Fracture process in bone cement: XFEM analysis of micro-structured models with pores

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INTRODUCTION: Aseptic loosening is the most common reason for long-term revision of total joint replacement (TJR). Infection is the main reason for short-term revision of TJR. In our previous studies, experimental results showed that acrylic bone cement loaded with antibiotics had a detrimental effect on cement strength such as bending strength, compressive strength, and fracture toughness. This result implied that the mechanical failure of bone cement loaded antibiotics was related to porosity volume fraction. Hence, the objective of this study was to investigate the effect of porosity and its distribution on bone cement fracture toughness. The effect of pores was analyzed using the X-FEM crack propagation simulation method with different sizes of pores and location. Predicted force-displacement behavior and fracture toughness were compared to experimental results. Crack growth and propagation are affected by porosity parameters, for example, pore shape an independent parameter and dependent parameters such as pore-pore and pore-crack interactions. These dependent porosity parameters are primarily affected by pore size and pore location. The experimental and simulation results of the current study contribute to a better understanding of the effect of porosity on bone cement fracture toughness.

METHODS: A plane-strain finite element (FE) simulation of the ASTM-D5045 fracture toughness test for bone cement with pores and micro-cracks was created. The effect of pores on the mechanical properties of bone cement was investigated with parametric finite element modeling. Mechanical properties, Young's modulus (E = xx MPa) and yield strength (S_y = xx MPa), were adopted from four-point bend and compression test results from our previous study (Bishop, 2018). Figure 1 shows a two-dimensional XFEM model of bending fracture toughness test of bone cement sample with randomly distributed pores. The FE mesh consists of four-noded plane strain quadrilateral with hourglass control (CPE4R) with 0.5 mm global edge lengths. The maximum principal stress criterion was assumed for damage in the traction separation law. Three porosity conditions were tested:

I. Pore locations were fixed, and pore radius was increased from 0.2 mm up to 1.0 mm with xx mm increments. Three different pore location sets were tested.
II. Pore locations were randomly distributed, and the radius of the pore was fixed at 0.2 mm, 0.6mm, and 1.0 mm.
III. Pore locations were randomly distributed, and a normal distribution of radius (0.2 ± 0.07 mm, 0.6 ± 0.2 mm, 1.0 ± 0.18 mm) was assigned.

RESULTS: Three different cases were analyzed as described in the methods section. Their results were compared with that of the experimental force-displacement curves. For the case I, the pore size significantly impacted the force-displacement curve. A decreasing trend for the peak force and stiffness were observed with increasing pore size and porosity volume fraction. The effect of pore location was tested with five different models containing randomly distributed pores with a fixed radius at 0.2 mm. The stiffness and peak force for all models were consistent regardless of pore location but the crack propagation after fracture varied. This trend was also exhibited in the other models with larger fixed radii, 0.6 mm and 1.0 mm. Case III randomized both pore location and size. The size of the pores had a larger effect on the force-displacement behavior than the pore location.

DISCUSSION: Our analysis has established that pore size is a dominant contributor to failure in bone cement, demonstrating the difference of cement fracture toughness between the less porous and more porous groups. Evans et al. studied that larger pores are more critical because a crack emanating from a large pore is subjected to a greater volume of stress and therefore will grow more quickly (Evans, 2006). This size effect is captured well by the current finite element analysis. For the distributed pore locations, pores under 1.0 mm, typically classified as microspores, have no effect on the cement strength as shown in Figure 2; whereas, pores over 1.0 mm have increased interactions and likelihood of failure as shown in Figure 3. It is not clear whether porosity is the main factor of failure in the cement mantle in vivo (Hoey and Taylor, 2008; Ling and Lee, 1998; Meyer et al., 2011). However, it is clear that porosity is detrimental to the fracture toughness of the specimens in current size, with pore size and pore location. Similar results have been found by others (Hoey and Taylor, 2008; Murphy and Prendergast, 2000). Porosity has also shown beneficial effects for the clinic. The antibiotic is typically added to the bone cement for the treatment and prevention of prosthetic joint infection in the surgical area. The elution of antibiotic from bone cement is related to the surface roughness and the porosity (van de Belt et al., 2000). In addition, the porosity may increase fracture toughness of bone cement by dispersing the energy at the crack tip, forming a larger damage zone, and effectively blunting the crack (Topoleski et al., 1993). Therefore, the compromise between the positive and negative effects is essential to find the best solution. The compromised solution as suggested by the results of the present study may be an even distribution of relatively small pores (radii less than 1.0 mm) for an effective elution rate and reduction of large pores (radii greater than 1.0 mm) which decrease fracture toughness.

SIGNIFICANCE/CLINICAL RELEVANCE: Aseptic loosening is the most common reason (57.5 % of revisions during the period 1999 - 2016) for long-term revision of TJR (Gundtoft et al., 2016; Stelmach et al., 2016) and infection is the main reason (90% of revisions) for short-term revision of TJR. Antibiotic-loaded bone cement is viable treatment option to address both of these clinically relevant failure modes.

IMAGES AND TABLES:

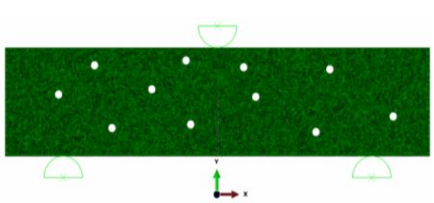

Figure 1. Two-dimensional XFEM model of fracture toughness test for bone cement with pores.

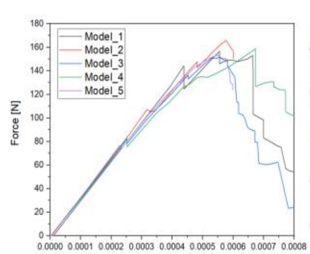

Figure 2. Force-displacement curves for 0.6 mm pore size with randomized locations.

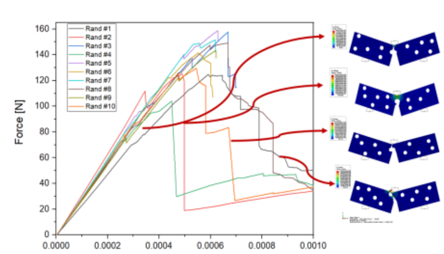

Figure 3. Force-displacement curves for 1.0 mm pore size with randomized locations.