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Finite element analysis of circumferential crack behavior in cement–femoral prosthesis interface

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ABSTRACT

Investigating the crack behavior in the cement mantle can improve total hip replacement performance by lessening the effects of crack failure and femoral prosthesis loosening. This study analyzed the behavior of the internal circumferential cracks located in the cement layer of the cement–prosthesis interface during the main phases of the gait cycle. The extended finite element method was used in determining the stress intensity factors to identify the crack behavior. An adverse relationship was found between the stress intensity factors and the distance from the distal end. Consequently, the maximum stress intensity factors were observed at the distal part, specifically at the corner of the cement mantle. Additionally, the highest values of K_I, K_{II}, and K_{III} were presented during the single leg stance and push off phases, whereas the swing phase showed the minimum stress intensity factors. In addition, K_I and K_{III} were identified to be the dominant stress intensity factors and were respectively enhanced along the proximal to the distal end by about 89.5% and 65.9% in the lateral side and 63.7% and 56.5% in the medial side. This finding indicates higher risks of cement mantle fracture and fatigue crack propagation at the distal area.

1. Introduction

Total hip replacement (THR) has become the second most performed surgical procedure every year [1]. In THR, the femoral prosthesis can be fixed by either cement or cementless methods in the patient's bones. In both procedures, the stability of the prosthesis in the hosted bone plays a significant role in the long-term durability of the THR [1,2]. In the cemented femoral prosthesis, the structural strength of the THR is provided by the cement, which must withstand the mechanical stresses that may potentially result in the generation and propagation of cracks and in the eventual failure of the entire THR structure [3–5]. Therefore, analyzing the crack behavior in the cement layer is vital to the prediction of femoral prosthesis stability and to the prevention of cement mantle failure in the hosted bone.

Jasty et al. [5] determined that most of the cracks in the cement are initiated at the corners, or where the cement mantle is thin or incomplete. Verdonschot and Huiskes [6] reported that damage accumulation is affected by the prosthesis–cement deboning, which significantly accelerates the failure process. Damage accumulation causes longitudinal and radial cracks along the bounded stem and circumferential cracks along an unbounded one, which is more consistent with actual conditions. Achour et al. [7] and Flitti et al. [4] presented that the mixed-mode crack propagation and the single-mode crack opening growth occur at the distal and proximal zones of the cement layer, respectively. The majority of previous studies were performed using a two-dimensional (2D) crack analysis on THR by the standard finite element method (FEM). However, a FEM is a powerful tool in a multiscale analysis [8]; using the standard FEM in crack analysis has some limitations, such as mesh and singularity generation. The extended finite element method (XFEM) as a powerful tool for conducting crack analysis with minimal re-meshing was introduced by Belytschko and Black [9,10]. This method has shown good accuracy in measuring crack growth paths and fracture parameters [11]. Nowadays, the XFEM is widely employed in deriving stress intensity factors (SIFs). This method has been employed to compute for the SIFs in functionally graded materials [12], interface cracks [13], orthotropic biomaterial [14], bending plates [15], and sharp V-notches [16]. In the XFEM, the standard finite element shape functions are enriched locally with asymptotic and Heaviside functions to present singularity at the crack tip and discontinuity [17,18]. The displacement vector function u can be approximated with the partition of unity enrichment as.

$$u = \sum_{I=1}^{N} N_I(x) \left[u_I + H(x)a_I + \sum_{\alpha=1}^{4} F_\alpha(x) b_I^\alpha \right], \tag{1}$$

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where $N_I(x)$ and u_I are the standard finite element shape functions and the nodal displacement vector associated with the continuous part of the finite element solution, respectively. a_I is the additional nodal degrees of freedom vector. $H(x)$ is the discontinuous jump function across the crack surfaces, which is given by

$$H(x) = \begin{cases} 1 & if(x - x^*) \cdot n \geq 0, \\ -1 & \text{otherwise}, \end{cases} \quad (2)$$

where x is a sample (Gauss) point, x^* is the point on the crack closest to x, and n is the unit outward normal to the crack at x^*. b_I^α is the product of the nodal enriched degree of freedom vector. $f_\alpha(x)$ is the asymptotic crack tip functions in an isotropic elastic material, which are given by

$$f_\alpha(x) = \left\{ \sqrt{r}\cos\left(\frac{\theta}{2}\right), \sqrt{r}\sin\left(\frac{\theta}{2}\right), \sqrt{r}\sin\left(\frac{\theta}{2}\right)\sin(\theta), \sqrt{r}\cos\left(\frac{\theta}{2}\right)\sin(\theta) \right\}, \quad (3)$$

where (r, θ) is a polar coordinate system with its origin at the crack tip, and $\theta = 0$ is tangent to the crack at the tip.

Although a number of studies have focused on crack behaviors in the THR cement layer, all influential parameters are yet to be fully explored. Therefore, the knowledge and understanding of the impact of the cracks on the THR cement layer must be improved. Accordingly, this study aimed to investigate the behavior of circumferential cracks located in the cement–prosthesis interface at different heights during the main phases of the gait cycle. The XFEM was employed to identify the crack behavior by studying various SIFs, that is, tensile, sliding, and tearing, which are denoted by K_I, K_{II}, and K_{III}, respectively. Therefore, this research may help identify the regions susceptible to crack growth, predict the residual life of THR, optimize the cementing procedure, and postpone THR failure by knowing the crack behavior in the cement layer.

2. Materials and methods

This study aimed to simulate the internal circumferential cracks within the cement layer to analyze the SIFs variations in different cross sections (hoop direction) throughout the cement mantel length (longitudinal direction) during the main phases of a gait cycle. Orthopedic cement is classified as a brittle material [19,20]. Therefore, crack analysis can be performed through linear elastic fracture mechanics. The following sections describe the details of a three-dimensional (3D) modeling of a cemented implanted femur with circumferential cracks.

2.1. Three dimensional model of implanted femur components

A 3D model of the femur analyzed in this study was developed using computed tomography (CT) images comprising 998 slices. The image quality was 512 pixels × 512 pixels, and the thickness was 0.549 mm. Using Mimics (Materialise NV, Belgium), the 3D models of the femur was constructed based on the CT images. The Pro/Engineer software (Version 5, Parametric Technology Corporation, Needham, MA, USA) was used to create the 3D model of

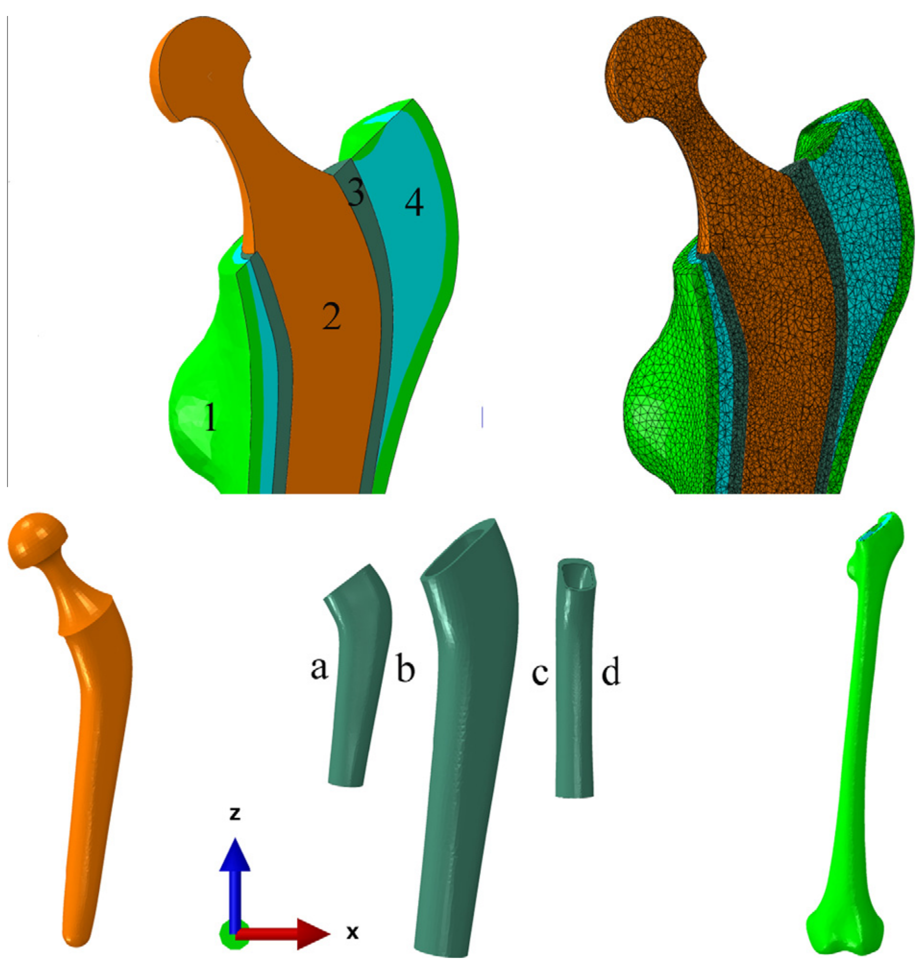

Fig. 1. Three dimensional model of implanted femur components (1) cortical bone, (2) femoral prosthesis, (3) cement ((a) medial, (b) lateral, (c) anterior, (d) posterior), (4) spongy bone.