fig. 6 and 7.

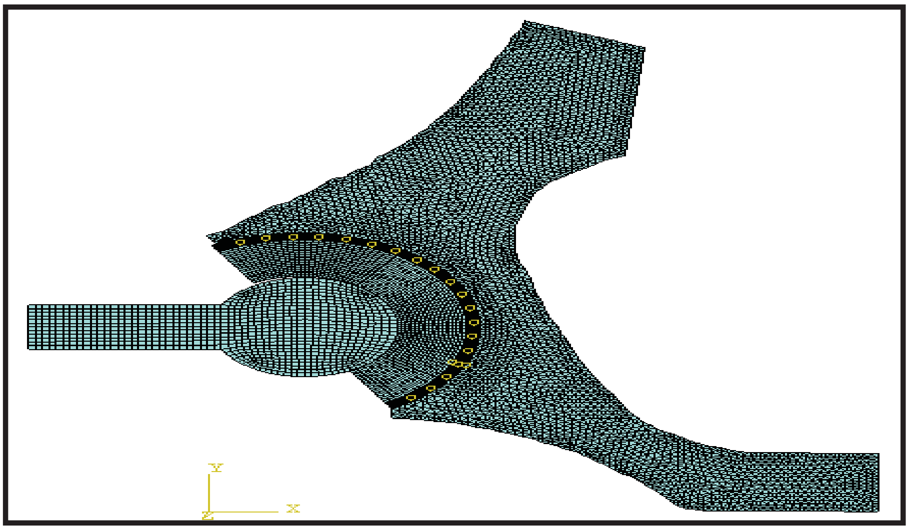

**Figure 6** Mesh of the prosthesis analyzed

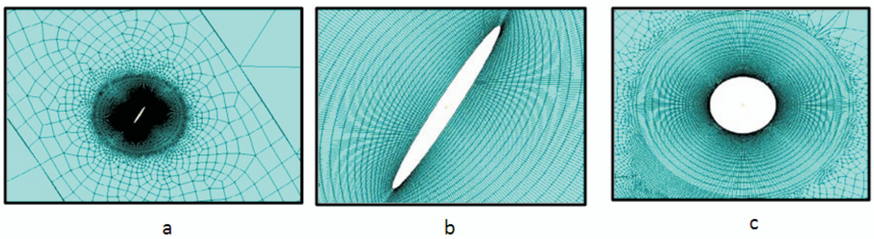


**Figure 7** Mesh of the prosthesis analyzed

### 2.7. *Loading model*

The analysis of the distribution of the damage parameter (D) in the acetabular bone cement needs different types of orientations characterized by the position of the neck of the implant relatively to cup axis (Fig. .8).We opted for the following inclinations $0^\circ$, $10^\circ$, $20^\circ$, $30^\circ$, $40^\circ$, $50^\circ$, and $60^\circ$ [20–22].

The sacroiliac joint was fully fixed while the pubic joint was allowed to move in sagittal plane. The boundary conditions were considered to be representative of an anatomic configuration. The contact between bone and cement and between cement and cup was taken as fully bounded, therefore, between femoral head and cup was assumed to have a frictionless tangential behaviour and a hard contact normal behavior.

A uniformly distributed load of 10 MPA of magnitude is applied to the implant, this load was found by Pustoch [22].

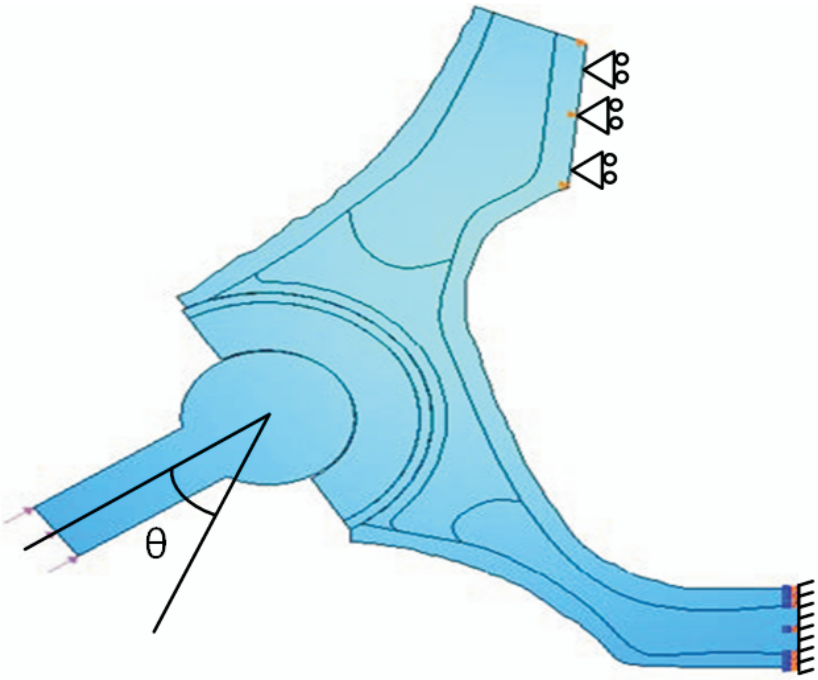


**Figure 8** Schematic representation of the boundary conditions

## 3. Results

### 3.1. *Damage distribution of the parameter in pure cement*

We analyzed the distribution and the level of the damage parameter (D) for different loadings (the alignment of the implant neck with respect to the cup axis , characterized by an orientation angle $\theta$ (Fig. 8)). The results are represented in Fig.

9. This figure shows that the distribution of the D parameter is not homogeneous in the cement. The high D parameter values are located in the cement on the axis of loading or slightly shifted downwards. For pure cement the D parameter values are weak. The maximum values are about 0.04 which means that there is no damage risk of pure cement. [23] showed that in a pure cement the stress distribution in the cement is lesser than 10 Mpa and the damage could not initiate in pure cement.

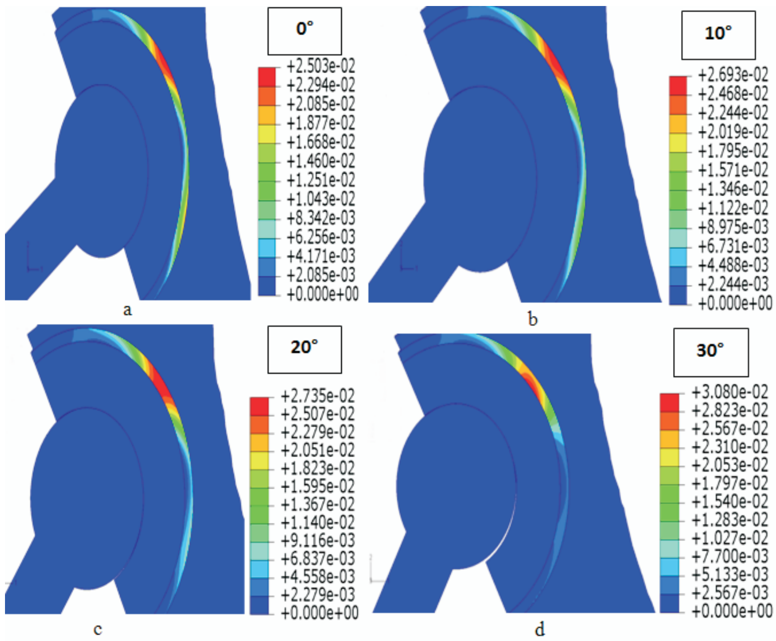


**Figure 9** Effect of the orientation of the implant on the damage parameter in cement

### 3.2. *Representation of the damaged areas in PMMA*

Fig. 10 represents the damaged zone of the cement in the vicinity of the cavity. This figure. clearly shows the damage criterion efficiency.

Using these criteria the damaged zone is well predicted because of this latter is emanated from the cavity (the zone where the stresses are concentrated). This damaged zone can be considered as a crack emanated from this cavity.

Fig. 11 presents the distribution of the Von Mises stress in the cement, in the vicinity of the edge of the cavity. This figure shows a similarity between a distribution of stress around a crack emanate from a micro–cavity and the damaged area and thereby we can approximate our damaged area to a small crack. In the present case the criterion predicts the initiation of two cracks emanating from the micro-cavity.

Because the program eliminates the elements stiffness of the damaged ones; the damaged areas is showed with neutral color (non stress distribution in it).

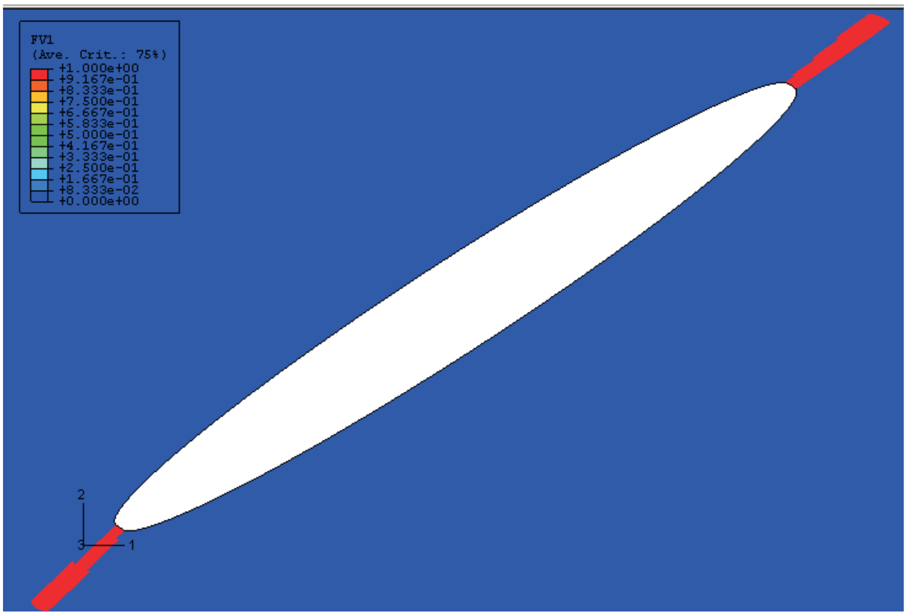


**Figure 10** Representation of the damaged areas

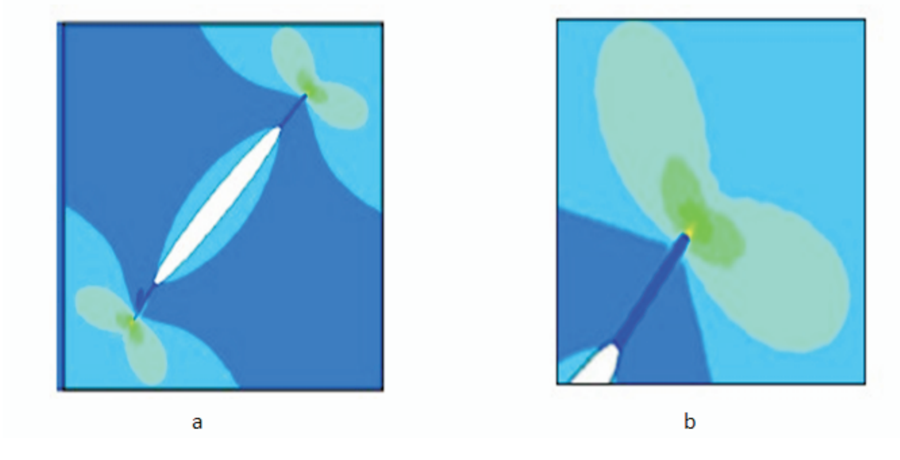


**Figure 11** Distribution of the stress

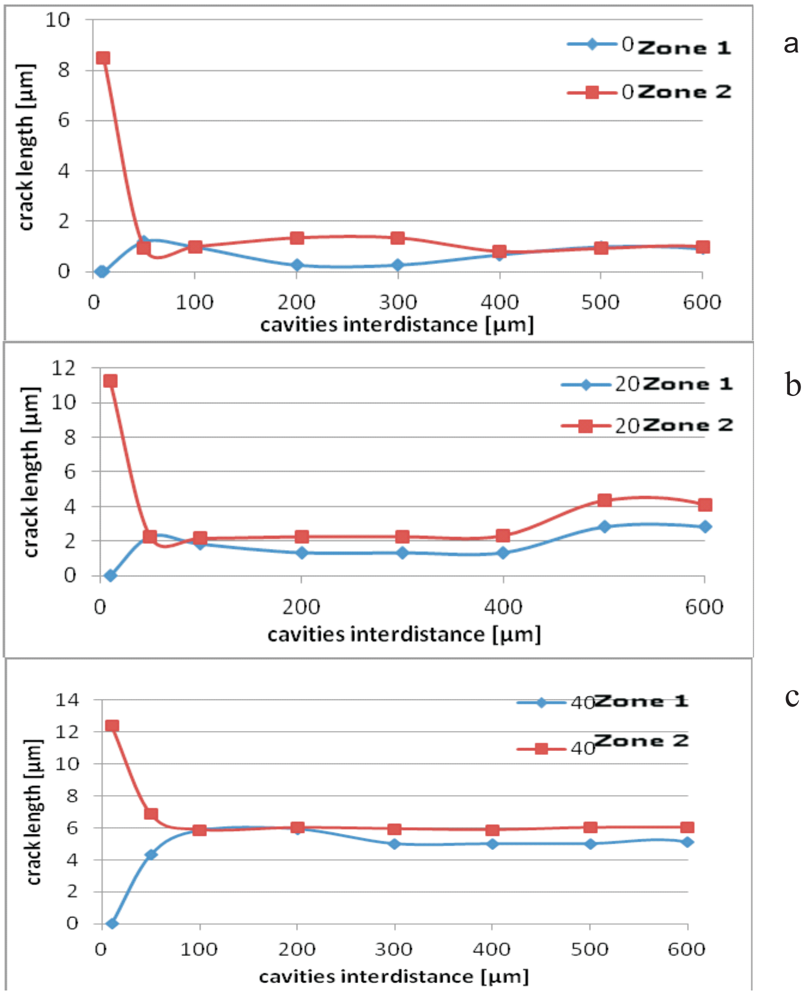


**Figure 12** The variation of the crack length with respect to the distance between cavities for an implant orientations 00 $^\circ$, 20 $^\circ$ and 40 $^\circ$ for both damaged zones

### 3.3. *Effect of the interaction between elliptical and circular cavity on the estimated crack length*

In Fig. 12 we represent a comparative analysis of the estimated crack length between both elliptical cavities with respect to the inter–distance between the elliptical cavity and the circular cavity. The circular cavity has 200 $\mu$m of diameter, the analysis is done using the three stem positions 00 $^\circ$, 20 $^\circ$ and 40.

The curves in Fig. 12 were splitted into two parts; in the first part when the interdistance is greater than 50$\mu$m; the crack size seems to be independent of the cavities interdistance (Le). The estimated crack length was insignificant in the second part of the graph, when the inter–distance (Le) was less than 50$\mu$m, the crack behavior on the edges changes. The zone that lies between both cavities can produce an important damage both cavities gave an important damage which can initiate important cracks.

One notice that the crack which can be initiated from the second zones were very small (no risk of crack initiation for this kind of interaction). In previous study [24] one consider a crack of 50$\mu$m of size for a fracture analysis of the orthopaedic cement; in an other study [25] supposed the existence of a 0.2–0.3 mm crack length for a 3 mm cement thickness.

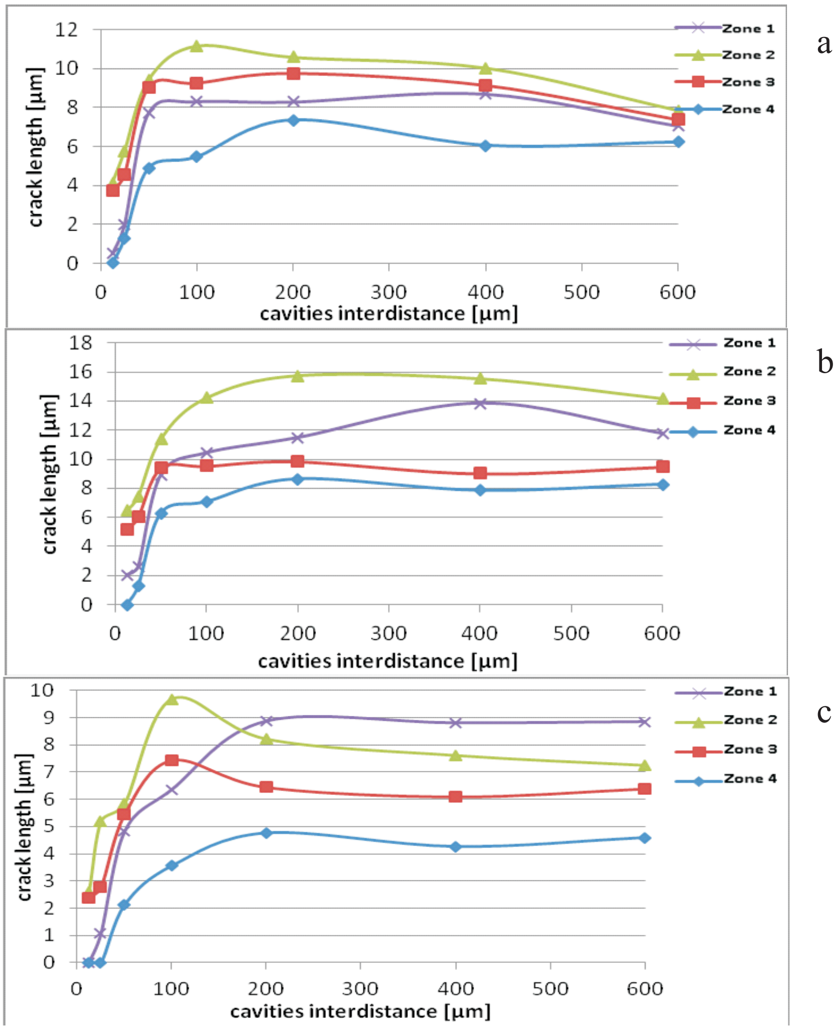


**Figure 13** The variation of the crack length with respect to the distance between cavities for an implant orientation f 20 $^{\circ}$

### 3.4. *Effect of the interaction between two elliptical cavities on estimated crack length*

In the second part we study the effect of the interaction between two elliptical cavities having the shape parameter C/A = 0.1. Results were showed in Fig. 13. The damage behavior in this case changes completely compared to that observed in the interaction between elliptical and circular cavities. There is no effect of interaction when inter–distance is greater than 100 $\mu$m. the behavior is the same of that of an isolated cavity. These damage behavior changes when the stress changes its orientation (a change of stem position). When interdistance (Le) is less than 100 $\mu$m the interaction effects appears, the damaged area was very small (negligible). The maximum crack length founded (for a 200 $\mu$m cavities interdistance with a 20$^\circ$ stem orientation) was 16 $\mu$m (Fig. 13b). This behavior was the same on the four edges zones of both cavities. We explain this phenomenon with the stress concentration around the tip of both cavities witch causes a relaxation of stresses in cement far from the tip of both cavities.

## 4. Conclusion

The presence of micro–cavities in the bone cement fixing the total hip prosthesis can't be avoided; it has the inconvenient to be the origine of stress concentration and may causes the crack initiation which causes the loosening of the prosthesis. The present study has been conducted in order to analyze using the finite element methods, the damage around a micro-cavity in the cement fixing the hip prosthesis. As a result of this work some conclusions can be drawn:

In pure cement, no damage risk was registred.

The highest level of the damage parameter was located when the cavity is in the middle of the cement socket ($\theta$=110$^\circ$).

The most significant damage in the cement is located on both edges of the elliptical cavity (type C/A = 0.1). It's due to the compression of the cement in the radial direction around the cavity. An inclination of the implant generates a different damage levels and states.

The effect of the interaction between two cavities on the damage exists if the inter-distance is less than 100 $\mu$m between two elliptical cavities and 50 $\mu$m between circular and elliptical cavities. If the interdistance is important, each cavity has a behavior of an isolated cavity.

The study of the interaction of elliptic–elliptic cavity revealed that the damage is inversely proportional to the inter–distance.

The interaction between an elliptic and a circular cavity is the most dangereous.

From this study one can predict the initiation of a crack with 16 $\mu$m of length.

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