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Communication

Stress shielding in bone of a bone-cement interface

Qing-Hang Zhang [a], Andrew Cossey [a,b], Jie Tong [a,*]

[a] Mechanical Behaviour of Materials Laboratory, School of Engineering, University of Portsmouth, UK
[b] Spires Portsmouth Hospital, UK

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ABSTRACT

Cementation is one of the main fixation methods used in joint replacement surgeries such as Total Knee Replacement (TKR). This work was prompted by a recent retrieval study [1,2], which shows losses up to 75% of the bone stock at the bone-cement interface ten years post TKR. It aims to examine the effects of cementation on the stress shielding of the interfacing bone, when the influence of an implant is removed.

A micromechanics finite element study of a generic bone-cement interface is presented here, where bone elements in the partially and the fully interdigitated regions were evaluated under selected load cases. The results revealed significant stress shielding effect in the bone of all bone-cement interface regions, particularly in fully interdigitated region. This finding may be useful in the studies of implant fixation and other related orthopedic treatment strategies.

1. Introduction

Bone cement, or polymethylmethacrylate (PMMA), is widely used to anchor joint replacement prostheses to host bone. It acts as a grout, adapting the surface irregularities of the surrounding bone tissue to the surface of the inserted prosthesis. Pressurising cement during insertion improves cement penetration into the cancellous bone interstices, enabling a better mechanical interdigitation thought critical for long-term durability. Despite of new joint replacement strategies introduced, the use of PMMA bone cement in TKR remains one of the most popular procedures, representing 84.3% of the annual total TKRs performed in England and Wales [3].

Aseptic loosening is a major failure mechanism in joint replacement, and has been partially attributed to stress shielding of the bone due to the presence of a metal prosthesis [4,3]. Although periprosthetic bone density change around a metal knee implant has been known to occur [5–7], it is only recently that evidence came to light on bone resorption in the bone-cement interdigitated region in cemented TKR. Miller et al. [1,2] presented a post-mortem retrieval study, where 75% of bone loss was found at the bone-cement interface in metal-backed tibial components within 10 years of in vivo service, with extensive bony resorption at the periphery of the tibial trays. This finding has significant implications on the long-term prognosis of this type of fixation method, as excessive bone resorption will lead to increased micro-motion and eventual implant loosening.

It is well known that when stiff metal implants are used to replace native bones, stress shielding in the surrounding bones will occur, regardless of the fixation methods. The question we seek to answer is if bone cement, when interdigitated with the bone, would have an effect of stress shielding on the bone? Our previous work [8,9] seems to suggest that when trabecular bone is interdigitated with cement, the main damage occurred in the bone whilst the stress level in the bone-cement interdigitated region is relatively low. In the present study, we hypothesise that the loss of bone stock may be attributed to the stress shielding caused by cement, in addition to that by the implant.

2. Material and methods

A micro-finite element (μFE) model of a typical bovine bone-cement interface sample from our previous study [9], of which the BV/TV of the bone is 0.15, was used for the current work. A detailed description of specimen preparation, FE mesh generation and validation of the model was given elsewhere [9], but for completeness a summary is given here: Images of the bone-cement interface specimen from μCT were imported into Avizo 6.3 (Visualisation Sciences Group, Mérignac, France), in which the bone and the cement structures were reconstructed, meshed and imported into Abaqus (6.12) (Dassault Systemes, USA) to assemble a bone-cement interface model (model BC), which consists 2,506,235 tetrahedral elements and 571,756 nodes (Fig. 1a). The dimension of the model is 9 mm×8 mm×4.4 mm, and the maximum depth of cement penetration is 5.2 mm. In addition, the cement was removed

* Corresponding author. Tel.: +44 9284 2326, fax: +44 9284 2351.
E-mail address: jie.tong@port.ac.uk (J. Tong).

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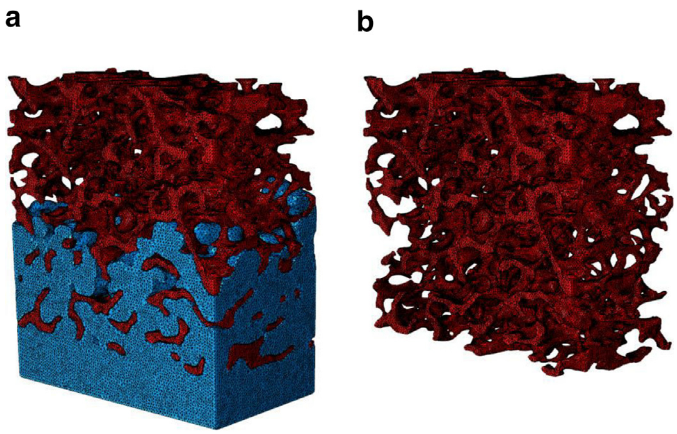

Fig. 1. The two finite element models used for the present study. (a) A typical bone-cement interface sample (model BC, with a dimension of 9.0 mm×8.0 mm×4.4 mm); (b) the same model as (a) but with the cement removed (model BB, with a dimension of 7.6 mm×8.0 mm×4.4 mm). Red – bone; Blue – cement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

from the model BC to form model BB for comparison purposes (Fig. 1b).

The trabecular bone tissue was modelled as an elastic–plastic material, with an asymmetric yield strain of 0.6% in tension and 1% in compression [10]. The elastic modulus, Poisson's ratio and post-yield tangent modulus were assumed to be 15 GPa, 0.3 and 750 MPa, respectively [10]. A similar asymmetrical elastic to perfect plastic constitutive law was also used for the cement, where the elastic modulus, Poisson's ratio, yield stress under tension and yield stress under compression were assumed to be 3 GPa, 0.33, 30 MPa, and 70 MPa, respectively [11,12]. The interaction between the contact surface of the bone and the cement was modelled as surface-to-surface finite sliding contact with a friction coefficient of 0.4 [9].

A compressive load of 88 N (Load 1) was applied to the top surface of model BC and model BB, and the stress distributions in the two models are compared. Load 1 was chosen to be close to the upper bound of stresses experienced during routine activities in a normal proximal tibia [13]. Two additional loading conditions, Load 2 (70.4 N) and Load 3 (35.2 N), representing 80% and 40% of Load 1, respectively, were also applied to model BC. These two load cases were chosen to simulate the reduced stresses experienced in the bone due to the presence of an implant with a relatively low (Load 2) and high (Load 3) stiffness [14]. Under all loading conditions, the bottom surfaces of the models were fully constrained.

To assess the effects of stress shielding quantitatively, the bone was divided roughly into 8 layers, representing bone (Layers 1 to 3), partially interdigitated region (Layers 4 and 5), where only partial cement penetration occurred; and fully interdigitated region (Layers 6 to 8), where full cement penetration occurred to form a bone-cement composite structure. A height of approximately 1 mm was chosen for each layer, and the grey represents cement (Fig. 2).

A number of parameters [13–15] have been used to evaluate the effect of stress shielding in bones. A strain energy density criterion [16] was chosen in this work as it has been successfully used as a stimulus in bone remodelling [13,17]. An effective strain energy density in each bone layer may be obtained by averaging the strain energy of all the elements in that layer:

$$SED_{Layer\,j} = \frac{\sum_{i=1}^{n} SED_i V_i}{\sum_{i=1}^{n} V_i} j = 1 - 8 \qquad (1)$$

where *SED* is the strain energy density, V_i is the volume of element i, n is the total number of elements within the layer; and j is the number of layers. The difference between the SEDs of each bone layer from model BB (under Load 1) and model BC (under Load 1, 2, 3) were calculated and the percentage reduction of *SED* was used to measure the effect of stress shielding in bone across the bone-cement interface for the three load cases $k=1$, 2 and 3:

$$\Delta = \frac{SED_{Layer\,j.BB}^{Load_1} - SED_{Layer\,j.BC}^{Load_k}}{SED_{Layer\,j.BB}^{Load_1}} k = 1,\ 2,\ 3 \qquad (2)$$

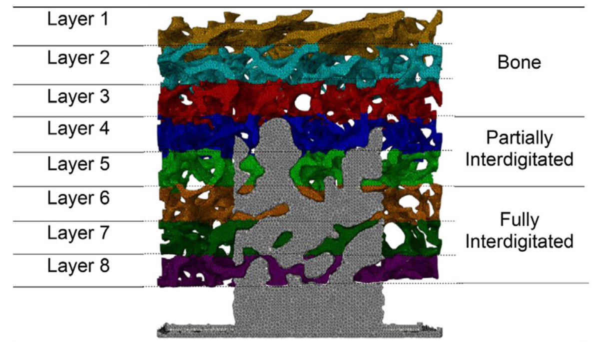

Fig. 2. A column (7.6 mm×8.0 mm×4.4 mm) of the eight bone layers defined for the comparison of the strain energy density (SED) between model BC and model BB. Layers 1 to 3 (a height of 2.9 mm) contain bone only; Layers 4 and 5 (a height of 1.9 mm) are partially interdigitated with cement whilst Layers 6 to 8 (a height of 2.8 mm) are fully interdigitated with cement. The central part of the cement is also included for illustration purposes.

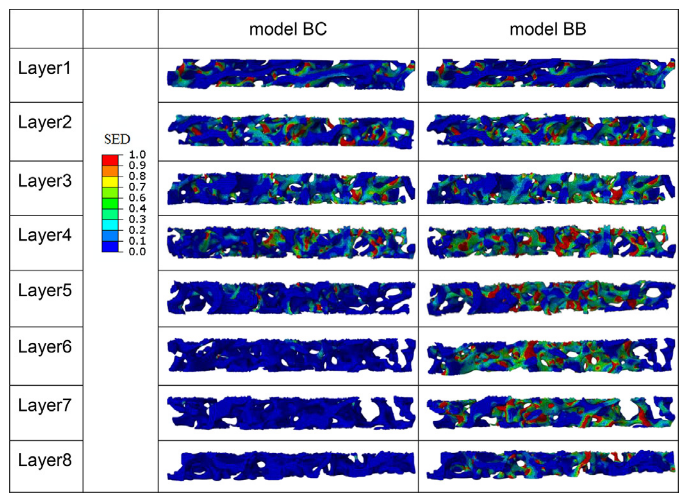

Fig. 3. A comparison of SED distribution in the eight bone layers from model BC and model BB under Load 1.

3. Results

The strain energy density distributions in the eight bone layers under Load 1 are shown in Fig. 3 for model BC and model BB. The load was distributed throughout the entire bone structure in model BB and the bone struts deformed most evenly. For model BC, however, the load applied from the top surface of bone was mainly transferred to the cement thus the lower part of the bone interdigitating with the cement is off-loaded with low stain energy (in blue). It is clear that the load is effectively distributed throughout the bone structure in model BB, whilst much reduced *SED* experienced in the bone in the bone-cement interdigitated region in model BC, indicating stress shielding of bone as a result of cementation. Stress shielding may be observed from Layer 4 onwards in model BC, where progressively increased stress shielding in bone is evident. The percentage reductions in *SED* of all layers of bone

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