Simulation of crack initiation and propagation in bone cement

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INTRODUCTION: Total hip replacement (THR) is one of the most common orthopaedic surgeries. The THR prostheses are loaded repetitively in daily activities, e.g., walking, which can limit their service life by provoking fatigue damage. In particular, the cement mantel, which provides a mechanical interlock between the implant and bone in cemented THR systems, is vulnerable to crack accumulation and fatigue. The resulting aseptic loosening is considered as a main mechanism of failure of cemented THR [1,2]. The fatigue behavior of the cement mantle has been investigated in several modeling studies using continuum damage mechanics, fracture mechanics and extended finite element (XFEM) approaches. These studies, however, have been limited by the available material data and simulation methods to simulate crack initiation and propagation in the cement mantle of THR systems. Therefore, the purpose of this study was to both enrich the material property data and enhance the methodology of simulation of crack initiation and propagation in bone cement. The first is proceeded by analyzing the voids and pores which are formed in the cement during its preparation and setting process, as well as the elution of added antibiotic, in bone cement specimens with different amounts of added antibiotic. The latter, on the other hand, is carried out by developing a model of the pore-included cement fatigue, using extended finite element (XFEM) and element free Galerkin methods in combination with the cohesive crack model. This paper describes the steps conducted and the preliminary results.

METHODS: An experimental study was performed to investigate the pore distribution in four groups of bone cement specimens, containing different amounts of added antibiotic. The seven prismatic specimens of each group were scanned using a μ-CT system (MicroXCT400, Xradia, Oberkochen, Germany) and the images were processed in Mimics Innovation Suite 20.0 (Materialise NV, Leuven, Belgium) and Dragonfly version 2021.1.0.977 (Object Research Systems, Montreal, Canada) software applications. The pores were first segmented automatically, and then edited manually by joining the ones with single interfacial voxels. The results were presented as the pore volume-frequency diagrams of the specimens. The details of this work are described elsewhere [3]. In the modeling part of this study, the three-point bending fracture toughness tests of cement blocks were simulated using XFEM in LS-DYNA smp d R12.0 (Livermore Software Technology Corporation, Livermore, CA, USA). The cement block was modeled as a 2D beam, shell elements (ELFORM 2, thickness 25 mm) and was subjected to concentric and eccentric impact loading, with the striker velocities of 20 m/s and 30 m/s, similar to the work of Tsuda et al. [4]. A pre-crack with the length of 26 mm was modeled in the middle length of the beam. Also, a number of pores, with random sizes and locations, were considered in the vicinity the crack. The region of interest, containing the crack and pores, was modeled using cohesive elements and the other parts of the model using elastic shell elements. The cohesive zone was modeled with SHELL_XFEM (ELFORM 54, BASELM 16, thickness 25 mm). The element edge length was 1 mm and the beam was 25 mm thick x 50 high mm x 250 mm long. The predictions of the model for the crack propagation paths were validated against previous experiments and simulations [2].

RESULTS: The pores were mainly of volumes less the 0.4 mm^3. However, there were also a very limited number of pores with large sizes, up to about 3.0 mm^3 (Fig. 1.) The predicted crack propagation path was affected by both the loading conditions and the pores adjacent to the initial crack (Fig. 2). The simulation results of the current study compared well to previous experimental and simulation studies [2].

DISCUSSION: These preliminary results indicated that analysis of the μ-CT images of bone cement specimens using advanced image processing techniques can quantify the volume distribution of pores within bone cement. We also showed that the XFEM method is well capable of modeling the discontinuities in the material without remeshing; and, provides predictions comparable with the experimental data in the literature [2]. In particular, XFEM models could simulate the important effects of the pores, and loading conditions, on the crack propagation. It was concluded that by enriching the pore distribution data for the cement mantle, and employing the XFEM method, it would be possible to obtain more detailed and realistic simulations of the crack initiation and propagation in the cement mantle of THR systems

SIGNIFICANCE/CLINICAL RELEVANCE: This study addresses the improvement of the computer modeling method for simulation of the crack initiation and propagation within the cement mantle of the THR systems. By enriching the experimental data and employing the advanced modeling methods, more detailed and realistic simulations of the fatigue behavior of cement mantel could be achieved which is of great importance for studying the parameters which affect the aseptic loosening of THR.

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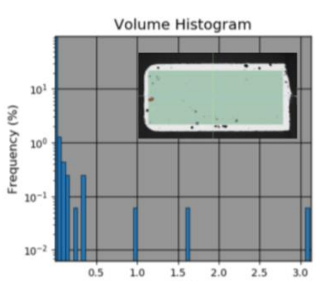

Figure 1. Pore volume distributions in a specimen containing 0.3 wt/wt% added antibiotic.

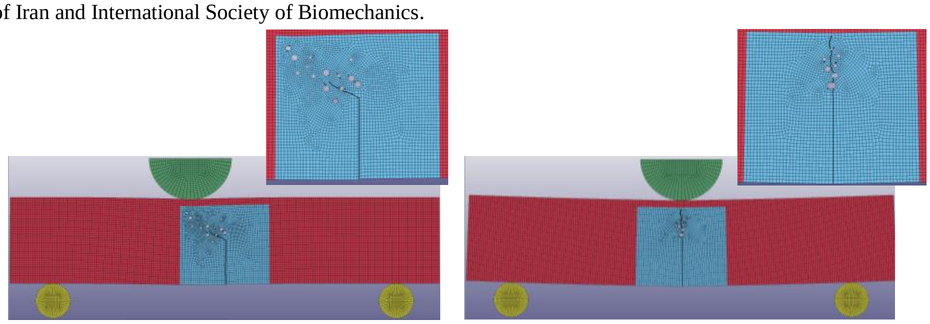

Figure 2. Crack propagation in three-point bend models under eccentric impact loading (left) and concentric impact loading (right).