**Experimental Micro-mechanics of the Cement-Bone Interface**

Kenneth A. Mann1, Mark Miller1, Richard Cleary3, Dennis Janssen2,1, Nico Verdonschot2

1SUNY Upstate Medical University, Syracuse, NY; 2Radboud University Nijmegen Medical Centre, Nijmegen, Netherlands; 3Bentley College, Waltham, MA

mannk@upstate.edu

**Introduction:** A mechanically stable cement-bone interface is essential for long-term viability of joint replacements that utilize cement for fixation. Despite the widespread use of cement as a means of fixation to bone, surprisingly little is known about the micro-mechanical behavior in terms of the local interfacial motion. In this work we utilized digital image correlation techniques to quantify the micro-mechanics of the cement-bone interface of laboratory-prepared cement-bone specimens subjected to non-destructive, quasi-static tensile and compressive loading. Using this approach we addressed four research questions: (1) does the majority of deformation localize to the contact interface between cement and bone?; (2) is the interface more compliant in tension than in compression?; (3) is there a relationship between interface compliance, interface contact area and interface strength?; and (4) when loaded to failure, does the majority of damage occur at the cement or bone adjacent to the interface?

**Materials and Methods:** Cement-bone specimens were created in a laboratory setting using an approach to create interfaces that would represent those that are generated at the time of surgery for cemented total hip replacement. Parallel-piped cement-bone specimens were prepared by transverse sectioning of femurs using a water irrigated diamond blade saw followed by further sectioning to produce cement/bone composite specimens that were nominally 4 x 8 mm in cross section. The mechanical testing apparatus consisted of a set of parallel grips housed in an environmental chamber into which the specimen was placed. The initial mechanical testing consisted of fully reversible tension-compression loading for ten cycles to displacements of (±) 0.01 mm based on the grip-to-grip displacement. This displacement magnitude was chosen based on pilot work to ensure that permanent damage did not occur to the specimens. Specimens were then loaded in uni-axial tension to failure, defined here as a 50% drop in peak applied load. The goal was to impart substantial damage to the specimen, while still allowing the specimen to remain intact for post-processing analysis. Prior to mechanical testing, a black enamel paint overspray was used to provide contrast and texture for one face of the test specimen containing the cement and bone [Figure 1]. A digital camera (Spot RT) with 8.9 micron/pixel resolution and tele-centric lens was used to capture surface images of the specimens during mechanical loading at a frequency of 4 Hz. Digital image correlation (DIC) software was used to determine displacements between the bone, contact interface, visible interdigitated region, and cement.

To document specimen microstructure, microCT scans were obtained (12 micron resolution) and the contact area between cement and bone was determined. Damage to cement and bone was determined using fluorescence imaging and total new crack growth to the cement and bone was determined.

**Results:** Upon tensile and compression loading, the majority of the displacement response localized at the contact interface region between the cement and bone. The contact interface between cement and bone was more compliant ($p<0.00001$) in tension (0.0067 ± 0.0039 mm/MPa) than compression (0.0051 ± 0.0031 mm/MPa) and there was substantial hysteresis due to sliding contact between the cement and bone. The tensile strength of the specimens was negatively correlated with tensile interface compliance ($r^2=0.47$, $p=0.0006$) indicating that specimens with less motion at the interface were stronger. In addition, tensile strength and the contact area between cement and bone were positively correlated ($r^2=0.48$, $p=0.0005$). Interestingly, the interface compliance and contact area measures were very weakly correlated ($r^2=0.096$, $p=0.174$). In a step-wise regression model, both interface compliance and contact area contributed to interface strength ($r^2=0.72$, $p=0.0001$). When loaded beyond the ultimate strength, the strain localization process continued at the contact interface between cement and bone with micro-cracking (damage) to both the bone and cement. There was more overall damage to the cement (length sum:5.61±3.49 mm) when compared to the bone (2.68±1.40 mm).

**Discussion:** Results of this study show that the actual contact interface is responsible for the majority of motion of cement-bone structures when subjected to tensile or compressive loading. This interface is more compliant in tension when compared to compression, but even in compression, there was still considerable ‘closing’ motion occurring at the interface. To date, the compliance of the contact interface has not been considered in terms of modeling the load transfer in cemented implant application. However, a simple exercise with a one-dimensional system can illustrate the potential relevance. If one considers a 3 mm thick cement mantle between stem and bone subjected to 1 MPa tensile load, there would be a displacement of 1 micron attributable to the cement and nearly 5 microns attributable to the contact interface, based on compliance measurements in this study. Hence, inclusion of a realistic compliant interface would be equivalent to reducing the cement modulus in this example to 17% of a nominal level. Of course, the load transfer is much more complex than what is described here, but this clearly shows that the ‘micro-motion’ at the contact interface could affect considerably the load transfer mechanism.

Both interface stiffness (inverse of compliance) and contact area contribute to interface strength. Further exploration is needed to understand what morphologies produce strong interfaces. When loaded to failure, most crack growth was found in the cement suggesting that the cement is at greater risk of damage.

With regards to clinical relevance, interface motions on the order of 5 microns for a nominal 1 MPa load across the cement–bone interface, suggests that the contact interface has the potential to serve as a conduit for submicron size particles and as a mechanism to generate fluid pressures locally. Both of these factors have been associated with focal osteolysis. The primary limitation of this study was that no biological changes were included; results presented here would represent immediate post-operative conditions.

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**Figure 1:** Surface of cement-bone structure indicating where digital image correlation measurements were made. Graph to the right represents vertical displacement field along centerline of the specimen.