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# Analysis of the biomechanical behavior of orthopedic cement: effect of crack morphology

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## ABSTRACT

In orthopedic surgery and more particularly in total hip arthroplasty, the fixation of the implants is generally done by means of a surgical cement consisting essentially of polymer (PMMA), It is necessary to know the forces applied to the right of the prosthetic articulation during routine activities performed by the patient in their daily life in order to establish the distribution of the stresses in the system (bone - cement - implant). Damage accumulation and failure in polymethylmethacrylate (PMMA) cement are the most important in total hip cemented leading to eventual loosening of the implant. In this study, we used the three-dimensional finite element) method (FEM) to analyze and calculate the three modes (I, II and III) of stress intensity factor (SIF) of form Plane inside the cement mantle for different sizes and depending on the different activities of the patient. The comparison was made between 2 types of elliptical and rectilinear crack, applying the same boundary conditions. From the results obtained, we show that the crack mode of The opening is proportional to the stress applied to the damaged part (compression or traction) The FIC values are less important for the elliptic crack than the rectilinear crack, which reaches the threshold of rupture under certain conditions, and is propagated essentially by shearing of the two crack lips in mixed modes II and III, these values show that the most probable mode of rupture is mode II.



## Introduction

The loosening of cemented implants is generally the result of local damage to bone cement PMMA developed during repeated cycles of total hip prosthesis activities under cyclic loading. Par sa nature fragile et ses faibles propriétés mécaniques, le ciment est le maillon le plus faible du système os-ciment-implant. His analysis has been the subject of several works. Thus, the effects of micro-defects in orthopedic cement on its mechanical behavior of a total hip arthroplasty was analyzed by Benbarek S et al [1] and Murphy BP et al [2]. These authors show that such defects weaken this binder by notching effect. This presence of micro defects promotes the initiation of cracks thus presenting discontinuities. Other authors have analyzed the effect of bone inclusions, the trapping of blood in cement on mechanical behavior [2]. They show that such defects are sources of additional constraints.
Numerical simulation of initiation and propagation of cracks has been used by a number of authors. Indeed, Ingraffea [3], Kemeny and Cook [4] and Dyskin et al [5] used the linear fracture mechanics (LEFM) to model crack stability and propagation trajectories by incorporating an intensity factor of constraint in the numerical formulation to determine whether the propagation of the crack would occur or not.
Other authors K. A. Mann et al [6] and G. Lewis [7] have stated that cracks initiated in bone cement can spread under cyclic loading during normal human activities. The authors have published on the propagation of a rectilinear crack in 2D in orthopedic cement as T. Achour et al [8]. In a study by president Belgherras.ME and all [9] have calculated the effect of the presence of a pre-existing 3D elliptical crack in the cement, the result shows that the crack initiated in the posterior part of the cement propagates essentially by shearing two crack lips in mixed modes II and III, these values show that the most likely is mode II.The objective of this study is to analyze the behavior of a rectilinear crack in 3D initiated inside the orthopedic cement, applying the same conditions to the limit of the elliptic crack [9], the aim is to see the effect of the crack geometry on risk of loosening of the total hip prosthesis. This prediction is analyzed in terms of variations of the stress intensity factors in modes I, II and III.Recall that the software abaqus 6.14, based on the finite element method, was for the analysis of these parameters of rupture. The estimation of these rupture criteria allows the prediction of bone cement damage. The rupture parameters were analyzed on the two cracking fronts, noted here point 1 and point 2 (Fig.1).

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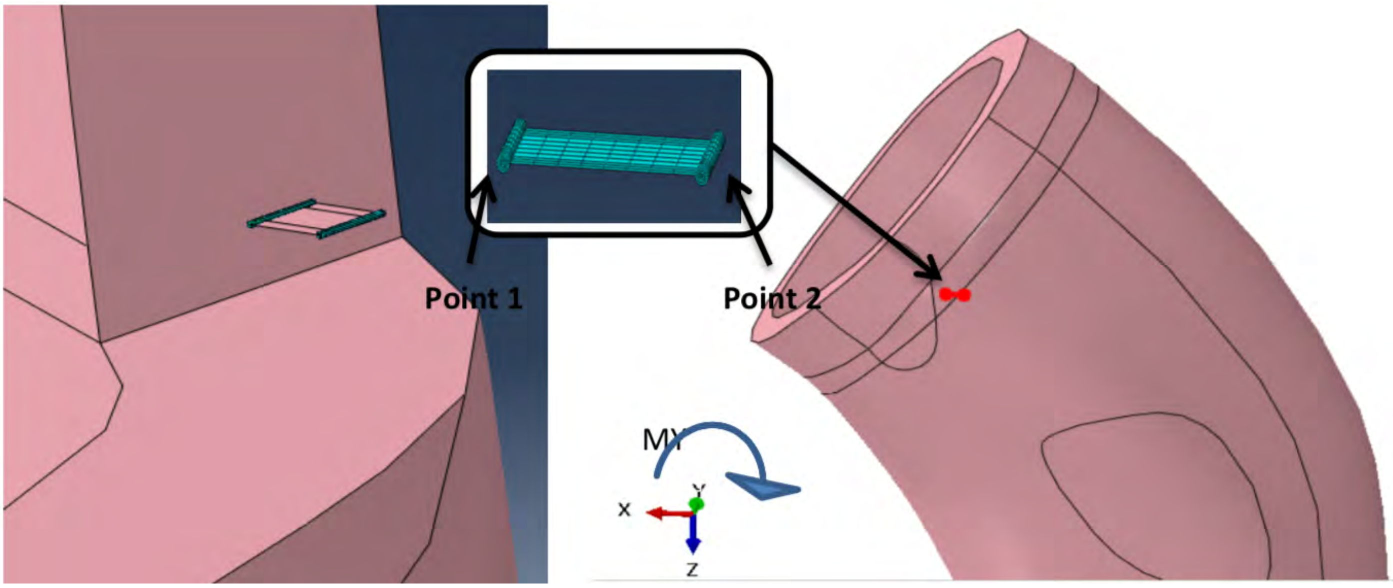


Fig. 1. Rectilinear crack geometry in the proximal part of the orthopedic cement.

## Model study

This study is based on a three-dimensional numerical modeling of the total hip prosthesis. In this work, we have used the third-generation model, CARNLEY MILLER KERBOUL (CMK 3). This model has the advantage of being closer to the actual structure [10], The modeling was carried out using finite element calculation software ABAQUS 6.14 [11] (Fig.2).

The objective of this study is to analyze the effect of the presence of a microcrack in the part of the cement under very strong constraints. To do this, a three-dimensional analysis by the finite element method was done for the computation of the stress intensity factor on the two lips of the rectilinear microcrack (Fig.1). That spreads in both directions,

## Effect of the size of the crack

For a better illustration of the mechanical behavior in rupture of the bone cement, we lead in this part of the work, and under the same conditions of simulation, that of a rectilinear crack. The same priming sites and loading conditions for an elliptical crack [9] were selected for this study. The results obtained are shown in Fig.3. This figure shows the variation of the stress intensity factor in modes I, II and III. We note, however, that this variation is almost similar to that resulting from an elliptical crack. In other words, the shape of the functions: K = f (crack size) is the same whatever the shape of the crack, as shown in Figures 3 a, b and c. the factors in elliptic and rectilinear fissure heads differ only in the intensity of the mechanical energy localized in crack points and whatever the crack head. Indeed, and because of its strong singularity, the rectilinear crack is more unstable. This instability is characterized by high values of stress intensity factors in modes I, II, and III. Just like an elliptical crack, a straight crack propagates in mixed mode I, II, III. These two cracks develop preferentially in mode II. The risk of loosening is very likely under strong shear stress, knowing that the orthopedic cement has a low mechanical resistance to shear. The other criteria of rupture are relatively weak.

Table.1 lists the mechanical properties of the three elements constituting the total hip prosthesis. The behavior of the three materials is assumed to be elastic and isotropic.

Table 1. Mechanical properties of cemented PTH system.

| | Materials | Young's modulus(Mpas) | Poisson Coefficient | Density (kg /m3) |
|---|---|---|---|---|
| Cortical bone | / | 21.000 | 0.3 | 1990 |
| Cancellous bone | / | 132 | 0.3 | 600 |
| PTH | Stainless steel (316L) | 210.000 | 0.3 | 7900 |
| Cement | PMMA | 2000 | 0.3 | 1200 |

The generated forces by each muscle contraction are determined in table.2

Table 2. The external forces exerted on the PTH system.

| Force (N) | X | Y | Z |
|---|---|---|---|
| Force applied to PTH head | Fx(t) | Fy(t) | Fz(t) |
| Muscle Abductor | 465.9 | 34.5 | 695.0 |
| Muscle Vastus Latera | -7.2 | -148.6 | -746.3 |

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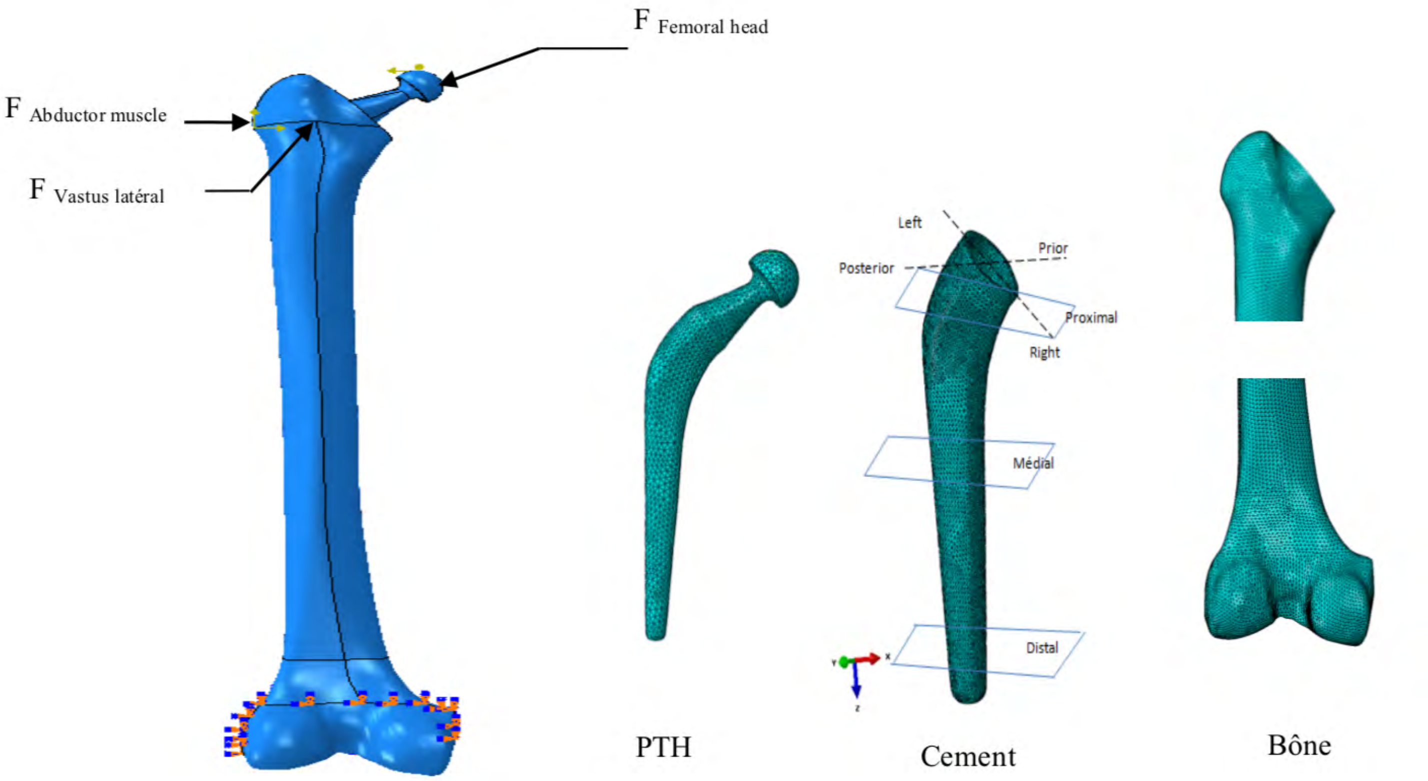
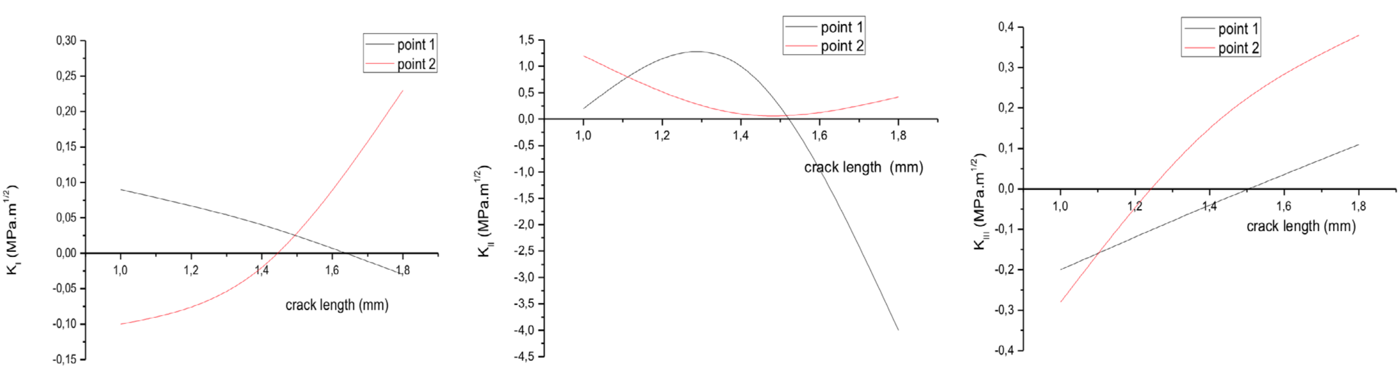



Fig. 2. The conception of the model of PTH CMK 3 with software ABAQUS

from an elliptical crack. In other words, the shape of the functions: K = f (crack size) is the same whatever the shape of the crack, as shown in Fig. 3 a, b and c. the factors in elliptic and rectilinear fissure heads differ only in the intensity of the mechanical energy localized in crack points and whatever the crack head. Indeed, and because of its strong singularity, the rectilinear crack is more unstable. This instability is characterized by high values of stress intensity factors in modes I, II, and III. Just like an elliptical crack, a straight crack propagates in mixed mode I, II, III. These two cracks develop preferentially in mode II. The risk of loosening is very likely under strong shear stress, knowing that the orthopedic cement has a low mechanical resistance to shear. The other criteria of rupture are relatively weak.

## Effect of orientation

In the same way as the elliptical defect [9], the rectilinear crack, of size 1mm, initiated in the proximal left part, was oriented at an angle θ along the cement in order to analyze the effect of this orientation on its behavior. The results of this analysis are shown in Fig.4. It shows the variation of the stress intensity factors in mode I, II and III as a function of the orientation θ around the axis ox (according to the thickness) and the axis oy (according to the length). These results clearly illustrate that this variation is practically independent of the shape of the crack. Indeed, the shape of the function K = f (of the orientation of the crack) is almost the same for these two cracks and whatever the mode of propagation. This behavior differs only in the high values of the fracture factors in mode I, II, III resulting from a rectilinear crack (Fig. 4 a, b, c). Thus at the crack front, denoted 1, results in a stress intensity factor higher than the resistance to cracking of the cement. This constitutes a danger of sudden rupture of the orthopedic cement.
Compared to the elliptical fissure [9], the initiation of a straight crack in the bone cement can lead to catastrophic damage in the short-term.




(A) mode I (B) mode II (C) mode III

Fig. 3. Effect of straight crack size on the F.I.C.

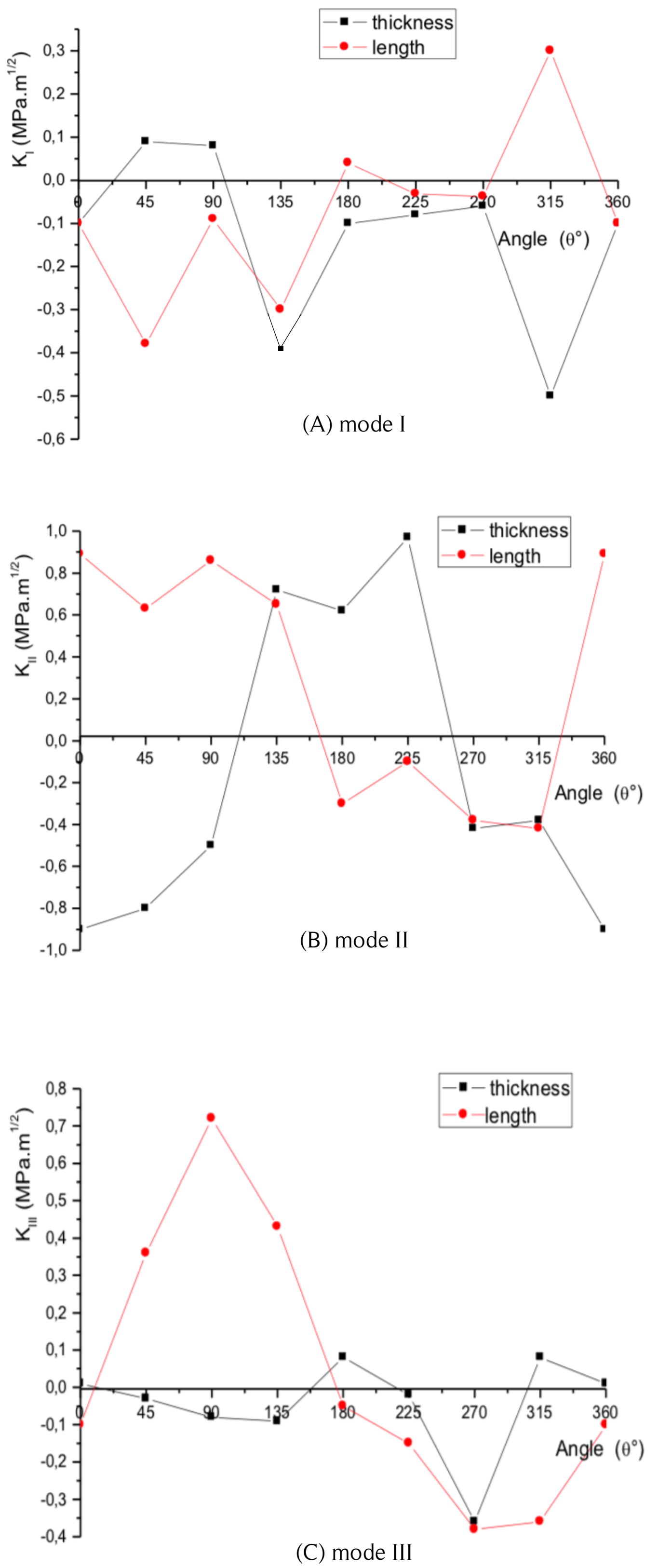



Fig. 4. The value of stress intensity factor as a function of the orientation θ around the axes ox(thikness) and oy(length).

## Effects of the patient's activities

In the same way as the elliptical crack [9], initiated in the left proximal part of the orthopedic cement, and under the same simulation conditions, an analysis of the effect of the nature of the activities on the behavior of a rectilinear crack was conducted. Remember that the five daily activities were selected for this analysis. The results obtained are shown in Fig. 5, showing the effect of each activity on the peak stress intensity factor, denoted 1 and 2, mode I, II, III respectively. However, when descending or going up the stairs, we note that the patient is more likely to use the crack initiated in the cement, whatever the mode of propagation (Fig. 5.a, b, c). The values of these fracture parameters are greater than those resulting from an elliptical crack, whatever the nature of the activity. As mentioned above, these two activities performed daily, in cases of great need, induce in the orthopedic cement, in its proximal left part, constraints of high intensities. This part therefore constitutes a seat of high stress concentration and therefore an area exposed to damage to the cement by sudden failure. This risk is all the greater as the patient's activity is intense. In our conditions of analysis, the risk of propagation can come from a rectilinear crack so the presence is very likely in the materials presenting a linear elastic fragile behavior, like the bone cement.

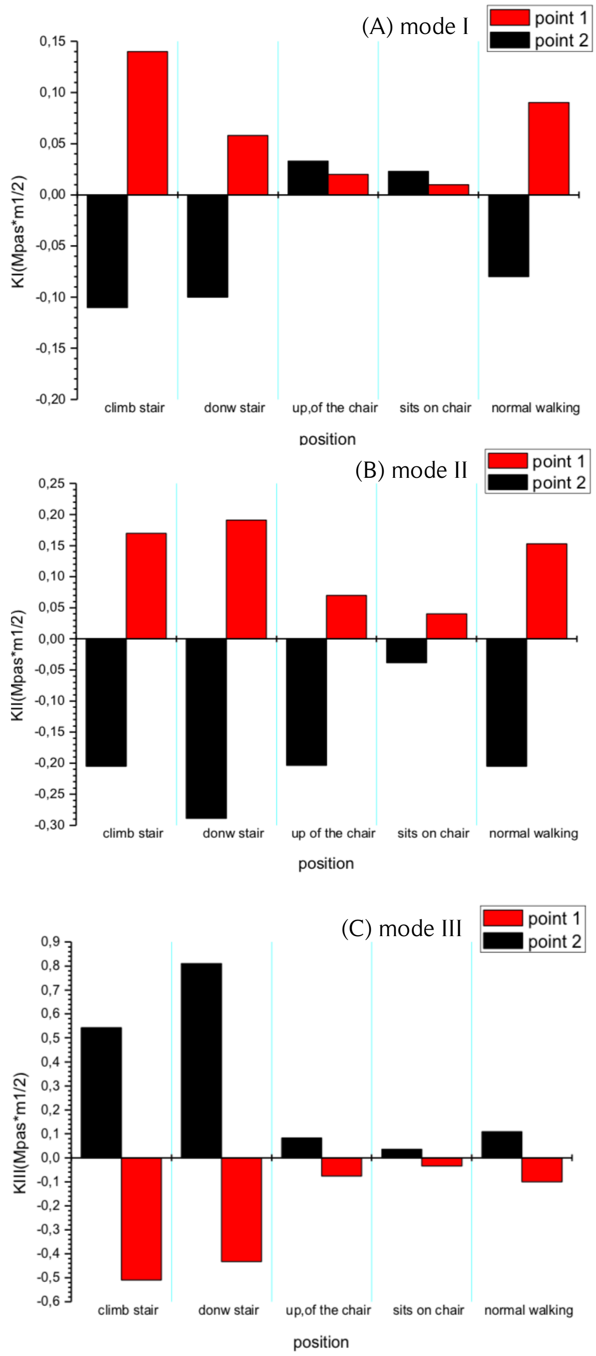



Fig. 5. The value of F.I.C depending n the patient's daily activities.

## Conclusion

The results obtained show that:

- The mode of propagation of the rectilinear crack, initiated in the proximal zone left of the bone cement, is rather complex.
- The resultant peak stress intensity factor 1 of a rectilinear crack located on the proximal part largely exceeds the threshold of the fracture, in mode I;
- The variation of the stress intensity factor is practically independent of the crack morphology. The shape of the function K = f (of the orientation of the crack) is almost the same the elliptic and rectilinear crack and whatever the mode of propagation. This behavior is distinguished only by the high values of the fracture factors in mode I, II, III resulting from a rectilinear crack. In tip 1 of the crack, in mode I the tenacity of the bone cement is crossed. This behavior explains the abrupt breaking of the cement;
- Activities carried out daily, in cases of great need, induce in the orthopedic cement, in its proximal left part, constraints of strong intensities. This part therefore constitutes a seat of high stress concentration and therefore an area exposed to damage to the cement by sudden failure. This risk is all the greater as the patient's activity is intense. In our conditions of analysis, the risk

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## Conflicts of interest

Authors declare no conflict of interests.

## Notes

The authors declare no competing financial interest.



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