Mixed-Mode Behavior of the Cement-Bone Interface: A Finite Element Study

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Introduction

The stability of cemented hip implants relies on the fixation of the cement mantle in the bone. During patient functioning, the cement-bone interface is loaded under different angles [1]. To predict outcome of cemented reconstructions, it is there important to include such phenomena. However, experimental data on this mixed-mode behavior shows a large variation in strength and stiffness, due to differences in interface morphology [2]. This data is therefore of limited value for Finite Element Analysis (FEA) of the cement-bone interface on a macroscopic scale [3].

The aim of this study was to investigate the mixed-mode behavior of the cement-bone interface with micromechanical FEA-models while excluding interface morphology as a confounding factor. The responses were decomposed in the normal and tangential direction, making them suitable for implementation in cohesive elements for macro scale studies in a later stage.

Materials and methods

Four quasi-3D FEA models were generated from µCT-data of small cement-bone interface specimens (Fig.1). These four models had distinct differences regarding the interface morphology. The models were mirrored to make them suitable for multi-scale analysis. Frictional contact was assumed between the bone and cement with a friction coefficient of 0.3.

The models were loaded until 0.3mm displacement under 11 different angles while monitoring the normal and tangential displacement (Δ_N and Δ_T) and the corresponding apparent tractions (T_N and T_T). Cracks in the bone and cement could arise when the principal stress in an element exceeded the local strength. The resulting crack patterns in pure tension and shear were compared. In addition, the contact area and interdigitation depth were established to further characterize the interface morphology.

Results

In pure tension (0°) the four models showed differences in strength (1.3-2.8MPa) and stiffness (65-270MPa/mm; Fig.2). In both pure tension and compression no tangential traction, T_T, occurred.

However, for all four models loaded in pure shear (90°) a substantial normal compression (T_N) was needed to preserve zero normal displacement of the interface. None of the four models did fail in pure shear after 0.15mm tangential displacement.

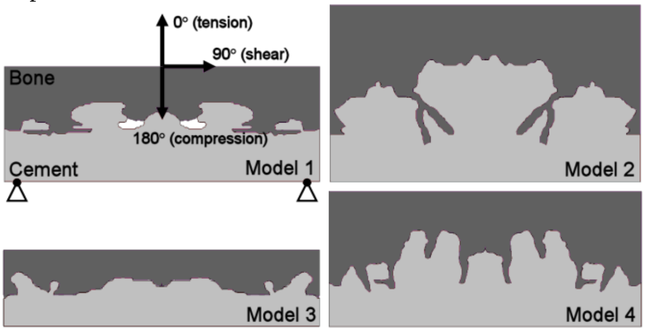

Fig1: The four different models used in this study.

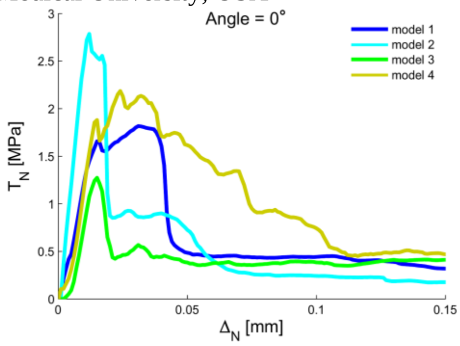

Fig2: Traction-displacement responses in tension

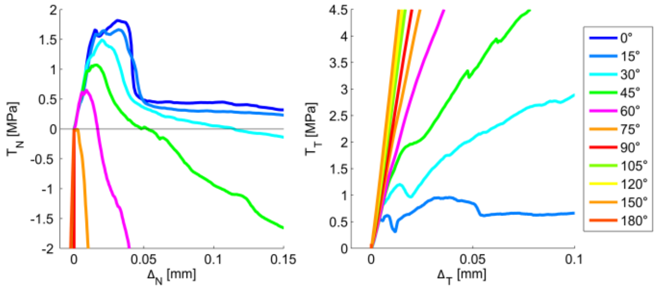

Fig3: Mixed-mode responses of model 1 in normal (T_N, left) and tangential direction (T_T, right)

For each model, the mixed-mode response showed a gradual transition from pure tension, to pure shear and pure compression (Fig.3).

In pure tension cracks are situated around the contact interface causing loosening of cement and bone spurs. On the other hand, in pure shear the cracks progressed deep into the bulk of cement and bone (Fig.4).

The response of the cement-bone interface could not be related to contact area or interdigitation depth, due to the complexity of the interface morphology when considered under different loading angles.

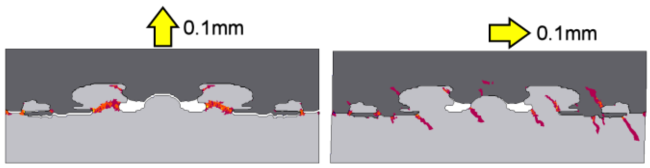

Fig 4: Crack patterns of model 1 after 0.1mm displacement in pure tension (left) and pure shear (right).

Discussion

The current study revealed features of the mixed-mode behavior of the cement bone interface, such as considerable compressive tractions and no failure in shear. The latter could be clarified by the crack patterns. These features have never been shown or implemented in the past. When fit to a numerical expression, the responses of the four micro models of the cement bone interface can used for multi-scale modeling in cemented total hip arthroplasty.

Acknowledgements

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References

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