THREE-DIMENSIONAL STUDY OF BEHAVIOR DAMAGE IN THE ORTHOPEDIC CEMENT, INTERACTION-SIZE EFFECT ON THE POROSITY

BENOUIS ALI [1,2]*, AIT KACI DJAFAR[2],ZAHI RACHID[3], MOULGADA ABDELMADJIDÉ[2,4], ZAGANE MOHAMMED EL SALLAH[2,4],MOHAMMED BENTAHAR[1], BOUTABOUT BENALI[2]

[1]*Faculty of technology, University of Saida, BP 138 Saida, 20000, Algeria*
[2]*University of SidiBel Abbes, Laboratory of LMPM, BP 89 City Ben Mhidi, Algeria*
[3]*University of Relizane, City Bourmadia, 48000, Algeria*
[4]*Department of Mechanical Engineering, University of Tiaret, City Zaâroura BP 78, Tiaret 14000, Algeria*

This study represents an in-depth exploration of stress distribution within polymethylmethacrylate (PMMA) orthopedic cement, a critical material used in hip prostheses. Focusing on the inherent fragility of the cement and its intricate interface with implants, our research meticulously investigates stress patterns surrounding individual cavities. What sets this study apart is its nuanced examination of interactions between multiple cavities and their consequential effects on both stress intensity and distribution. The findings from this research offer nuanced and illuminating insights into the interconnected nature of cavities, aligning closely with observations derived from real-world experiments. This study significantly advances our understanding of potential damage phenomena within total hip prostheses. Moreover, it establishes a robust foundation for potential advancements in the design and performance of prostheses, taking into account the complex interplay within orthopedic cement. These insights pave the way for more targeted improvements in the mechanical behavior of hip prostheses, thereby contributing to the ongoing evolution of orthopedic implant technology.

Keywords: *Cement, implant, stress, bone, defect, rupture*

1. Introduction

The transfer of the stresses from one to the other of the materials constituting the total hip prosthesis depends essentially on the mechanical strength of the interface. Indeed, the rigidity of the interface is one of the essential properties determining the degree and level of charge transfer.

The cement used to fix the hip prosthesis is a very fragile material with very low mechanical characteristics. Therefore, the knowledge of the stresses in this material, their state, their distribution and their intensity is of great importance for understanding the conditions of the serviceability of the prosthesis and its loosening. On the other hand, the cement-bone charge transfer intensity controls the effect of the prosthesis on the patient. The cement used in this analysis is the PMMA commonly used to fix hip prostheses to the bone.

Several studies on the distribution of stress in orthopedic cement have been carried out. Thus Benbarek et al [1,2] numerically analyzed by the finite element method the effect of the orientation of the axis of the implant with respect to that of the cup on the level and distribution of the stresses in the orthopedic cement containing a microcavity and consequently on the intensity factor of stresses in crack heads emanating from this cavity. In another study, BBA et al [3] investigated the breakage behavior of acetabulum cement by analyzing the intensity factor. They show that the mode of rupture depends on the position of the crack. Benbarek et al. [4] have shown that the mode-one mode-of-stress intensity factor depends not only on the orientation of the crack initiated in the cement but also on the orientation of the implant relative to the cup. Serier et al [5] analyzed the effect of the position of the crack initiated in the cement as a function of the position of the implant with respect to the cup on the stress intensity factor. Bouziane et al [6] analyzed three-dimensionally by the finite element method showed that the presence of the cavity cement or bone fragment is a source of stress concentration.

This study goes in this context and makes it possible to numerically analyze three-dimensionally by the finite element method the amplitude of the stresses induced in the orthopedic cement around a cavity and on the other hand its effects of interaction with the interface cement-implant, with another cavity on the intensity and distribution of stresses in this material. The results obtained to allow an explanation of the cavity interconnections by cracks observed experimentally. Zagane et al [7] studied the phenomena of damage in the weakest element of THP, due to the interaction ofthe defects observed experimentally. Other analysed the behavior of different geometrical forms of elliptical cracks in the surgical cement of the femur THP, and computed the evolution of SIFs at the cracks tip using X-FEM[8].

This study investigates stress transfer in total hip prostheses, emphasizing the interface's mechanical strength. Focusing on fragile cement, the research analyzes stress characteristics to understand their impact on prosthesis functionality and potential loosening. The study explores how

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*Autor corespondent/*Corresponding author*,
E-mail: alymoh1980@yahoo.fr

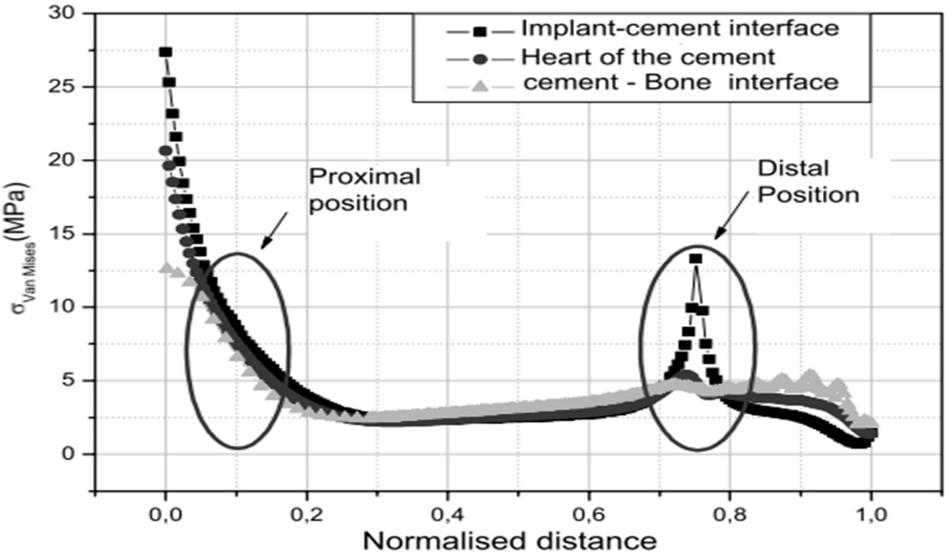

Fig. 1- Variation of the Von Mises stress induced in the proximal and distal zones of the sound cement in the extrados part as a function of the load applied to the implant.

Table 1

Mechanical and geometric properties of the implant, bone and orthopedic cement [13 - 15].

materials	Young's modulus, E (MPa)	Poisson's coefficient, v
Implant Ti-6A1-4V	110.000	0.30
The Cortical Bone	Ex=Ey=11.500, Ez=17.000 Gxy=3600, Gxz=Gyz=3300	vxz= vyz=0.31 vxy=0.51
Cement (PMMA)	2700	0.35

cavities in orthopedic cement interact with the implant interface, influencing stress intensity and distribution.

Results aim to explain experimentally observed cavity interconnections, contributing insights into damage phenomena in total hip prostheses. The analysis of elliptical cracks in femur surgical cement using the Extended Finite Element Method (X-FEM) further enhances understanding.

2.The model analyzed

This analysis uses the modeling of the three-dimensional femoral implant. This modeling was done using the finite element calculation software: Abaqus 9.1 (ABAQUS Ver 6-5, 2004, User Guide). The cylindrical geometry of a femoral implant, linked to the bone via the orthopedic cement, is shown in Figure 1. This model was developed by Huiskes [9]. In his static analysis, this author considers the transverse load applied equally to 600N. It shows that the effect of axial compression is very small [10, 11and 12]. The cavities analyzed are located in the area of the most highly mechanically stressed cement. That is to say on the part of the cement which is under high-stress intensities. It is in this part where the risk of rupture of the cement, and therefore of loosening, is most likely.

Due to its high geometrical symmetry, a half-model of the structure made up of more than 100000 elements was analyzed. The mechanical properties of the constituents of the total hip prosthesis, whose behavior is assumed to be elastic, are shown in Table 1.

3.Results

3.1 Stress distribution in the cement

For a better illustration of the effect of the presence of a cavity in the orthopedic cement on the intensity and distribution of Von Mises equivalent stress induced in this component subjected to mechanical stresses, we have shown in Figure1 the variation of this stress in the two proximal and distal parts of the healthy cement, that is to say, containing no defects (cavities). This figure shows that the implant-cement interface concentrates the stresses more strongly. Indeed, their intensity at this interface is clearly higher than that at the core of the cement and its interface with the bone. At the Neighborhood very close to the interface with the implant, in its proximal part, the cement is strongly mechanically stressed. This high level of stress is due to the interface interaction (cement-implant) -element. It is in this zone of strong stresses of the cement or will be localized the cavities in order to analyze their effect on its mechanical behavior.

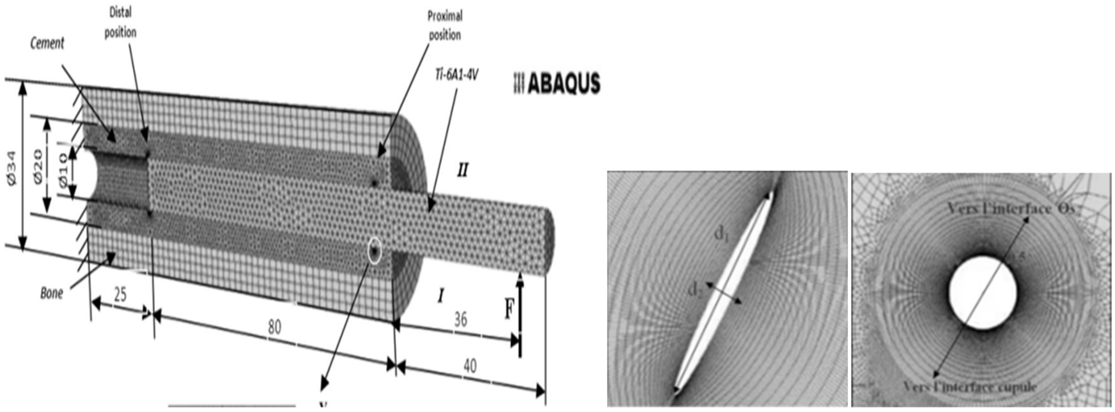

Fig. 2-Position and size cavity in the cement and mesh used around this defect.

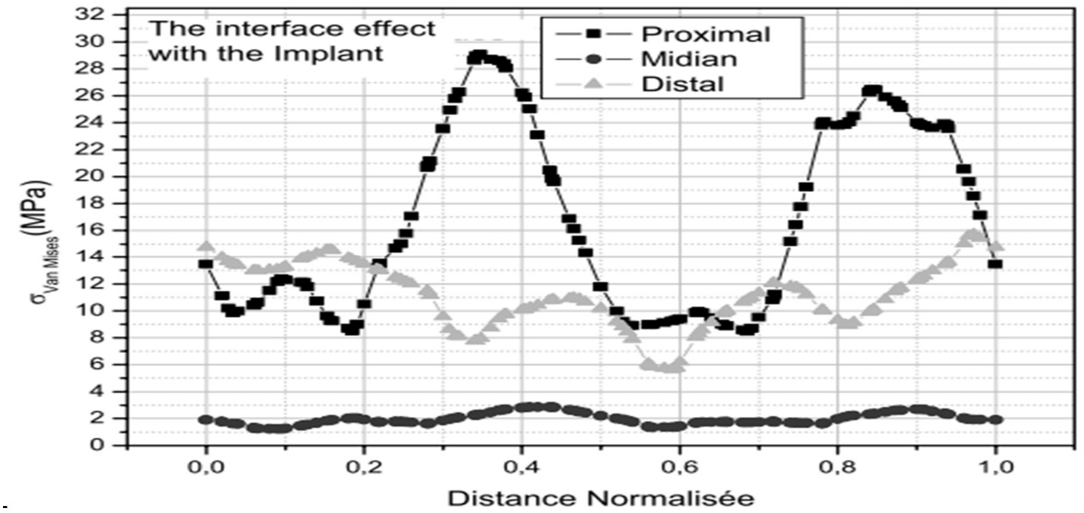

Fig. 3- The distribution of Von Mises equivalent stress induced in the cement around the cavity located in this constituent near the interface with the implant.

3.2 Effect of cavity position

The effect of two positions of the cavity in the orthopedic cement on the level and distribution of the equivalent stress of Von Mises induced by mechanical forces was analyzed (Figure 2).

3.3 Localized cavity near the interface with the implant

In Figure 3 is illustrated the amplitude of the stress induced in the orthopedic cement under the effect of the mechanical stresses applied to the implant. This figure clearly shows that the cement is strongly stressed in its proximal part and that this stress is higher the greater the mechanical loading. It is in the distal part where the effect of this position of the cavity is more marked. In this part of the cement, the induced stress has practically doubled in intensity.

The cavity is located in the part of the cement most strongly mechanically stressed. That is, in the proximal and distal areas of the cement in the vicinity very close to the interface with the implant. It is in this part where the risk of damage to the cement is higher. An analysis of the distribution of the equivalent stress of Von Mises and of its induced intensity in the orthopedic cement around the cavity was carried out.

The results thus obtained are shown in Figure 4. (a, b), (c, d), respectively for the proximal and distal part. The latter shows that the level of the Von Mises stress induced in the orthopedic cement around the cavity has two maxima corresponding substantially to the angles of 45 ° and 225 ° (π / 4-5π / 4) and two minima at 157 ° and 300 ° around the cavity. These stresses put the orthopedic cement in tension, the intensity of which depends on the position around the cavity. The effect of the diameter ratio does not appear at the contour of the defects; the results illustrated in these figures show that the presence of a cavity located in the cement in the vicinity very close to the interface with the implant and subjected to mechanical stresses induced equivalent stresses whose intensity tends towards that of rupture in cement traction. Such stresses may lead to loosening of the prosthesis. Such a level of the equivalent stress can be explained by the combined effect of the interactions between the cement-interface and cement-cavity stress fields.

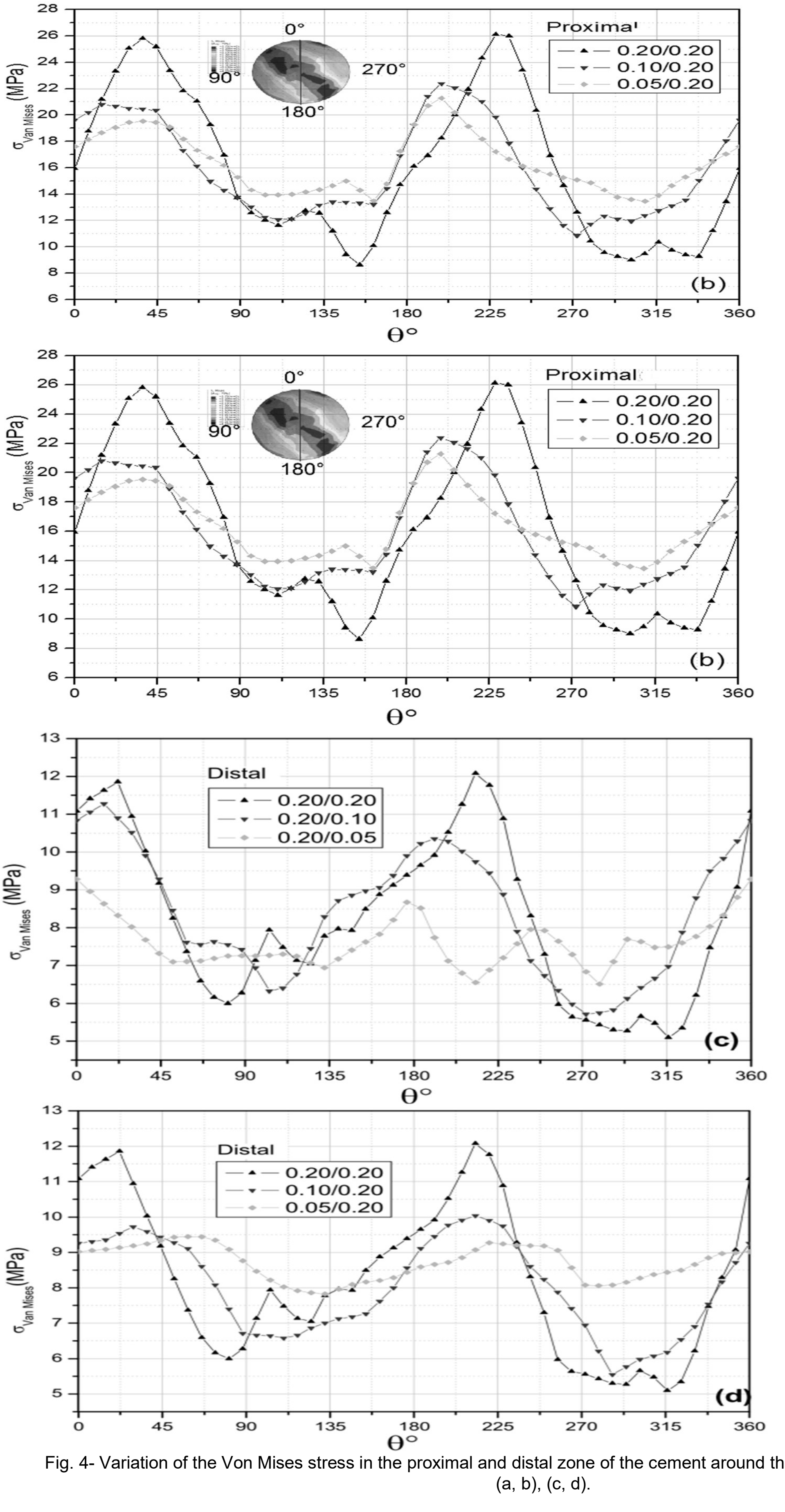

Fig. 4- Variation of the Von Mises stress in the proximal and distal zone of the cement around the cavity as a function of its shape (a, b), (c, d).

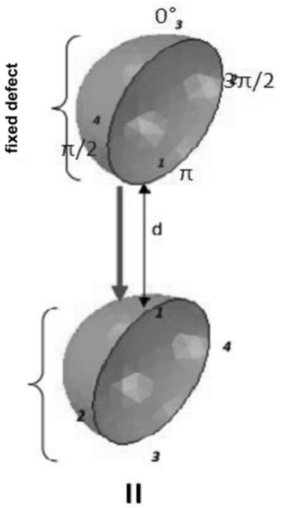

Fig. 5- Representation of the inter-cavity distance simulating their volumic fraction of these defects in the cement.

3.4 Effect of cavity interaction

If the volume fraction of the cavities present in the orthopedic cement facilitates the transport of matter (transport of antibiotics) at a great distance, it is a determining factor in the mechanical behavior of the cement. Indeed, the presence of cavities can weaken the cement by interaction effect and therefore condition the durability of the total hip prosthesis. The objective of this part of the work is to analyze the cavity-cavity interaction effect, characterized by cavity-cavity inter-distance (Figure 5), on the level and the distribution of the equivalent stress of Von Mises induced in the orthopedic cement between two cavities

The cavity is located in the part of the cement under very high tension stresses (near the interface with the implant). This localization makes it possible to analyze the effects of cement-interface interaction. The level of the equivalent stress of Von Mises around the cavity was analyzed in the cement in its proximal and distal parts.

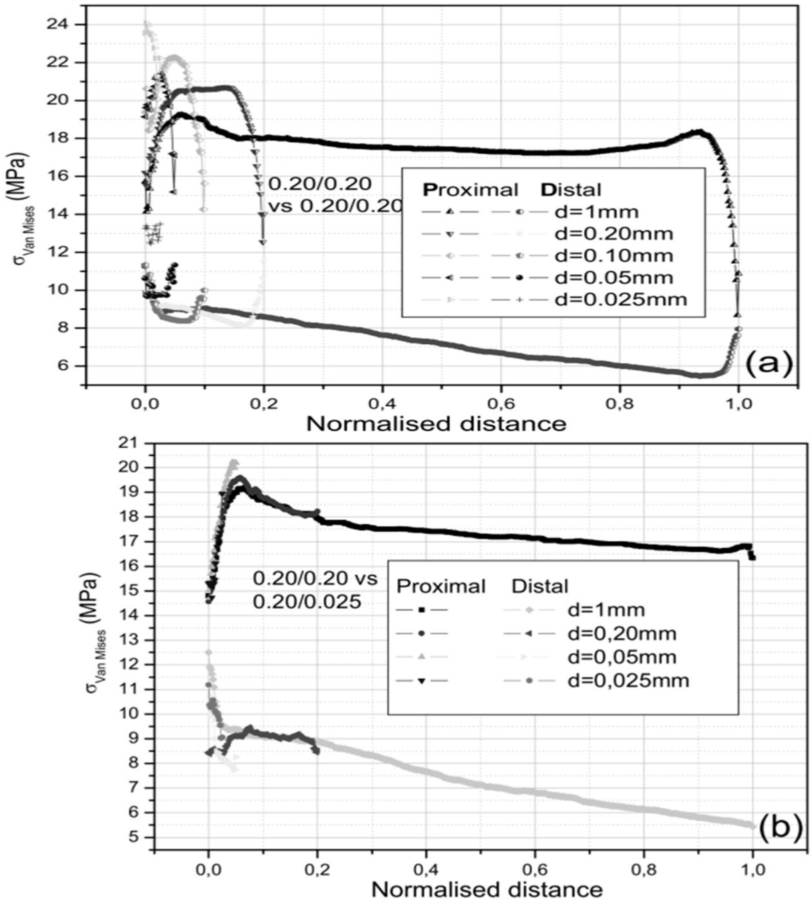

Fig. 6 continues on next page

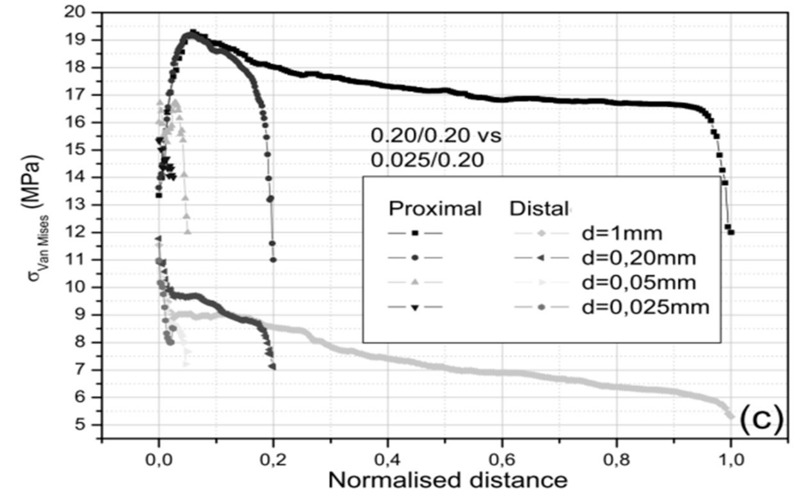

Fig. 6- Distribution of the stress at the inter-distance of a circular cavity with another of different ratio d1/d2 (a, b and c).

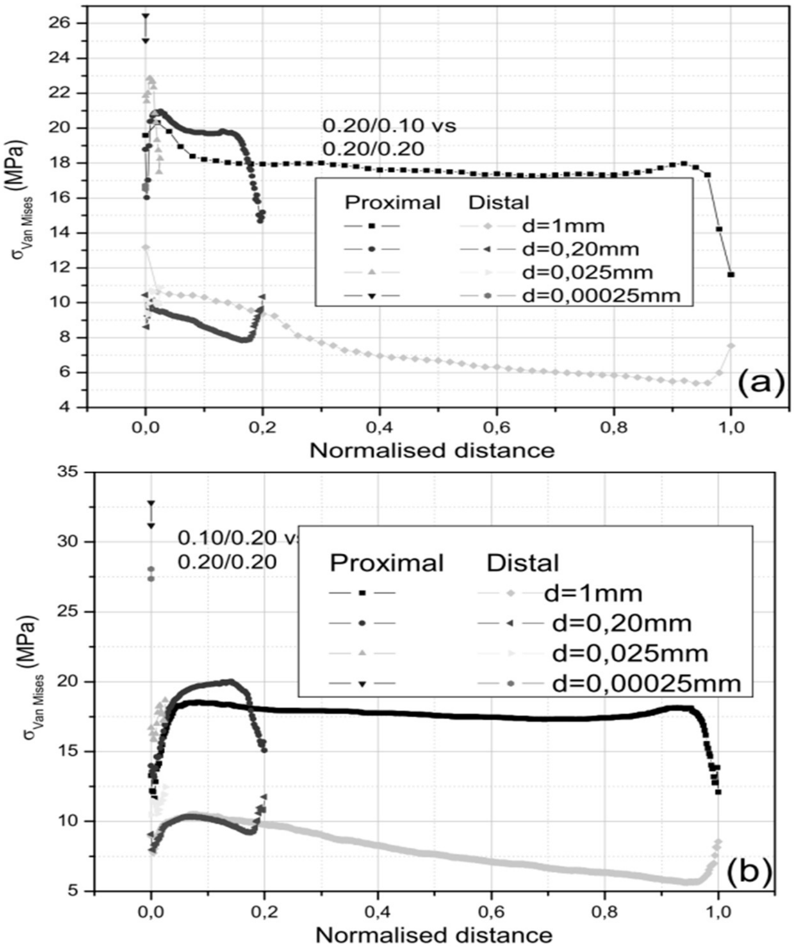

Fig. 7- Distribution of the stresses at the ellipsoidal cavity inter-distance (0.10 / 0.20) with a circular cavity (a, b).

In Figure 6 (a, b, c) and Figure7 (a, b) is shown the variation of Von Mises equivalent stress induced in the cement in its proximal and distal parts as a function of diameter ratio and the cavity-cavity inter-distance (d), defined by the angles d1 / d2, of the second cavity with respect to the first. These figures clearly show that, compared to a single cavity, the location of a second close to another armature in the cement between these two cavities represents a much more significant equivalent stress whatever its position. This is mainly due to the interaction of stress fields induced in the cement around these two cavities. However, a significant increase in the stresses relating to Figure 7 (a, b) in the cement around the cavity under consideration will be noted.

The latter show that, compared to a single cavity, an approximation of the movable defect to the fixed one leads to an intensification of the equivalent stress in the cement between these two cavities in its proximal and distal parts. The circular defect concentrates the constraints more than the other ratios; if the defect is fixed, the inverse phenomenon when the fixed defect becomes ellipsoidal; the constraints are very fatal.

3.5 Cavity Fraction Effect

In this part of the work we are interested in the effect of the volume fraction simulating by the finite element method the interaction effect of several cavities (Figure 8).

Whatever the shape of the microcavity in the cement, it is subjected to a field of tension and compression stresses. In other words, the cement in the vicinity very close to the microcavity is stressed on one side by tension stresses and on the side perpendicular to the first, at compression stresses. This stress field can lead to the deformation of this defect which passes from its initially spherical shape to an ellipsoidal shape.

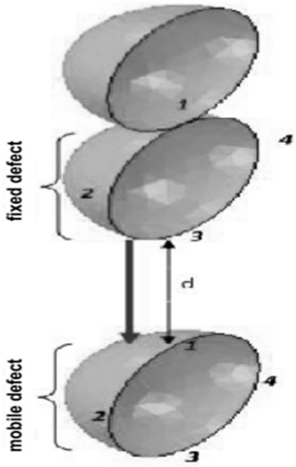

Fig. 8- Representation of the inter-cavity distance simulating their volume fraction of these defects in the cement.

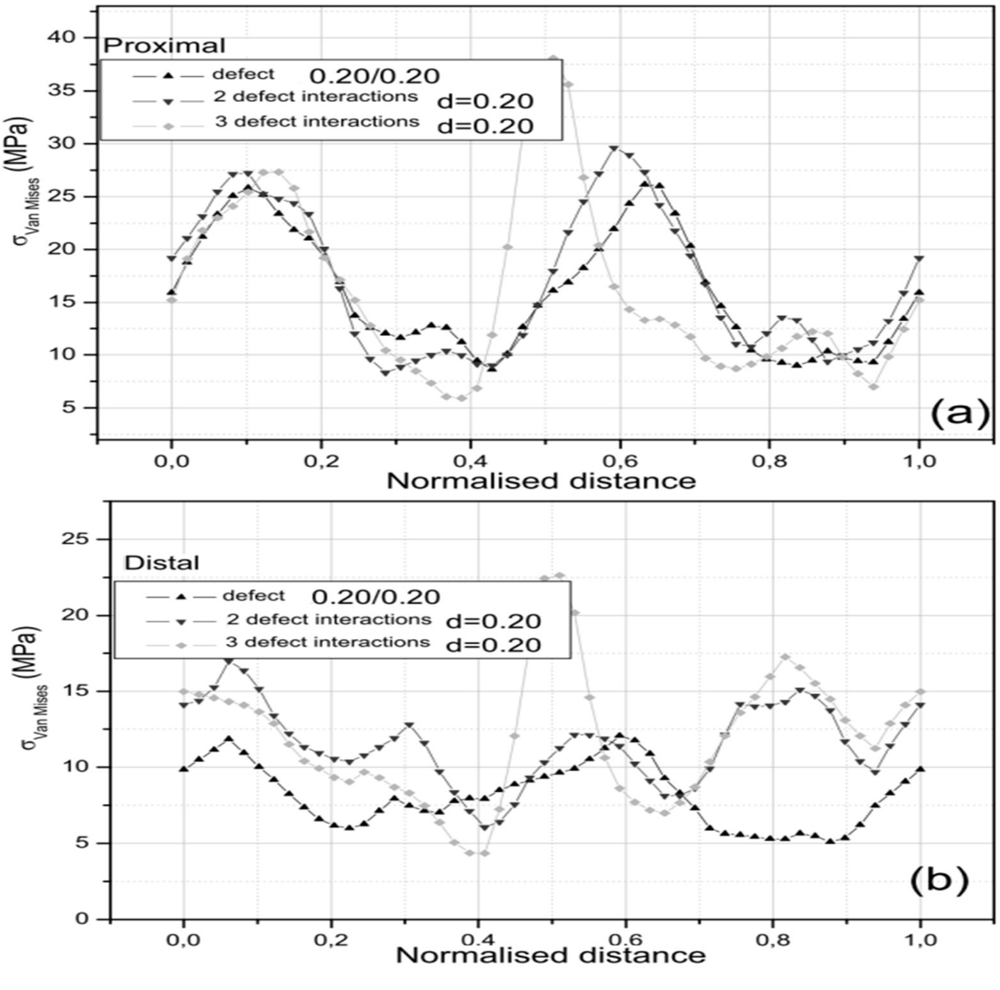

Fig. 9- Comparison of the Von Mises equivalent stress around the fixed cavity as a function of the distance separating it to the mobile cavity for the three studied cases at a distance d = 0.20mm

Figure 9(a,b) shows the stress distribution in the cement at the mediator defect contour and close vicinity of a fixed defect at a distance of 0.20 mm, and as a function of the third defect distance. The comparison of the stresses in the cement ensuring the junction is very strongly concentrated in the vicinity of this defect; farther into the cement, their intensity drops considerably. This clearly shows that the presence of a volume fraction generates a large increase in the Von Mises stress.

4. Discussion

The porosity in the orthopedic cement plays a decisive role in the diffusion of antibiotics. It constitutes a material transfer pathway. The results obtained in this work show that its presence in the orthopedic cement is a source of stress concentration by notch effect. This effect is all the more important as the cavity is located in the vicinity very close to the interface with the implant. This cavity-interface interaction weakens the cement in tension. From the interaction of strongly localized stress fields at this interface and near the cavity results from the stresses of Von Mises in the cement between these two defects equivalent to the tensile stress of this component. Such a position of the cavity presents a great risk of loosening the total hip prosthesis. This behavior is strongly accentuated by the location, in this cement zone, of two cavities very close to one another. Indeed, the level of the stresses induced in the cement between these two defects reaches that of its rupture stress in compression.

5.Conclusion

The results obtained in this work show that:

- The cement-implant interface is the seat of stress concentration, the equivalent stress of Von Mises induced in the cement, in its proximal part, in the vicinity very close to this interface tends towards the tensile stress of this constituent;
- The presence of the cavity in the orthopedic cement is an additional source of stress by notch effect. Its location near this interface generates greater stresses in the cement. This increase is the result of a double effect: cement-interface interaction and cavity-cement;
- The most important Von Mises equivalent stress induced in the cement at the interface with the cavity is located along an oriented axis of π / 4 - 3π / 2 with respect to the center of gravity;
- Compared to a cavity, the existence of the second cavity near a first generates stronger Von Mises stresses in the orthopedic cement. The intensity of these stresses depends on the position of second with respect to the first.

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