

Ceramic Total Hip Liner Fracture Modeling in Abaqus using co-Simulation and Extended Finite Element Modeling

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Abstract: *Due to concerns over particle generation in conventional metal-on-polyethylene hip bearings used in total hip arthroplasty (THA), interest in advanced low-wear bearing alternatives such as ceramic-on-ceramic (CoC) couples has reemerged. While ceramics demonstrate excellent compressive strength, the brittle nature of the material reduces tensile strength, possibly leading to catastrophic fracture when loads exceed material limits. Impingement between the femoral neck and acetabular liner gives rise to areas of extreme transient stress concentration, which have been clinically linked to fracture. This work presents methodology for the investigation of 3D ceramic fracture initiation/propagation using Abaqus' co-simulation and extended finite element modeling (XFEM) capability. An anatomically realistic and physically validated FE model of a THA-implanted hip joint was developed, which employs physiologically accurate hip joint soft tissue capsule utilizing Abaqus' built-in Holzapfel-Gasser-Ogden Anisotropic Hyperelastic material model. Given the complex contact and non-linear material behavior of the capsule during large rotational displacement of the implant, the use of Abaqus' co-simulation allows for seamless Abaqus/Explicit analysis of soft-tissue and Abaqus/Standard analysis of hardware interaction and fracture mechanics. The use of XFEM has proven to be a valuable technique to investigate crack initiation and propagation, phenomena which have been tedious or impossible to adequately explore using conventional finite element fracture mechanics. The utilization of these Abaqus capabilities allows for a quantitative assessment of surgical- and patient-specific factors which predispose ceramic hip liners for catastrophic failure.*

Keywords: *Orthopaedics, Fracture, Crack Propagation*

Introduction

Advances in implant material design as well as surgical technique and instrumentation have made total hip arthroplasty (THA) one of the most successful interventions in medicine today (D'Antonio, 2002). Total hip replacement provides rapid relief of pain and restoration of mobility for patients afflicted with lower-extremity pathologies including osteoarthritis, traumatic fracture, or other insults to the hip joint. It is estimated that approximately one million total hip replacement surgeries are conducted each year (Isaac, 2006), with over 250,000 cases performed

annually in the US, and with growth projected to exceed 200% in the next two decades (Kurtz, 2007).

The earliest total hip replacement implants had been constructed from either stainless steel or Cobalt Chrome (CoCr) alloys. High failure rates led to the development of a newer bearing couples favoring metal-polymer articulation. Early implant designs utilized polytetrafluorethylene articulating with a metal femoral stem. These systems were prone to failure due to in-vivo material degradation, and this early failure led to the development of hard-on-hard bearing implant systems, specifically next generation metal-on-metal (MOM) and ceramic-on-ceramic (COC) bearings. Nevertheless, shortcomings in the design and fixation of these devices led to a high failure rate, and these were soon abandoned (again) by most practitioners in favor of new metal on polyethylene constructs (Garino, 2000). However, with long-term data available for patients with conventional metal on ultra-high molecular weight polyethylene constructs demonstrating high levels of particle-induced osteolysis, there has been resurgence in the use of hard-on-hard bearings for THA (Sedel, 2000). However, due to the brittle nature of ceramics materials, concerns still persist regarding implant failure due to catastrophic fracture.

For first generation ceramics, the risk of fracture was substantial, reaching 13.4% (Knahr, 1987). Fracture of the femoral head was especially common, arising due to point-loading of the ceramic head onto a tapered metal trunnion, creating high hoop stress and subsequently fracture (Willman, 2000). However, extensive computational (Drouin 1997; Weisse 2003) and experimental (Dorre, 1991; Heimke, 2004) analysis of key design factors led to design optimization of this metal-ceramic interface. Coupled with other advancements in ceramic quality control, these design modifications resulted in a significant decrease in the incidence of ceramic head fracture, with contemporary fracture rates at 0.004% (Willmann, 2000). In contrast, ceramic liners have significantly shorter track records of experimental or computational analysis regarding fracture risk mitigation. Current liner fracture rates of 3.5% (Ha, 2007), 1.12% (Park, 2006) and 0.22% (Toni, 2006) have been identified, values which far exceed that for head fracture.

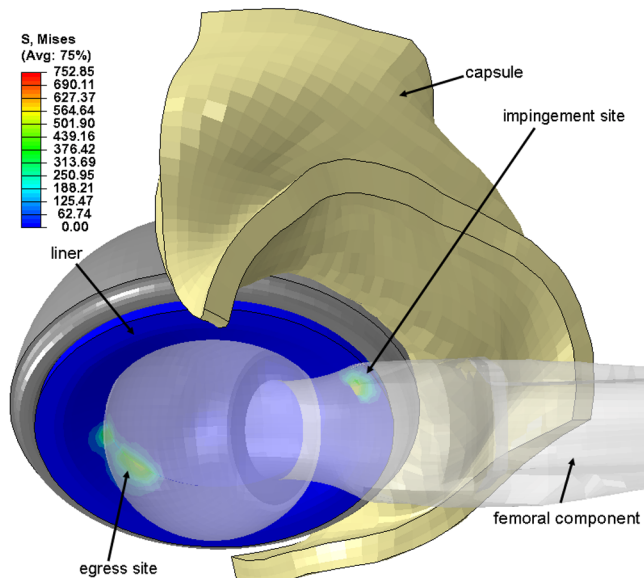


Figure 1. FE model of THA impingement

While many mechanisms for fracture initiation in ceramic heads have been suggested, fracture due to neck-on-liner impingement is the most commonly encountered (Ha 2007; Park 2006; Hasegawa 2003). During hip flexion, impingement occurs between the femoral neck and acetabular cup, resulting in a stress concentration (impingement-site, Figure 1). This creates a levering-out action of the femoral head, causing subluxation of the head from the cup and edge-loading (egress-site). These high stresses pose a significant risk for fracture initiation and subsequent catastrophic failure of the implant.

Avoidance of implant impingement is a driving force for many THA component design parameters, such as the use of larger femoral heads, increased head-neck ratio and optimized neck geometry. Additionally, optimal surgical placement (the so-called “safe zone”) of THA components has been described in an effort to maximize joint stability (Lewinnek, 1978). However, the effects of these implant- and surgical-specific designs on ceramic liner fracture propensity are currently not known. As next-generation CoC components become more routine and with concerns about fracture persisting, the need for rapid parametric analysis of component design and surgical positioning has come to the fore. Our initial efforts at fracture modeling of THA liners (Elkins 2010) used classic linear elastic fracture mechanics (LEFM) FE modeling of a cracked liner (Figure 2) to assess fracture propagation propensity. However, the utility of this approach was restricted by several modeling limitations. First, a crack location (initialization) had to be assumed *a priori* and required significant effort to generate the 3D mesh and assign specialized fracture element properties. Second, fracture propagation required prohibitively laborious remeshing routines requiring third-party mesh generation support.

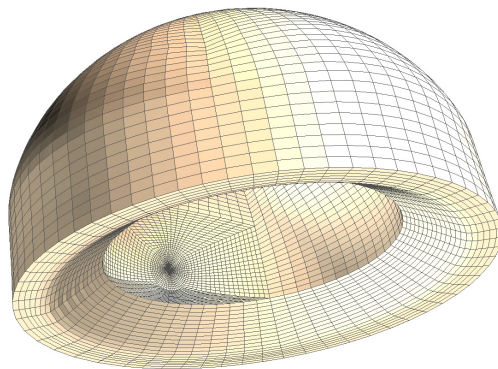


Figure 2. Initial crack location in a LEFM mesh of the cup liner

However, recent Abaqus modeling capability advancements, specifically extended finite element analysis (XFEM) and co-simulation hold particular attraction for rapid parametric analysis of design and surgical influence over fracture initiation and propagation in THA ceramic liners. We utilized these capabilities to investigate the effect of cup-lip fillet geometry as well as surgical cup orientation on fracture initiation propensity and propagation behavior.

Materials and Methods

A previously developed and physically and analytically validated FE model of THA impingement (Elkins 2010) was used as the base model for all XFEM analyses. The FE model consisted of THA hardware (28-mm head, 46-mm OD liner and cup backing) preprocessed using manufacturer-provided CAD files, and the hip-joint capsule (Figure 1). The CoC implants were modeled as linearly elastic third-generation alumina (elastic modulus=380GPa, Poisson's ratio=0.23, density=3.98gm/cm³), with radial clearance of 0.034mm and friction coefficient of 0.04 (Brockett, 2007). The hip capsule, which acts to stabilize the joint, was assigned a fiber-based anisotropic hyperelastic constitutive model (Holzapfel-Gasser-Ogden) within Abaqus as follows:

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*MATERIAL, NAME=material_name
*anisotropic hyperelastic, holzapfel, local directions=1
0.004, 0.1, 11, 17.33, 0.1
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Material coefficients were determined from a custom-written optimization routine based on cadaveric physical experimentation. From dissection studies and imaging analysis, the capsule was divided into 27 material regions, each assigned a unique fiber direction within Abaqus.

Boundary conditions for driving the impingement model consisted of an input sequence of prescribed incremental rotations of the femoral head, along with corresponding modulation of the hip joint contact forces. These input kinetics and kinematics were determined using motion data previously collected for 10 subjects performing a stooping motion (Nadzadi, 2003). These entire motion sequences were discretized into multiple (43) incremental steps, each with prescribed triaxial rotations and time-variant three-dimensional joint reaction force. Each of the three rotations and force vectors were written as amplitude curves for job execution within a single step.

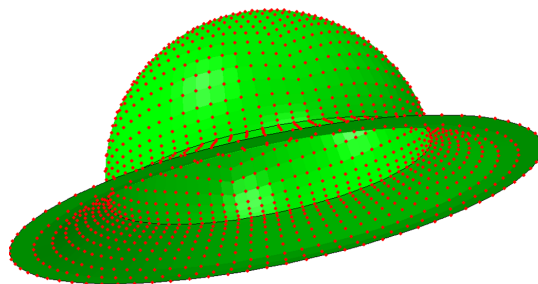


Figure 3. Driven nodes on the liner for submodeling.

Owing to complex contact interfaces as well as highly non-linear material response, Abaqus/Explicit was required to execute analyses involving the capsule. However, the XFEM capability is available only in Abaqus/Standard. Therefore, two separate XFEM modeling abstractions were used, submodeling and co-simulation, to couple an Abaqus/Explicit solution to an XFEM analysis. Node-based submodeling coupled a complete (THA hardware and capsule) Abaqus/Explicit global model to a submodel of the liner only. Nodes on the articular and inferior surfaces of the cup were selected to be driven by the global solution (Figure 3). Two separate enrichment regions were specified for fracture initiation and propagation, corresponding to the

egress and impingement stress concentrations (Figure 4). The submodel liner was rigidly fixed using a rigid body definition (Figure 4).

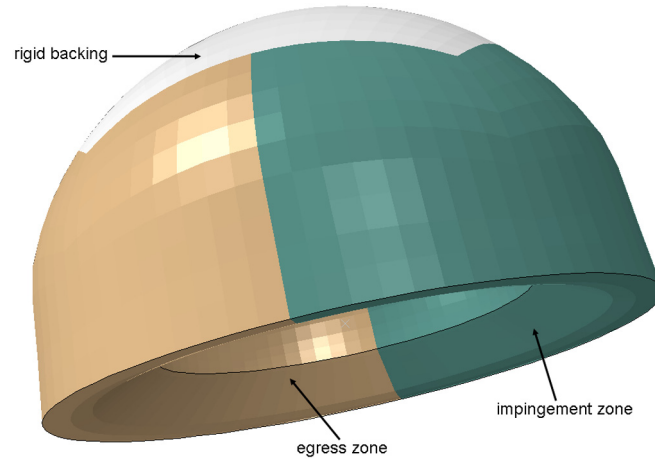


Figure 4. XFEM enrichment regions within the liner.

The co-simulation analyses consisted of the femoral component, capsule and rigid backing (Abaqus/Explicit) and the femoral head, neck and ceramic liner (Abaqus/Standard). Three-hundred-twenty nodes were selected at the inferior aspect of the femoral neck as interface region between the two domains (Figure 5).

Four separate models were created by varying the cup-lip fillet radius between 0mm and 4mm at a constant cup inclination of 40° (Figure 6) to simulate different edge profiles in contemporary THA use. Four additional models were generated to investigate surgical orientation by varying the cup inclination between 30° and 60°, each with a constant 10° of anteversion (Figure 7).

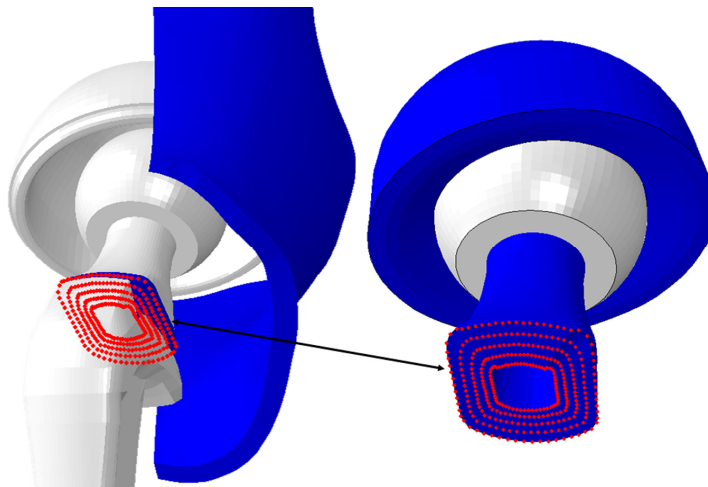


Figure 5. Abaqus/Explicit co-simulation domain (left) and Abaqus/Standard (right)

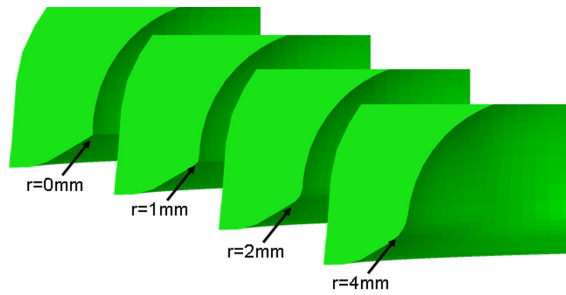


Figure 6. Four cup fillet radii were modeled for fracture initiation

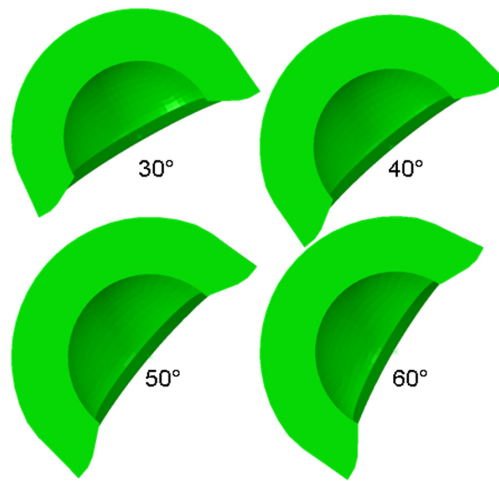


Figure 7. Four separate surgical orientations used in XFEM analyses

For each XFEM analysis, damage initiation criteria for the alumina ceramic were specified at 300MPa maximum principal stress, with mixed mode (power law) damage evolution. The fracture energy release rate for each mode was specified as 0.042 MPa*mm (42 kg/s²), corresponding to the critical stress factor (K_{IC}) for alumina (Willmann, 2000). Each analysis was re-run assuming a pre-existing flaw, simulating an analysis challenging the initial stress intensity factor (K_{IO}), with damage initiation reduced to 150MPa and energy release rate set to 0.0026 MPa*mm. Double-precision was specified for each Abaqus/Explicit analysis. All jobs were executed on a dual quad-core Intel® Xeon platform configured with 24 GB of RAM using a 64-bit Linux operating system.

Results

Each analysis was tracked for crack initiation at both the egress and impingement sites. Fractures typically developed at the egress-site (Figure 8).

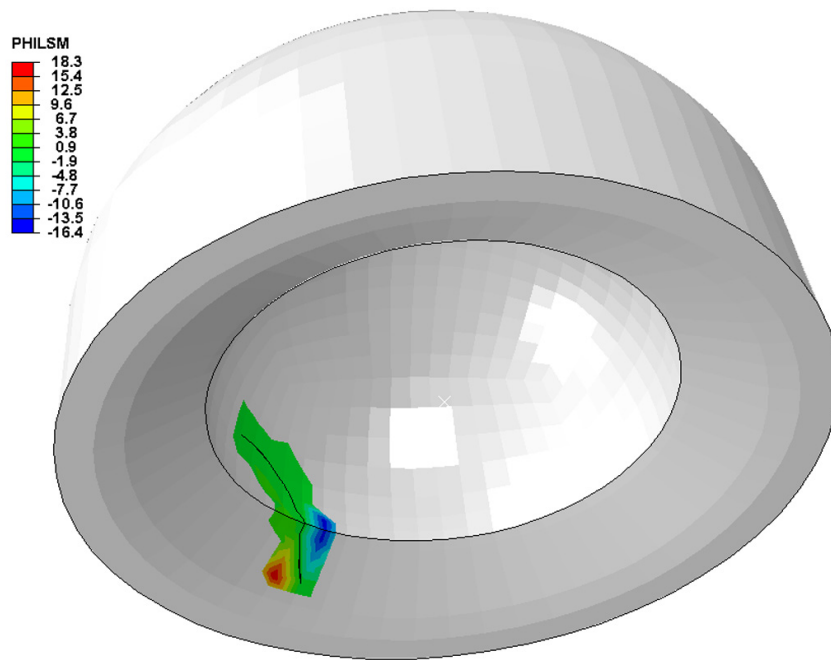


Figure 8. Signed distance function for fracture initiation and propagation at the egress-site for a r=0 cup at 40° of inclination

For the submodeled cup-radius series, fractures initiated at the egress site only for the 0mm-lipped cup (Table 1). No fractures occurred at the impingement site for this series (Table 1). When the fracture initiation and damage evolution criteria were reduced, significantly more fractures were encountered (Table 2).

Three out of the four cup orientations modeled using submodeling fractured at the egress site only (Table 3). Again, with reduced damage criteria, many more fractures were observed (Table 4)

Table 1. Cup radius series fracture initiation

Radius (mm)	Egress-site fracture	Impingement-site fracture
0	Yes	no
1	No	no
2	No	no
4	No	no

Table 2. Cup radius series fracture initiation (reduced fracture properties)

Radius (mm)	Egress-site fracture	Impingement-site fracture
0	yes	no
1	yes	yes
2	yes	yes
4	no	no

Table 3. Cup orientation series fracture initiation

Cup inclination (deg)	Egress-site fracture	Impingement-site fracture
30	No	No
40	yes	No
50	yes	No
60	yes	No

Table 4. Cup orientation series fracture initiation (reduced fracture properties)

Cup inclination (deg)	Egress-site fracture	Impingement-site fracture
30	yes	No
40	yes	No
50	yes	yes
60	yes	yes

Discussion

Although recent advances in material science and quality control have significantly improved long-term survival of ceramic bearings, fractures remain a clinical concern. Catastrophic failure of a ceramic hip yields devastating consequences for the patient, substantially worse than other modes of THA implant failure. While fracture rates of ceramic heads have been reduced to 1/25000 hips, rates for fracture of alumina liners are several orders of magnitude higher. Ceramic liners, unlike ceramic femoral heads, have no well-recognized fracture mechanism or causative factor. Therefore, mitigation of fracture risk requires greater scrutiny of specific factors, whether design, patient and surgical, which influence fracture propensity during impingement. The rationale for the present work was to identify a computational platform conducive to rapid parametric investigation of these factors. This work, to the authors' knowledge, is the first application of extended finite element analysis related to THA.

Surgical cup orientation was found to influence fracture initiation, with greater fracture risk seen for cups positioned at higher inclination. Similar trends with elevated orientations have been reported clinically for wear of ceramic couples (Nevelos, 1999). While “optimal” cup orientations have been identified as regards impingement avoidance, excessive contact stresses challenging implant failure strengths have been identified in the absence of component impingement (Elkins 2010). Additionally, with current clinical practice trending toward larger head sizes to reduce dislocation risk, added safeguards against fracture beyond simple impingement avoidance need to be identified. In all analyses reported here, stress at the egress site exceeded that experienced at the impingement site, owing to the occurrence of edge-loading between the head and cup lip. As the radial diameter of the cup contact surface increases, contact area, and therefore contact force during this engagement decreases. Therefore, the reduction in fracture incidence when larger cup lip fillet radii are used is not surprising. However, as the cup lip becomes more rounded, joint stability decreases as the displacement required for the head to dislocate (jump distance) is reduced.

The FE modeling techniques described here offer multiple advantages over more conventional LEFM fracture formulations. Of primary importance is the avoidance of a mesh-dependent fracture solution. While fracture mesh generation and subsequent modifications allowing for crack propagation are relatively trivial for 2D fracture analyses, they present serious impediments for complex 3D analyses. Additionally, the reduced requirement for mesh refinement also carries significant advantages in terms of computational economy. The current submodeling scheme described here executed several times more quickly than a more conventional model. Co-simulation of an Explicit/Standard XFEM analysis as described in the present study holds promise for an even more streamlined fracture analysis protocol, which allows the seamless coupling of complex contact and material behavior with fracture analysis.

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