Biomechanical Finite Element Analysis of Bone Cemented Hip Crack Initiation According to Stem Design

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The purpose of this investigation was to determine the specific fracture mechanics response of cracks that initiate at the stem-cement interface and propagate into the cement mantle. Two-dimensional finite element models of idealized stem-cement-bone cross-sections from the proximal femur were developed for this study. Two general stem types were considered ; Rectangular shape and Charnley type stem designs. The FE results showed that the highest principal stress in the cement mantle for each case occurred in the upper left and lower right regions adjacent to the stem-cement interface. There was also a general decrease in maximum tensile stress with increasing cement mantle thickness for both Rectangular and Charnley-type stem designs. The cement thickness is found to be one of the important fatigue failure parameters which affect the longevity of cemented femoral components, in which the thinner cement was significantly associated with early mechanical failure for shot-time period.

Key Words : Total Hip Replacement, Bone Cement, Femoral Stem, Crack Propagation, Finite Element Method, Biomechanics

1. Introduction

Fracture of the cement mantle in cemented total hip replacements is often indicated as a precursor to eventual clinical loosening of the implant. Fractures are believed to initiate at the stem-cement interface and propagate through the cement mantle, thereby reducing the integrity of the mantle. The mechanism of this process is poorly understood, but evidence of well fixed components retrieved at autopsy reveals these cracks suggesting that a fatigue process may be responsible for the crack initiation and propagation.

Numerous design parameters have been discussed that may contribute to the loosening process of cemented femoral hip components including cement mantle thickness, stem design, bonding characteristics of the stem-cement interface, as well as, presence of pores near the stem-cement interface. However, the consequence of changing these mechanical features on the crack propagation process in the cement mantle is unclear.

The purpose of the present investigation was to first, determine the specific fracture mechanics response of cracks that initiate at the stem-cement interface and propagate into the cement mantle. Second, determine the effect of changing stem geometry, cement mantle thickness, and stem geometry on the propensity of crack propagation within the cement mantle. A series of parametric

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studies with finite element models of the stem-cement-bone implant system were used.

2. Materials and Methods

Two-dimensional finite element models of idealized stem-cement-bone cross-sections from the proximal femur were developed for this study. Two general stem types were considered. One (Fig. 1(A)) had a rectangular shape with fillet radius, $r=1$ mm, that is similar to existing stems with a double tapered stem design. The other geometry (Fig. 1(B)) had two flat sides with broad medial and lateral rounded ends ($R=5.7$ mm) that is similar to existing Charnley type stem designs. The rectangular double-tapered and Charnley style stem designs will be termed Rectangular and Charnley-type, respectively. A nominal cement mantle thickness of $t=3.6$ mm was chosen and was defined as the distance from the medial edge of the stem to the endosteal surface of the bone. The bone, which has radius of 18.6 mm, was considered to be concentric circles into which the stem (width=18 mm and depth=9 mm) was inserted.

Plane-strain, linear elastic, isotropic eight and six node quadratic elements were used for the stem ($E=210$ GPa), cement ($E=2.2$ GPa), and bone ($E=17$ GPa) (Fig. 2). More than 4000 elements were used in this model. A Poisson's ratio of 0.3 was used for all materials. Zero-thickness interface elements were added between the stem and cement and a Coulomb friction interface model was applied with a coefficient of friction of 0.3 (Mann et al., 1991). The interface between the cement and bone was assumed to be perfectly bonded to model a well integrated interface. All analyses were performed using the fracture analysis code FRANC developed in Cornell University and this code provides a useful crack tip element (Bittencourt, 1993).

The periosteal surface of the bone and center of the stem were fixed to allow no translation in the x or y direction (Fig. 2). Torsions applied to the stem were used to create stresses within the cement mantle shown in fully three dimensional finite element models of cemented femoral hip

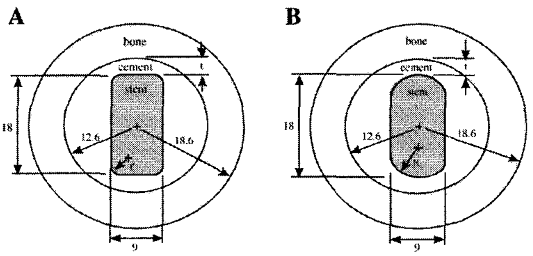


Fig. 1 Geometries of stem-cement-bone cross-sections for Rectangular (A) and Charnley-type stems (B). All units are in millimeters where t=cement mantle thickness, r=fillet radius of the Rectangular stem, and R=medial-lateral radius of the Charnley stem

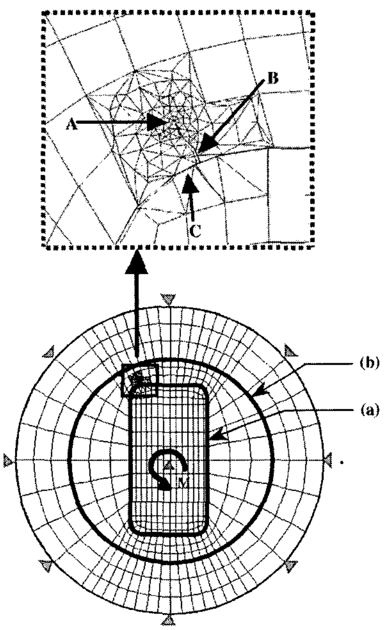


Fig. 2 Finite element mesh of the idealized stem-cement-bone structure used to determine stress intensity factors (SIF) at the crack tip. The stem-cement interface (a) was modeled using a Coulomb friction interface and the cement-bone interface (b) was modeled using displacement compatibility. The model was fixed along the outer perimeter of the cortical bone and coupled point loads, which generate a torque M, were applied to the stem. The focused crack tip rosette (A), crack location in the cement mantle (B), and boundary of the stem and cement (C) are shown as an enlarged inset

components. Coupled point loads were applied to the stem, which provided an equivalent torque of $M=2.58$ N-m/mm depth. The magnitude of the torque was determined in a preliminary study such that it resulted in a maximum tensile stress in the cement mantle of 11 MPa, before introduction of the crack, which is consistent with results from fully three-dimensional models (Mann et al., 1997).

An initial non-linear finite element analysis of each model was performed to determine the location of the maximum principal stress in the cement mantle. An initial crack with very small length ($a=0.2\sim0.3$ mm) was then introduced at this point beginning at the stem-cement interface into the cement mantle in a direction normal to the stem-cement interface (Fig. 3). The crack was then propagated manually in small ($0.2\sim0.3$ mm) increments, using a maximum principal stress criterion to determine the direction of crack propagation (Leis et al., 1986). Crack tip displacement correlation techniques were used to calculate Mode I (K_I) and Mode II (K_{II}) stress intensity factors (Bittencourt, 1993). Although Mode I stress intensity factors dominated the results, at times Mode II stress intensity factors were not negligible, and thus an effective Mode I stress intensity (K_{eff}) factor was determined. The K_{eff}, based on the maximum principal stress criteria, was calculated along with the angle, θ at which the crack would tend to extend (Leis et al., 1986). The value of θ and K_{eff} were determined using, respectively,

$$\tan\frac{\theta}{2}=\frac{K_I}{4K_{II}}+\frac{1}{4}\left[\frac{K_I}{K_{II}}+8\right]^2 \tag{1}$$

$$K_{eff}=K_I\cos^3\frac{\theta}{2}-3K_{II}\cos^2\frac{\theta}{2}\sin\frac{\theta}{2} \tag{2}$$

Paris Law relationships (Barsom et al., 1987) for the fatigue crack propagation rate were applied to simulate how cracks would propagate under cyclic loading and given,

$$\frac{da}{dN}=CK_{eff}^m \tag{3}$$

where N is number of loading cycles, da is increment of crack growth, C and m are material

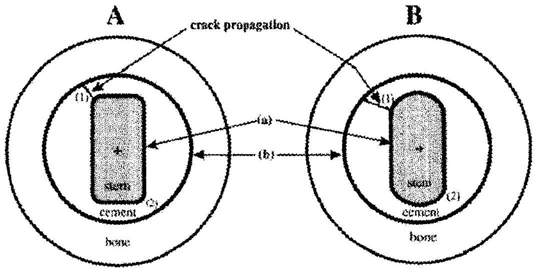


Fig. 3 The crack path within the cement mantle for Rectangular (A) and Charnley-type stem (B) shows the direction of the crack propagation and total crack lengths. The through-crack growth in the cement mantle was assumed to be the point where the crack extends through to the cement-bone interface due to cyclic loading. The highest tensile stresses occurred at points (1) and (2) in the models due to the applied torque

constants for PMMA cement. A number of loading cycles (N) was calculated by integration of equation (3) with respect to a small increment of crack growth. Total number of fatigue cycles was finally estimated by summing the number of cycles at each crack length. Paris Law model constants were taken as $C=9.5\times10^{-4}$ and $m=4.98$ based on previous experimental study measured in meters per cycle (Rimnac et al., 1986).

In addition to the analysis performed on the baseline Rectangular and Charnley-type stems, two fracture propagation parametric studies were performed to evaluate the role of changing cement mantle thickness and Rectangular stem fillet radius. Two additional cement mantle thicknesses ($t=1.6$ mm and $t=2.6$ mm) were created by modifying the initial mesh through reduction of the endosteal bone radius. Thus, the stem geometry remained the same in each case. Finally, the fillet radius for the Rectangular stem was modified ($r=2, 3$, and 4 mm). The $r=4$ mm case resulted in a nearly round end to the stem that was similar to the geometry used in the Charnley-type stem ($R=5.7$ mm). Therefore, changing the fillet radius of the rectangular stem from 1 to 4 mm provided a method to investigate a continuum of stem shapes from nearly rectangular (with no fillets) to a stem with broad medial and lateral radii.

3. Results

The highest principal stress in the cement mantle for each case occurred in the upper left and lower right regions adjacent to the stem-cement interface. The principal stress was directed parallel to the stem-cement interface in each case. There was also a general decrease in maximum tensile stress with increasing cement mantle thickness for both Rectangular (Fig. 4(a)) and Charnley-type (Fig. 4(b)) stem designs. Fillet radius had an appreciable influence on maximum tensile stresses in the cement mantle with decreasing stresses associated with increasing fillet radius (Fig. 4(c)).

The effective Mode I stress intensity factors (K_{eff}) were found to decrease with increasing crack length for all cases (Fig. 5) with SIF values decreasing from 0.2-0.37 MPa·m to near zero as the cracks approached the cement-bone interface. This suggests that the propensity for crack propagation will decrease as the crack grows in the cement mantle. For the Rectangular stem design (Fig. 5(a)), there was a general trend of increasing K_{eff} with increasing cement mantle thickness indicating that cracks would grow more quickly in situations with thicker cement mantles. However, a different trend was found for the Charnley-

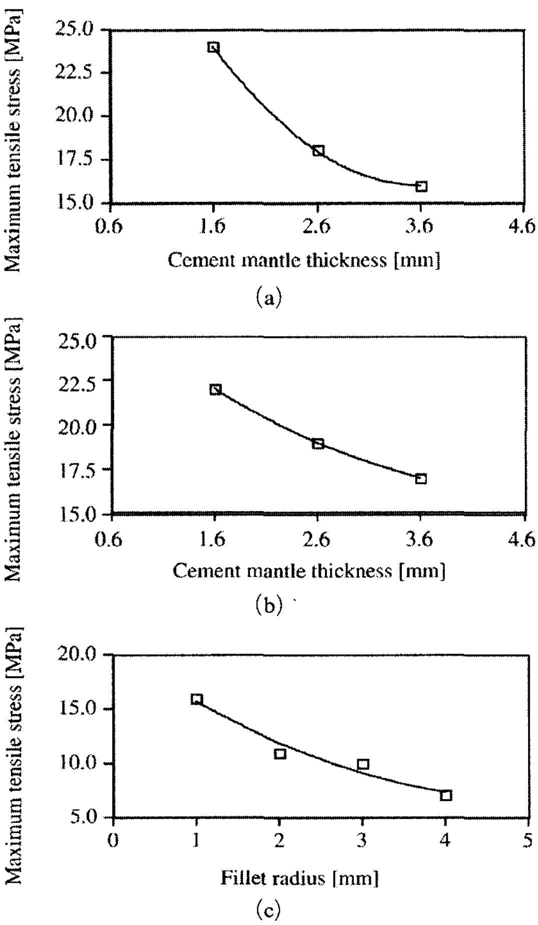


Fig. 4 Maximum tensile stresses within the cement mantle at directly adjacent to the stem-cement interface as a function of cement mantle thickness for Rectangular (a) and Charnley-type stem (b), and as a function of fillet radius for Rectangular stem (c)

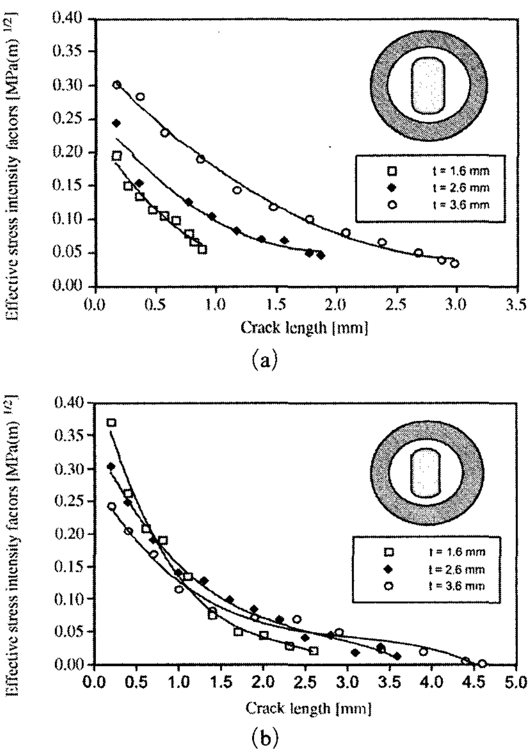


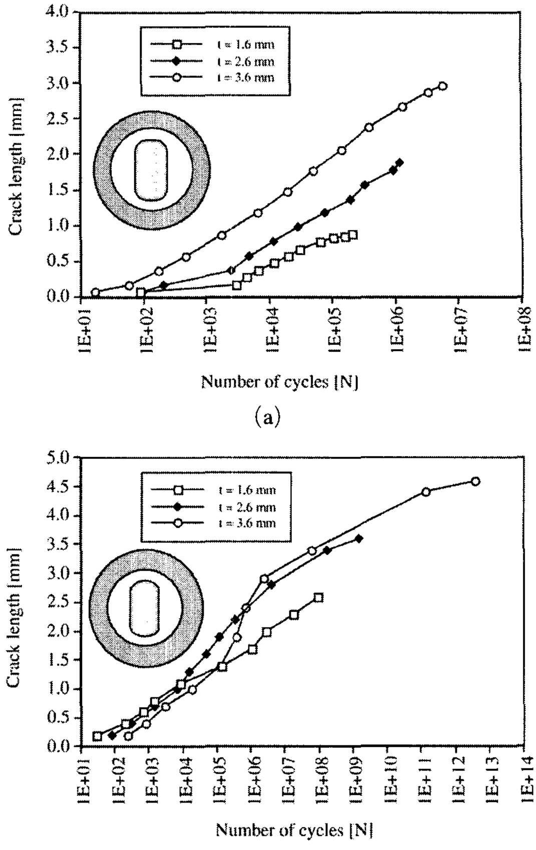
Fig. 5 Effective Mode I stress intensity factors (K_{eff}) on the effects of three different cement mantle thicknesses for Rectangular (a) and Charnley-type stem (b). The values of K_{eff} were plotted as a function of crack length. The highest value of initial K_{eff} occurred in the thin cement mantle case (t=3.6 mm) of the Charnley-type stem when compared to the Rectangular stem

type stems. For the Charnley-type stems with very small cracks (Fig. 5(b)), the results indicate that the K_{eff} can approach 0.37 MPa·m for a thin cement mantle (t=1.6 mm) as compared to 0.25 MPa·m for a thicker (t=3.6 mm) cement mantle. It should be noted, however, that as crack length increases, the trends of increased K_{eff} with increased cement mantle thickness is also evident for the Charnley-type stem.

The ramifications of the K_{eff} histories are most evident through use of the Paris Law models to predict how crack growth occurs under cyclic loading (Fig. 6). For all cases there was a general logarithmic decrease in crack growth rate with increasing number of applied loading cycles. Because cracks were propagated until they approached the cement-bone interface, the total crack lengths were different for the different stem geometries and cement mantle thicknesses. For both the Rectangular and Charnley-type stem designs, the total number of loading cycles needed for the crack to reach the cement-bone interface increased with increased cement mantle thickness. It was also found that the Charnley-type stem exhibited longer total crack lengths when compared to the Rectangular stem, which is due to the difference in orientation of the crack and the total distance between the point of crack initiation and the cement-bone interface (Fig. 3).

In order to compare the different stem type and cement thickness cases it is beneficial to observe the number of loading cycles required to reach a finite crack length (called short crack), chosen here as a=1 mm (Table 1). It was found that the number of loading cycles required to propagate a crack 1 mm was less than one million cycles for all cases (Table 1). However, the trends regarding number of cycles to failure and cement thickness were different for the two stem geometries. For the rectangular stem geometry there was a reduction in number of loading cycles required to propagate a crack one millimeter for thicker cement mantles. The opposite effect was found for the Charnley-type stem.

If it is assumed that failure occurs when the crack propagates through to the cement-bone interface, then the total number of loading cycles to



(b)

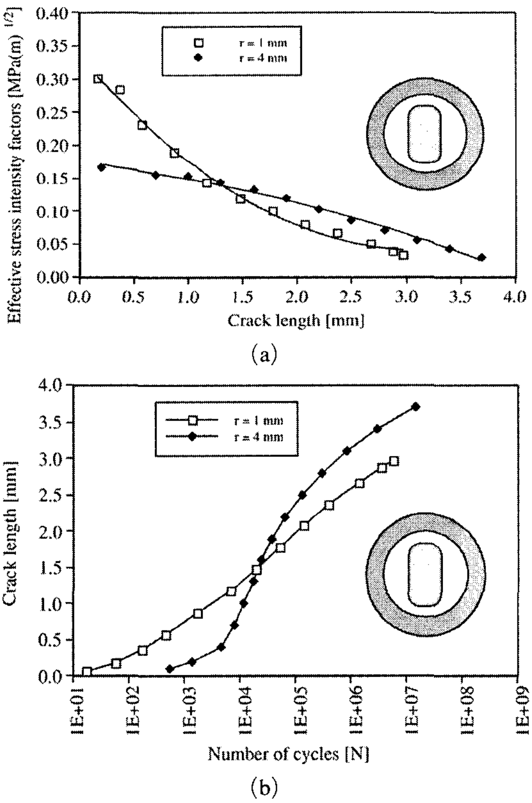
Fig. 6 Crack growth behavior of three different cement mantle thicknesses under cyclic loading for Rectangular (a) and Charnley-type stem (b). A number of loading cycles (N) to failure was plotted as a function of crack growth

failure can be estimated. Further, if it is assumed that a representative number of loading cycles per year is one million, then the estimated life in years for the construct can be calculated (Table 1). The results here suggest that the Rectangular stem would have a lifetime of 0.2 to 6 years before failure as compared to the Charnley-type stem which would have an expected life of between 100 and 4×10^{6} years. Note that for both implant systems the time to failure increases greatly with increasing cement mantle thickness.

Changes in fillet radius of the Rectangular-type stem from r=1 mm to r=4 mm resulted in a substantial (44%) decrease in the initial K_{eff} (Fig. 7 (a)) for small crack length a_o=0.2 mm. The mag-

Table 1 Number of loading cycles required to propagate a short crack (a=1 mm) and a complete through-crack in the cement mantle for the rectangular and Charnley-type stems. An estimate on total time to complete a through-crack is given (in parentheses) where the loading rate was assumed to be one million cycles per year. The largest number of loading cycles for through-crack growth was observed for a thick cement mantle with a Charnley-type stem

	Number of cycles (N) for Rectangular-type		Number of cycles (N) for Charnley-type	
Cement Mantle Thickness : t [mm]	Short Crack [a=1.0 mm]	Through-Crack	Short Crack [a=1.0 mm]	Through-Crack
1.6	209,200	0.21×10^6 (0.21 years)	6,000	96.8×10^6 (96.8 years)
2.6	29,020	1.21×10^6 (1.21 years)	7,000	1.57×109 (1,570 years)
3.6	1,710	5.81×10^6 (5.81 years)	18,300	3.98×10^{12} (3.98×10^6 years)



(b)

Fig. 7 Effective Mode I stress intensity factors (a) and crack growth behavior of the cement mantle (b) on the influence of changing fillet radius of the Rectangular stem. Initial values of K_{eff} shown in Figure 7(a) were 0.30 and 0.17 MPa·m for r=1 mm and r=4 mm, respectively. These values reduced by 44% as increasing fillet radius

nitude of the K_{eff} decreased with further propagation into the cement mantle for both cases. However, at crack lengths above 1.2 mm the K_{eff} for the larger fillet radius (r=4 mm) was greater than the smaller fillet radius case. Although not shown here for clarity of the Fig. 7, the K_{eff} for r=2 and r=3 mm cases resulted in responses between those bounded by the r=1 and r=4 mm cases.

The ramifications of the effective Mode I stress intensity factors are readily apparent through observation of the cyclic crack growth of the two cases (Fig. 7(b)). Here it is noted that the number of loading cycles required to propagate a short crack (a=1 mm) is lower for the stem with a small fillet radius (1,710 cycles) when compared to the stem with a larger fillet radius (10,000 cycles). However, as the crack length increases, the larger fillet radius exhibits much faster crack growth rates such that at one million loading cycles the larger fillet radius case has a crack of 3.2 mm as compared to the 2.6 mm crack for a small fillet radius. At the point of failure, again defined as the point at which the crack propagates through to the cement-bone interface, the total number of loading cycles for the larger fillet radius case (1.4×10^7 cycles) is greater than the smaller fillet radius case (5.8×10^6 cycles). Note that the total crack length is longer for the larger fillet radius because there was effectively a longer distance between the stem-cement and cement-bone interface, when compared to the smaller fillet radius case.

The relationship between fillet radius, cement mantle thickness, and effective Mode I stress intensity factors is shown in Fig. 8. When a small crack length is considered (a_o=0.2 mm), the opposite trend regarding the K_{eff} and cement mantle thickness for the Rectangular (r=1 mm) and Charnley-type (R=5.7 mm) stem is apparent. For the Rectangular stem with larger fillet radius (r=4 mm), it is found that the K_{eff} is relatively insensitive to changes in cement mantle thickness. This intermediate result suggests that there may be a continuum of responses which are a function of fillet or medial-lateral edge radii. Thus, stems with small fillet radii may exhibit increased K_{eff} with increasing cement mantle thickness, intermediate fillet radii may result in K_{eff} that are insensitive to cement mantle thickness, and large fillet radii resulting in decreased K_{eff} with increasing cement mantle thickness.

4. Discussion

The aim of this present study is to elucidate fracture mechanisms of a cement crack starting from the stem-cement interface under influences of cement mantle thicknesses and stem designs in cemented femoral hip components. Many authors (Maloney et al., 1990; Jasty et al., 1990; Star et al., 1994; Ebramzadeh et al., 1994) have clinically issued importance of cement mantle thickness, position of the stem, and stem shape, for example rectangular and round-back stem design, which resulted in mechanical failure and loosening of the cemented femoral component. McCormack et al. (1996) first developed crack model to investigate interfacial crack behavior in the implant system. The model, however, involves neither complete fatigue propagation mechanisms, nor fatigue life of the implant structure. In our knowledge, there is little basic science information to support above clinical evidences on the precise mechanism of crack initiation and fatigue failure process of these components.

The results from our study presented maximum tensile stresses and effective Mode I stress intensity factors (K_{eff}), which are directly correlated with fatigue life of the materials, as functions of cement mantle thicknesses and stem designs in the cemented femoral hip component. The maximum tensile stresses shown in Fig. 4(a) and 4(b) demonstrated that the thinner cement mantle thickness were exposed to higher stress level when compared to the thicker cement mantle. The results are consistent with experimental findings and finite element studies which show that increasing the cement mantle thickness were generally associated with decreasing cement strain and peak tensile cement stresses (Estok et al., 1997).

It was observed that the changes in fillet radius of Rectangular stem, which are correlated with longer cement mantle distance between the point of maximum principal stress at the stem-cement interface and the endosteal surface of the bone, were sensitive to maximum tensile stresses in the cement mantle (Fig. 4(c)). This result may be due to stress concentration effect by shape of the stem corners and partial increment of the cement mantle space (see Fig. 3).

James et al. (1993) first discussed about interfacial pores at the cement-femoral prosthesis interface from autopsy-retrieved femur which is a parameter to decrease strength of the cement-implant interface and may contribute as an initial crack. In this study we assumed that the pore or void in the cement (James et al., 1993) was related with generating a small initial crack under cyclic loading, and the small crack will propagate into the cement mantle, subsequently reaching to the cement-bone interface. The K_{eff} curves and fatigue cycle results from present finite element model describe complete fatigue crack behavior of the cement mantle in the situation of debonded stem-cement interface.

In Fig. 5, highest initial K_{eff} value observed for the Charnley-type stem with thinner cement thickness (t=1.6 mm) intuitively implied that the thin cement with Charnley stem had a rapid crack initiation as compared to other cement thicknesses as well as those with the Rectangular stem. The remarkable decrease in K_{eff} values from initial crack to total crack lengths for all cement thickness cases intimates stable crack propagation which gradually develops fracture of the cement, finally leading to failure of the cemented femoral components.

A number of fatigue cycles shown in Fig. 6 evidently illustrates that the thicker cement mantle prolongs the longevity of the structure for both the Rectangular and Charnley stem when compared to the thinner cement. The trends of fatigue behavior observed in this study was similar to finite element study of Kim and Mann (1999), who simulated general fracture response of cemented femoral components using non-centrally positioned stem. Estimated fatigue life for the Charnley stem with thicker cement mantle was greatly larger than that of the Rectangular stem (Table 1). The thinner cement mantle with the Rectangular stem was shown to have much shorter fatigue life than thinner cement with Charnley stem. The thinner cement mantle tremendously reduced the fatigue life of cemented femoral component as compared to the thicker cement. Estimated fatigue life for short crack (a=1 mm) for all cases (less than one million cycles) clearly demonstrates short-term cement fractures which would be relevant to early loosening of the cemented femoral component (Table 1). The significant reduction of fatigue cycles in the thin cement mantle suggests that the thin cement increases the risk of progressive mechanical failure of the cement, subsequently releasing debris into the cement-bone. These results are consistent with the clinical observations of Ebramzadeh et al. (1994) and Star et al.(1994) who showed radiographic evidence of fractured cement and early loosening of the cemented femoral components in the thin cement. A clinical study by Kawate et al. (1998), also showed that cement thickness with less than 1 mm involved most cracks.

The estimated large number of fatigue cycles for the thicker cement cases (Table 1) indicates that the crack would exist and propagate into the cement mantle, but would not continue through to the cement-bone interface. This result has been observed by Jasty et al.(1990), who showed well tolerated cement-bone interface in retrieved autopsy study, regardless of presence of fractures in the cement-mantle which were debonded at the cement-stem interface.

The estimated fatigue life for all cement cases with Charnley stem (at least 97 years) was surprisingly larger than for those with Rectangular stem (Table 1). Results from changes in fillet radius of the stems also show obvious effects in K_{eff} and fatigue cycles of the structure (Fig. 7). Substantially increased fatigue life (from 6 years to 4 million years) with increasing the fillet radius, especially when rounded medial stem were used, suggests that elimination of the sharp corners of stem can improve fatigue life of the cement and contribute long term success of cemented femoral components. This has been demonstrated by clinical evidences which show that use of metal prosthesis without sharp corners may be an important factor to prevent early failure at the stem-cement interface and provide better outcomes and durability of cemented femoral components (Crowninshield et al., 1980 ; Mulroy and Harris, 1990).

We also investigated effective Mode I stress intensity factors as functions of fillet radius and cement thickness to establish sensitivity of fracture responses on the effects of continuum in fillet radius through r=1 mm to R=5.7 mm in different cement mantle thicknesses. The result shown

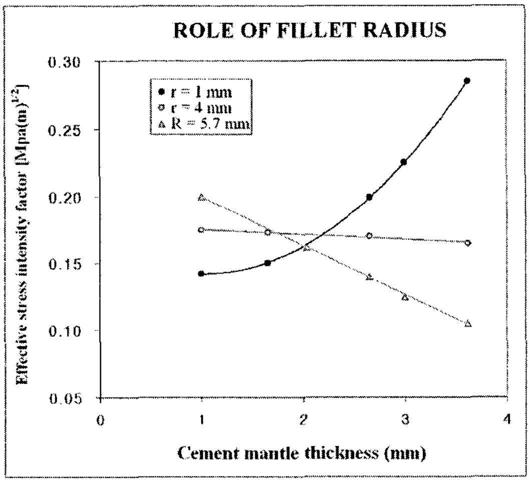


Fig. 8 Effective Mode I stress intensity factors as functions of cement mantle thickness, fillet radius, and medial-lateral radius of stem, showing the responses of the K_{eff} to stem geometries and cement mantle thicknesses. Where a small crack length, a_o=0.2 mm, was introduced

in Fig. 8 is well incorporated with the results of cement mantle thickness for Rectangular and Charnley-type stem and explains opposite effect for the Rectangular and Charnley stem.

It should be noted limitations of the present model. The model was idealized in two dimensions from proximal femur and did not consider the viscoelastic (creep) properties of bone cement, which may directly affect stress magnitudes at the crack tip. The complex three-dimensional loading occurring at the stem was also neglected in this model. The present study, however, provides a first step to look at the complete fatigue crack process behavior of the interfacial cement crack in the cemented femoral components using finite elements. The results from this study can be used to understand how the cement mantle thickness and continuum of stem design parameter interact between the role of cracked cement and long term failure of cemented femoral components. This study addresses that increased fillet radius and cement thickness provides substantially increased fatigue life associated with decreasing the K_{eff} in magnitude during the whole failure process of the cement mantle.

5. Conclusions

In conclusions, the simulated results made from present study were observed to have a remarkable correlation with experimental and clinical evidences. First, the cement thickness is found to be one of the important fatigue failure parameters which affect the longevity of cemented femoral components, in which the thinner cement was significantly associated with early mechanical failure for shot-time period. Second, the fatigue life of cracked cement is primarily dependent on the continuum design from nearly rectangular shape to stem with broad medial and lateral radii. This indicates that use of stem with broad medial and lateral radii would guarantee to improve the risk of mechanical failure due to fatigue crack and successful use of long-term period of the components. Third, based on the results nearly rectangular shape with thinner cement mantle provides worst result, so these two parameters should be considered as controlling variables to prevent early mechanical failure in cemented total hip replacements. For further investigation changes in stem size will be interesting subject to determine optimized stem size based on the complete fatigue propagation mechanisms for the cemented total hip components.

Acknowledgments

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