

FINITE ELEMENT ANALYSIS OF THE BEHAVIOUR OF A CRACK IN THE ORTHOPEDIC CEMENT

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In this paper, the finite element method is used to analyse the crack behaviour in the orthopedic cement of the total hip replacement by computing the stress intensity factors (SIFs) around the crack tip. In this work, three cases are studied: crack emanating from a cavity, interaction effect of the crack emanating from a cavity with another cavity and the interaction effect of two cracks emanating from two cavities. The stress intensity factors under mixed mode problems at the crack tip are computed for three zones of prosthesis: proximal, median and distal. The obtained results show that the crack initiated from a micro-cavity in the distal zone of cement can be propagated at the same time by opening and shearing of its lips. It is contrary to that initiated in the proximal zone which cannot be propagated. The mechanical behaviour of cracks in the medial zone depends of the crack initiation position.

Keywords: stress intensity factor, crack, cavity, orthopedic cement

1. Introduction

Over estimated 800 000 total hip replacements are being performed worldwide annually (Jasty *et al.* 1991; Leroy 1992). Primary hip arthroplasty is subjected to failure due to the loosening of the implant or the prosthetic cup. 15% of the hip arthroplasty today are revision operations. A successful surgical procedure is developed where a ball-socket structure is used to replace the deceased or damaged hip joint. The replacement cup socket is usually attached to pelvis by acrylic bone cement which consists of a solid component of polymethylmethacrylate (PMMA) powder and a liquid component of monomethylmethacrylate (MMA). After mixing, polymerization takes place and within a few minutes of application to the bone cavity, the mixture becomes solid (Poitout, 1992; Li *et al.*, 2002). The presence of a defect in the cement during mixing can locally lead to a region of stress concentrations producing possible fracture of the cement and consequently the loosening of the prosthetic cup. There are almost three kinds of defects: porosities, inclusions and cracks.

It is known that cracks are the most dangerous defect because of the presence of stress intensity on their front. The majority of cracks identified in the orthopaedic cement are (Hertzler *et al.*, 2002; Bachir Bouiadjra, 2007): cracks initiated at porosities, cracks initiated during cement withdraw and cracks initiated at the junction between the bone and cement or between the cement and cup.

In literature, numerical works have been devoted to study the mechanical behaviour of cracks in the orthopedic cement: Benouis *et al.* (2015) presented numerical modeling of the

crack propagation trajectory in the cement of reconstructed acetabulum. The direction crack was evaluated as a function of the displacement extrapolation technique and the strain energy density theory. Benouis *et al.* (2015) investigated the 3D-FE method to analyse the distribution of equivalent Von Mises stress around a cavity located in the bone cement polymethylmethacrylate (PMMA). The results showed that the micro-porosity located in the proximal and distal zone of the prosthesis was subject to a higher stress field. Sahli *et al.* (2014) studied damage of the orthopedic cement around the micro-cavity and estimated the length of the crack emanating from the microcavity for each position of the human body. The results showed that the damaged area was influenced by the cavity shape. Oshkour *et al.* (2013) investigated the X-FE method to analyze the behaviour of the internal circumferential cracks located in the cement layer of the cement-prosthesis interface during the main phases of the gait cycle. Benbarek *et al.* (2013) presented a numerical analysis of the crack growth path in the cement mantle of the reconstructed acetabulum. The maximal circumferential stresses criterion was used to determine the direction of the crack emanating from a micro-void in the cement layer. Bouziane *et al.* (2013) showed that the stress intensity factor evaluated for a crack emanating from an inclusion was higher than the crack emanating from a cavity. Ouinas *et al.* (2012) used the FEM to analyze the influence of the presence of microvoid and a crack emanating from the microvoid on the fracture behavior of bone cement. Flitti *et al.* (2010) analyzed the propagation criteria of cracks to predict the failure behaviour of cemented hip prostheses under monotonic loading conditions. That analysis was carried out on various zones of the cement along the bone, namely the proximal, the medial and the distal positions. Benbarek *et al.* (2007) investigated the FE method to analyse behaviour of the crack emanating from a microvoid by computing the SIFs at the crack tip. Taylor *et al.* (2003) used analytical and numerical methods to predict damage of the bone.

The use of crack propagation laws based on the stress intensity factor range is the most successful engineering application of fracture mechanics. The stress intensity factors are a very important parameter in fracture analysis. These factors define the stress field close to the crack tip of a crack and provide fundamental information on how the crack is going to propagate. The use of this factor can be an effective tool to analyse the fracture behaviour of cracks in the orthopedic cement.

The aim of this paper is to analyse the behaviour of cracks in the orthopedic cement by computing the SIFs. In this study, three cases are considered: crack emanating from a cavity, crack emanating from a cavity with another cavity and two cracks emanating from two cavities.

1.1. Geometrical model

Figure 1a shows the geometrical model used in this study. A force of 2400 N is applied to the structure as shown in Fig. 1b (Bergmann *et al.*, 1993). The prosthesis is divided into three zones: *proximal*, *median* and *distal* and two parts: *interior* (right part) and *exterior* (left part).

The Finite element standard code ABAQUS V 6.11 (Dassault Systèmes, RI, USA) has been employed for the modeling of the problem. For the mesh generation of our model, the element type 'CPS8R' of ABAQUS code is used. It is a higher order two dimensional, 8-node element having two degrees of freedom at each node (translations in the nodal x and y directions), quadratic displacement behaviour and the capability of forming a triangular-shaped element, which is required at the crack-tip areas (Fig. 2a).

Due to the singular nature of the stress field in the vicinity of the crack, the singular elements, shown in Fig. 2b, are considered at each crack-tip area, which is modeled with a finer mesh.

The model is divided into three regions of different elastic constants with isotropic material properties assumed in each region. The main regions are: implant (Ti-6Al-4V), cement (PMMA)

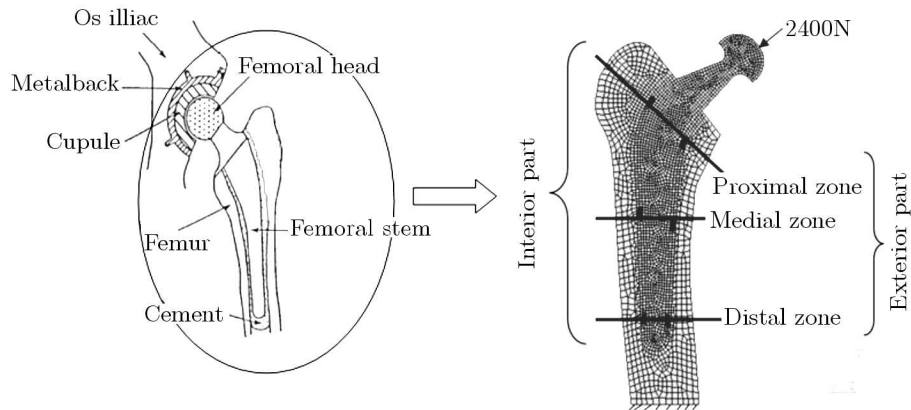


Fig. 1. (a) Geometrical model considered in the study, (b) typical mesh model

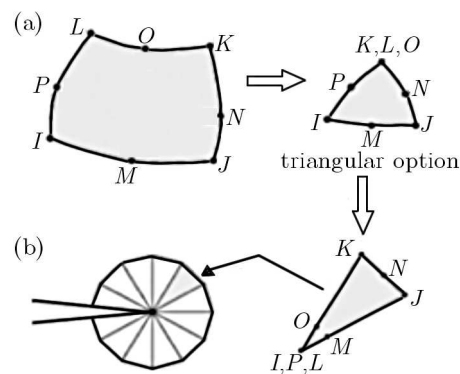


Fig. 2. (a) 'CPS8R' eight-node finite element and (b) singular option

and femoral bone. Table 1 shows the material properties used in this study (Kalapana, 2004; Flitti *et al.*, 2010).

Table 1. Material properties

Material	Young's modulus E [MPa]	Poisson's ratio ν [-]
Implant (Ti-6Al-4 V)	100 000	0.33
Cement (PMMA)	2000	0.25
Femoral bone	20 000	0.25

2. Results and analysis

To analyze the behaviour of cracks in the orthopedic cement, three cases are considered: the crack emanating from a cavity, interaction of the crack emanating from a cavity with another cavity and interaction of two emanating cracks from a cavity (Fig. 3).

2.1. Case I: crack emanating from a cavity

A crack of length a emanating from a circular cavity (with diameter $D = 200 \mu\text{m}$) is supposed to exist in the orthopedic cement for different zones: proximal, medial and distal. Figure 4 shows a typical mesh model of the prosthesis. The stress intensity factors K_I and K_{II} are obtained using the J -integral method. The plane stress state conditions are assumed.

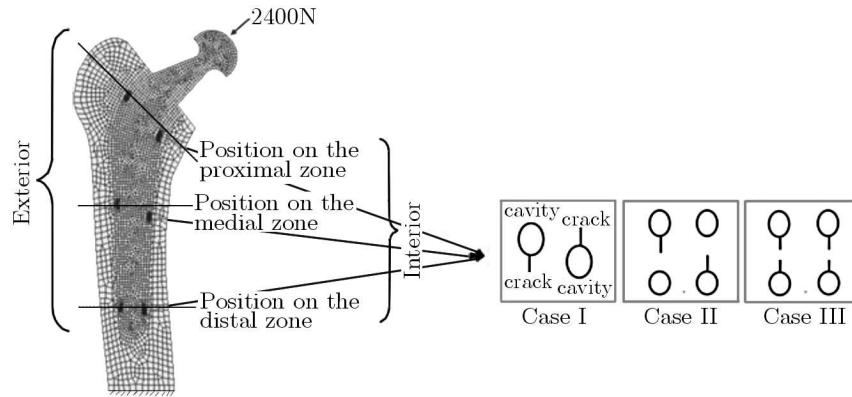


Fig. 3. Schematic representations of various cases: (a) case I: crack emanating from a cavity, (b) case II: crack emanating from a cavity with another cavity, (c) case III: two cracks emanating from two cavities

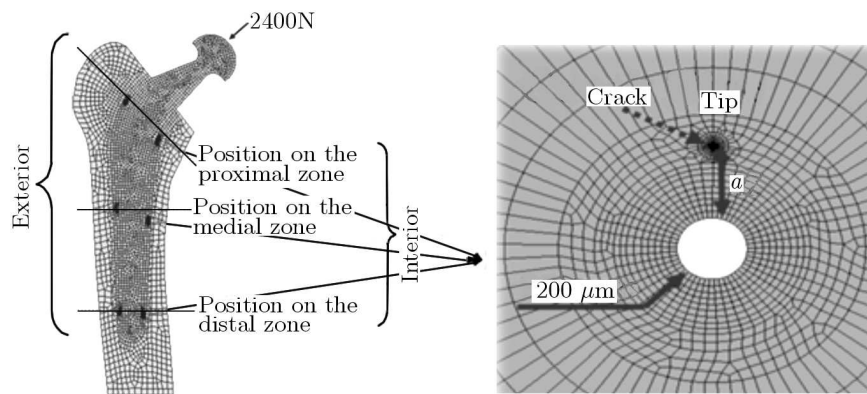


Fig. 4. Crack emanating from a cavity (case I)

Figures 5a and 5b show respectively the variation of mode I and II stress intensity factors (SIF) in function of the crack length for different zones of the prosthesis (proximal, median and distal) and for two parts (interior and exterior).

According to Fig. 5a, it can be seen that the exterior part of the prosthesis is solicited in compression because mode I stress intensity factors are negatives in the different zones (median, distal) except for the zone proximal where mode I SIF is null.

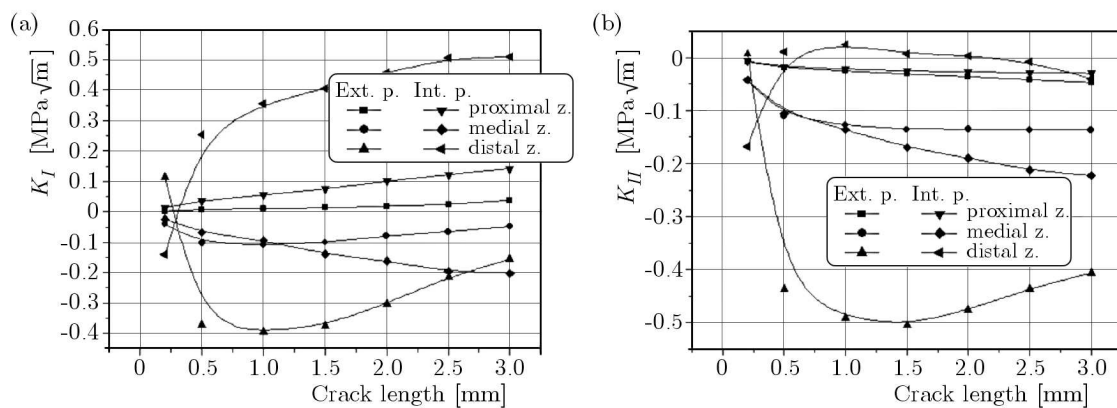


Fig. 5. Variation of SIFs K_I and K_{II} of the crack emanating from a cavity (Case I)

In the interior part, the SIFs K_I increases with the crack length in the distal and medial zones. In fact, the maximal SIFs values are in the distal zone ($0.5 \text{ MPa m}^{1/2}$) for a crack length

3 mm. On the other hand, the SIF value in the proximal zone is $0.15 \text{ MPa m}^{1/2}$ for a crack length 3 mm. One notes that the minimal values localized in the medial zone with negative values are $-0.1 \text{ MPa m}^{1/2}$ for a crack size 3 mm. The cement in the distal zone presents the maximal fracture risk of the prosthesis compared to the other zones.

According to Fig. 5b, it can be noted that mode II stress intensity factor (K_{II}) values are null in the distal zone of the interior part for a crack length varied between 0.5 and 2.5 mm. These results indicate that these cracks located in the distal zone can propagate according to the opening mode (mode I) with: $K_I > 0$ and $K_{II} = 0$.

2.2. Case II: interaction effect of the crack emanating from a cavity with another cavity

In this case, a crack of length $a = 0.5 \text{ mm}$ emanating from a circular cavity of diameter $D = 200 \mu\text{m}$ is supposed to exist in the three zones of the prosthesis. Another cavity (of the same diameter D) is located at a distance d from the crack-tip.

The prosthesis is modeled in two dimensions under plane stress conditions using isoparametric quadrilateral CPS8R elements. The crack-tip singularities are modeled using crack-tip elements. The stress intensity factors are calculated using the the J -integral technique. Figure 6 shows a typical mesh model of the prosthesis and the special elements around the crack tip.

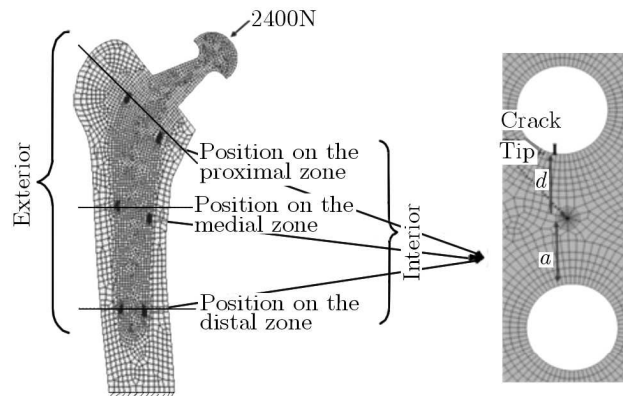


Fig. 6. Crack emanating from a cavity with another cavity (case II)

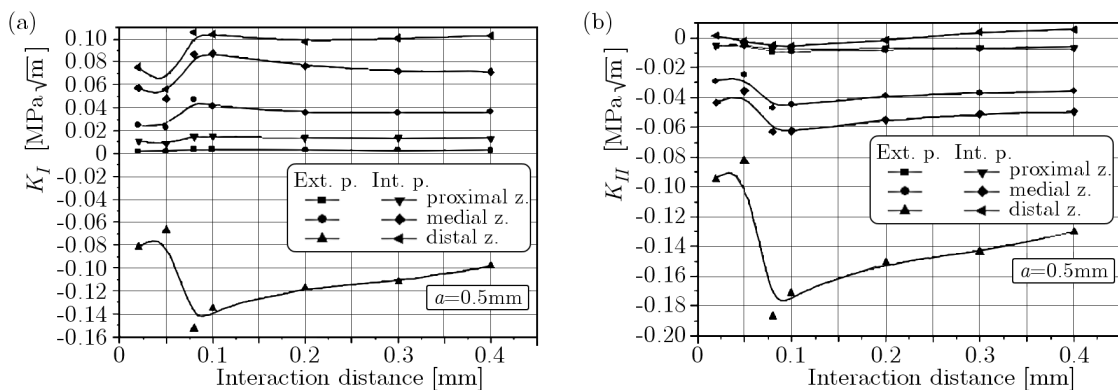


Fig. 7. Variation of SIFs K_I and K_{II} of the crack emanating from a cavity versus the interaction distance d (case II)

The results obtained are illustrated in Figs. 7a and 7b which show the variation of SIFs K_I and K_{II} as a function of the inter-distance d between the tip of the crack emanating from a cavity and the second cavity.

Figure 7a shows that whatever the zone of initiation of the crack (except for the distal zone of the exterior share), SIF K_I is positive. This shows that such a position of the crack leads to the opening of the crack. Indeed, it depends on the intensity of the stress field in which the crack is located. For a distance $d < 0.1$ mm, the SIF increases in a remarkable way. Beyond this distance, the variation of FIC K_I is independent of the distance d . In the distal zone of the exterior part, SIF K_{II} is negative. This shows that when the cavity is distant, the extension risk of the crack per opening is almost null. In Fig. 7b, for $d > 0.1$ mm, the values of SIF K_{II} are independent of the distance d . In the distal zone, this factor increases with an increase in the distance d .

2.3. Case III: interaction effect of two cracks emanating from two cavities

In order to determine the interaction effect of two cracks emanating from a cavity, we choose a crack of length a emanating from a circular cavity of diameter D . Another crack of length a is supposed to emanate from another cavity (of the same diameter D).

In Fig. 8, a and a' are the lengths of two cracks. The inter-distance between the two cracks is given by the parameter d .

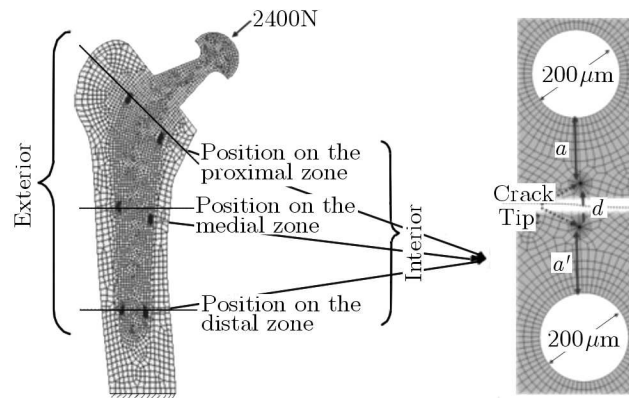


Fig. 8. Two cracks emanating from two cavities (case III)

Figures 9a and 9b show respectively modes I and II stress intensity factors (SIF) of the main crack emanating from a cavity as a function of the distance d between the two cracks tips. The SIFs K_I and K_{II} are evaluated for three zones of prosthesis (proximal, median and distal) and for two parts (interior and exterior).

The results obtained in Fig. 9a show that:

- For distance $d < 0.1$ mm, the SIF K_I increases with reduction in the distance d . This increase is observed in the three zones of the prosthesis, except for the proximal zone of the exterior part (where mode I SIF is null) and in the distal zone of the exterior part (where mode I SIF is negative). The negative values of K_I indicate that the distal zone is solicited in compression.
- The important values of K_I are observed in the distal zone of the interior part, for $d \approx 0.1$ mm. In all the zones, these values are stabilized for $d > 0.2$ mm.

In linear elastic fracture mechanics (LEFM), positive and negative values of K_{II} indicate the direction of crack propagation. This direction is opposite to the sign of K_{II} (Souiyah *et al.*, 2012; Alshoaibi Abdunaser and Ariffin, 2008). In Fig. 9b, the important values of K_{II} (absolute values) are observed in the distal zone of the interior part, for $d \approx 0.1$. Beyond this distance, the values of K_{II} (absolute values) decrease until the distance $d = 0.2$ mm is reached. For $d > 0.2$ mm, the SIFs K_{II} takes stable values.

The negative values of K_{II} (with $K_I < 0$) indicate that the distal zone of the interior part is solicited in compression.

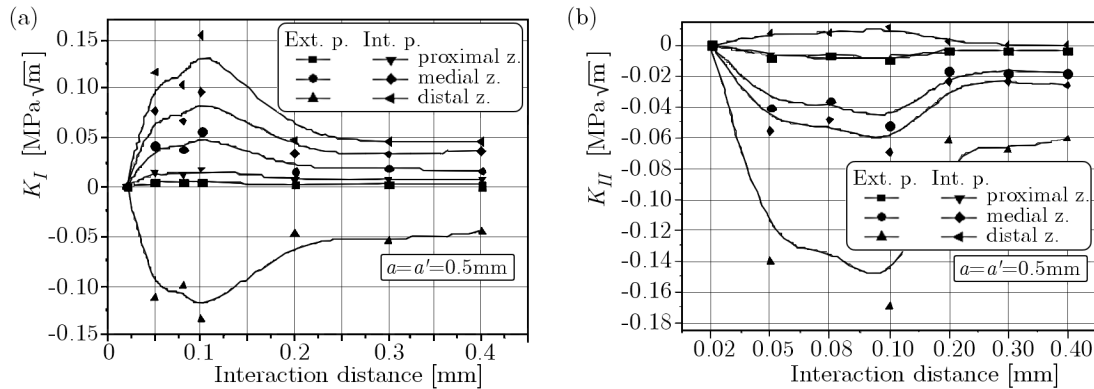


Fig. 9. Variation of SIFs K_I and K_{II} of the main crack emanating from two cavities versus the distance d between two cracks (case III)

3. Conclusion

The predicted values of SIFs for cracks behaviour in the orthopedic cement using the 2D finite element method are presented. In order to obtain a better approximation of the stress field near the crack tip, special quarter point finite elements are used. The analysis of the results obtained shows that a crack initiated from a micro-cavity or from bone debris in the distal zone of the external and interior parts of the cement can be propagated at the same time by opening and shearing of its lips; i.e. under mixed modes. It is contrary to the crack initiated in the proximal zone, which cannot be propagated. The mechanical behaviour of cracks in the medial zone depends on the crack initiation position.

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