MIXED MODE FRACTURE IN RECONSTRUCTED ACETABULUM

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ABSTRACT

In Total Hip Replacement surgeries, a ball-socket structure is used to replace the diseased or damaged hip joint. The replacement cup socket is usually attached to the pelvis by acrylic cement. It has been found that loosening of the acetabular cup is the most common cause for long-term instability of the reconstruction. Recently, we conducted a finite element analysis of a reconstructed acetabulum under physiological loading conditions. The results showed that the stresses in the cement mantel are multiaxial and higher than those in either the adjacent cup or bone. This finding, together with the unavoidable pores in the cement during mixing as reported, has prompted a research into mixed mode fracture behaviour in reconstructed acetabulum. Cracks of selected orientations and geometries in the cement mantel and at the bone-cement interface will be analysed. Crack driving force in terms of stress intensities K_I and K_{II} will be evaluated. Possible crack paths within the cement mantle and at the cement/bone interface will also be examined. The work aims to provide a predictive tool for pre/post operative assessment of cemented acetabular reconstructions.

1 INTRODUCTION

Total Hip Replacement (THR) is one of the most successful surgical procedures ever developed where a ball-socket structure is used to replace the diseased or damaged hip joint. The replacement cup socket is usually attached to the pelvis by acrylic bone cement, which consists of a solid component of polymethylmethacrylate (PMMA) powder and a liquid component of monomethylmethacrylate (MMA). When mixing together, polymerization takes place and within a few minutes of application to the bone cavity, the mixture becomes solid. Figure 1 shows a schematic of a cemented THR where the acetabular cup is fixed by the cement to the pelvic bone. The stability of the fixation critically depends on the integrity of the bone cement under typical physiological loading conditions. At least one million loading cycles per year would be experienced by the hip joint with the maximum hip contact force up to three times of body weight during walking.

Aseptic loosening in cemented acetabular components has been identified as the most common cause for the loss of long-term stability in THR [1]. The late failure rate in acetabular cups has been reported to be three times of that of femoral components twenty years postoperation [2]. Although the failure mechanisms have not been well understood, retrieval studies [3] seem to suggest that the predominant form of failure is fracture in the cement mantle and at the bone-cement interface. Despite of numerous studies on fatigue of cement [4] and sophisticated finite element models of damage accumulation in the cement mantle [5], the problem of crack propagation has not yet been dealt with using appropriate fracture mechanics techniques. This is particularly relevant to cemented reconstructions, where complex stress state around the implant may promote early crack initiation. Consequently, crack propagation would form the dominant part of the fatigue life, as opposed to the failure of smooth specimens where up to 90% of the fatigue life may be spent on crack initiation [5]. Detailed studies are needed to look at the crack driving force under multi-axial loading conditions with a view to developing a predictive tool for pre-clinical prosthetic assessment.

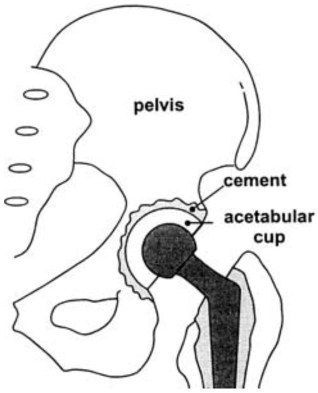

Figure 1 Schematic of cemented acetabulum.

The objectives of this work were to investigate the stress distributions in a cemented acetabular reconstruction, particularly the stress fields in the cement mantle and at the bone-cement interface using the finite element method. Local radial, tangential and shear stress components were obtained and subsequently used in a fracture mechanics analysis of a cracked acetabular reconstruction. Potential failure modes were identified and mixed mode fracture at the bone-cement interface and in the cement mantle was studied.

2 FINITE ELEMENT ANALYSIS OF IMPLANTED ACETABULUM

The plane strain finite element model of a natural hip joint was adapted from Rapperport *et al* [6]. The model was generated from a roentgenogram of a 4 mm slice normal to the acetabulum through the pubic and ilium. The model was divided into 24 regions of different elastic constants with isotropic material properties assumed in each region. The main regions were cortical bone, subchondral bone, trabecular bone and cartilage. The trabecular bone region was further divided into smaller regions to account for the different densities of the bone in different areas within the region. The femoral head was modeled as a spherical surface that was mated with a congruent spherical acetabular socket. The model was meshed using quadrilateral and triangular plane strain elements. The implanted hip model was developed by modifying the natural hip model. The cartilage on the acetabular side was substituted with an UHMWPE cup secured with bone cement and the natural femoral head with a replacement made of cobalt chromium alloy. The diameter of the replacement head was 28 mm while the thickness of the UHMWPE cup was 10 mm. The cement mantle was assumed to be uniform with a thickness of 2 mm. The configuration was chosen to be representative of a cemented THR. The interfaces between the cement and the cup, the cement and the subchondral bone were assumed to be fully bonded, while the articulating surfaces assumed to be frictionless. A total of 3673 elements and 3265 nodes were used for the reconstructed model, as shown in Figure 2. The bone properties were taken from Rapperport *et al* [6], properties for acrylic were from Taylor *et al* [7] and properties of Co-Cr alloy and UHMWPE were from Mak & Jin [8].

The hip contact force during normal walking was adopted from Bergmann [9]. Five selected load cases were used with an average body weight of 70 kg assumed. The sacroiliac joint was fully fixed while the pubic joint was allowed to move in the sagittal plane, a boundary condition considered to be representative of anatomic configuration [6]. The contact was assumed to be frictionless under small sliding conditions and the analyses were carried out using ABAQUS (6.2).

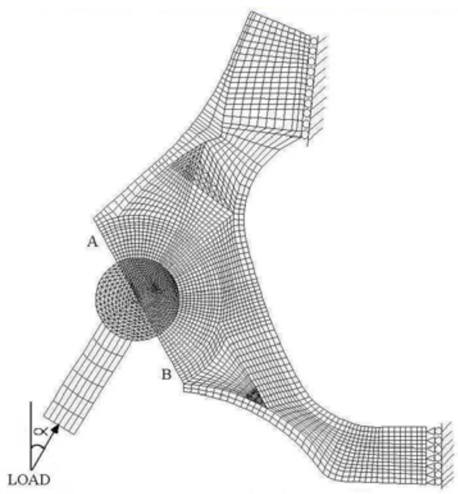

Figure 2   The finite element model used for the reconstructed acetabulum.

The stresses were obtained in a local polar coordinate system that is aligned normally with the joint surface. Radial, σ_{rr}, tangential, $\sigma_{\theta\theta}$ and shear, $\sigma_{r\theta}$ stresses in the cement mantle were calculated and presented in Figure 3 for one-legged stance where the hip contact force is maximum. The maximum tangential stress appears to occur around 70°, corresponding to the maximum compressive radial stress; while the shear stresses are generally small in comparison.

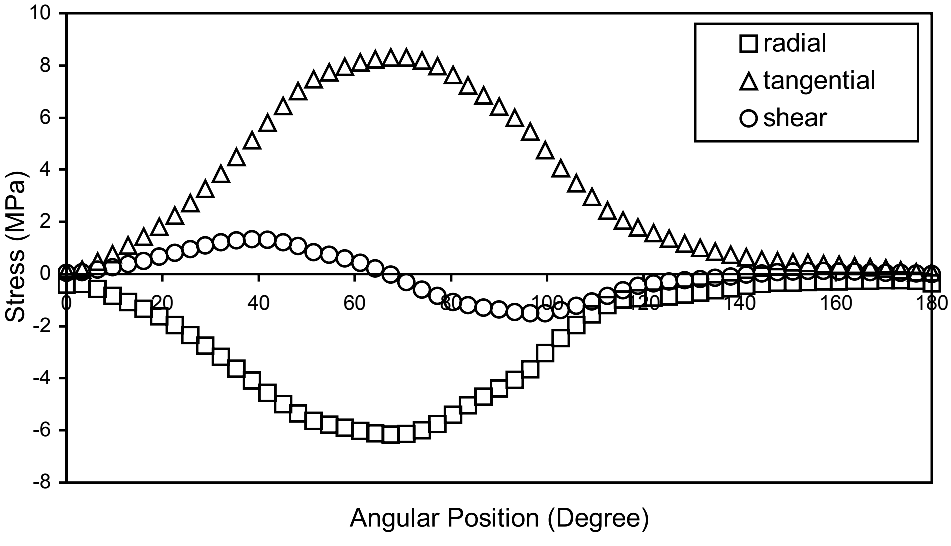

Figure 3 Stress distributions in the bone cement mantle.

3 FRACTURE MECHANICS ANALYSIS

Since the stress gradients in the cement mantle were found to be very small, the stress distributions at the interface between the cement and bone were assumed to be similar to those in the cement mantle. Potential sites and modes of fracture may be identified by examining the stress distributions in the cement mantle. At an angular position of ~70°, the maximum tangential stress would encourage radial growth from a pore in the cement. The radial stress is negative and shear stress is negligible, hence the crack growth may be predominantly mode I. At approximately 55°, combined tangential and shear stresses may promote mixed mode crack growth, again in the cement mantle. Failures by interfacial cracking seem to be unlikely where appreciable compressive radial stresses exist. However, there are other load cases where the direction as well as the magnitude of the hip contact force varies hence the stress fields in the cement will also change. In what follows, three cracks were assumed in the cement mantle and at the bone-cement interface, and fracture mechanics techniques were used to deal with these cracks for five typical loading conditions during one complete cycle of normal walking.

3.1 Fracture in the cement mantle

The acrylic cement was assumed to be elastic and LEFM analysis was used for the analysis. Finite element analyses of cracked reconstruction were performed and stress intensity factors K_I and K_{II} were calculated for each crack. The effective stress intensity factor k_I and the direction of the crack growth, θ, may be obtained using the MTS criterion:

$$k_I = \cos\left(\frac{\theta}{2}\right)\left\{K_I \cos^2\frac{\theta}{2} - \frac{3}{2}K_{II}\sin\theta\right\} \tag{1}$$

$$\theta = \cos^{-1}\left(\frac{3K_{II}^2 + \sqrt{K_I^4 + 8K_I^2K_{II}^2}}{K_I^2 + 9K_{II}^2}\right) \tag{2}$$

3.2 Fracture at the bone-cement interface

Interfacial cracks may be treated with complex stress intensity factors, as suggested by Rice [10]:

$$K = K_I + iK_{II} \tag{3}$$

The singular stress field may be given by:

$$\sigma_{22} + i\sigma_{12} = (K_1 + iK_2)(2\pi r)^{-1/2} r^{i\varepsilon} \tag{4}$$

The bi-material constant ε is given by

$$\varepsilon = \frac{1}{2\pi}\ln\left(\frac{1-\beta}{1+\beta}\right)$$

and $$\beta = \frac{1}{2}\frac{G_1(1-2\nu_2)-G_2(1-2\nu_1)}{G_1(1-\nu_2)+G_2(1-\nu_1)}$$

where G_1 and ν_1 are shear modulus and Poisson's ratio of the cement (G_1=1.54 GPa, ν_1=0.3); and G_2 and ν_2 are shear modulus and Poisson's ratio of the bone (G_1=0.13 GPa, ν_1=0.32). The calculated bi-material constants are $\beta = 0.22$ and $\varepsilon = -0.071$.

4 RESULTS AND DISCUSSION

Two radial cracks were inserted in the mid-plane of the cement mantle at angular positions approximately 55° (crack 1) and 70° (crack 2) and one tangential crack (crack 3) was inserted at the bone-cement interface at ~100°. For the convenience of the analyses, the crack length was assumed to be 1 mm in all cases. The stress intensity factors for each crack were obtained from the individual crack model. The interaction between the cracks was also examined using a multiple crack model and found to be negligible. Singular elements were created around the crack tips and a radial dimension of 10 μm and an angular division of 15° were used near the crack tip to ensure convergence of the *J*-integrals and subsequent extraction of the stress intensity factors.

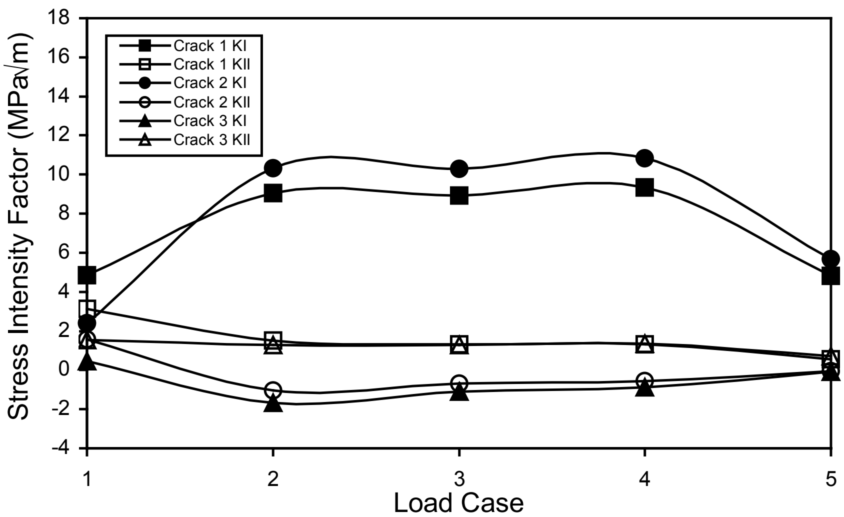

Figure 4 Calculated stress intensity factors at the potential failure sites.

Figure 4 shows a summary of the results of the stress intensity factors at the three crack tips, where only the stress intensity factors at the crack tips near the bone are presented. For the interfacial crack, the real and imaginary parts are presented as analogous K_I and K_{II} values. It seems clear that given the same probability of the distribution and size of the pores, crack growth in the cement mantle would seem to be the most likely event, as the stress intensities in the cement mantle are consistently higher than those at the bone-cement interface. The crack paths in the cement are predominantly in the radial direction, as predicted by the MTS criterion, with θ < 20°

except at the beginning of the heel strike (load case 1). The stress intensities of crack 3 are much lower than those of cracks 1 and 2, hence interfacial cracking seems to be unlikely at this location. For a crack originally at the bone-cement interface, the current study shows that the preferred path is to extend into the cement mantle. For interfacial cracks, the crack path depends on the relative fracture energy Γ_i / Γ_s, where Γ_i is the fracture energy of the interface and Γ_s is the fracture energy of the brittle constituent, and the phase angle ψ :

$$\psi \approx tan^{-1}\left(\frac{K_{II}}{K_I}\right)$$

A failure locus [11] has been proposed based on the above theory, where for $45^\circ \leq \psi \leq 90^\circ$, as in the current case, the predominant failure mode is substrate cracking when $\Gamma_i / \Gamma_S \geq 0.5$. In the present material systems, the fracture toughness of the cement was reported to be 1.5 MPa√m [12] or 570 J/m^2 for fracture energy. The interfacial fracture energy was reported to be 350 J/m^2 for mode I and 1000 J/m^2 for mode II loading condition [13]. This prediction appears to be consistent with the observation from our current retrieval studies [14], where cement fracture seems to be most common.

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