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MECHANICAL CHARACTERISATION OF FOAM-CEMENT INTERFACE UNDER SELECTED LOADING CONDITIONS

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SUMMARY

Open-cell AlSi7Mg (45ppi) foam was employed as trabecular bone substitute and used to interdigitate with acrylic bone cement to form foam-cement interface samples. The interfacial mechanical performance of such bone-cement models was investigated under tension, mixed-mode, shear and step-wise compression loading conditions using experimental protocols reported in Wang et al. [1] and Tozzi et al. [2]. Finite element (FE) models were also built from µCT images of the samples in order to predict the foam-cement behaviour and interfacial damage. The results show that the foam-cement mechanical responses under tension (0°), shear (90°) and mixed-mode (22.5°; 45°; 67.5°) loading conditions are broadly similar to those obtained from bone-cement interface samples under the same loading conditions, with the exception of compression where the response from the foam-cement interface is much lower than that of bone-cement interface.

INTRODUCTION

A step forward in the characterisation of open-cell foams for cemented arthroplasty simulation is to examine the mechanical performance of the foam-cement system under complex loading conditions relevant to physiological load cases.

In the current study an open-cell AlSi7Mg (45ppi) foam was selected as an analogous model for its resemblance to bovine trabecular bones [3] in morphology. Foam-cement coupons were produced similarly to the bovine trabecular bone-cement samples studied before [1]. The composites were mechanically tested under tensile, shear, mixed-mode and step-wise compression loading conditions, using the experimental protocols for bone-cement interface characterisation [1, 2].

FE simulations were performed on a typical foam-cement model under compression, tension and shear loading conditions. The predicted apparent behaviour and the simulated local interfacial damage were compared with the correspondent values obtained from the bone-cement specimens.

METHODS

The loading device used in Wang et al. [1] for bone-cement interface testing was adopted to allow tensile (θ=0°), shear (θ=90°) and selected mixed-mode (θ=22.5°; 45°; 67.5°) loads to be applied on the foam-cement composites. The specimens (n=10) were loaded to complete failure at a rate of 0.01mm/s.

A micromechanical loading device (Deben Ltd, UK) was used in combination with time-lapsed µCT imaging (X-Tek Systems Ltd, UK). The unloaded specimens (n=5) underwent µCT analysis (V=60kV, I=140µA, voxel size=20µm) and were then step-wise compressed at two selected displacements corresponding approximately to the ultimate apparent strength and just before the final failure, respectively. At each step a relaxation time of about 15 mins was allowed before CT imaging was carried out. All tests were conducted at a constant cross head speed of 0.01mm/s [2].

The three-dimensional reconstruction and FE mesh generation of the foam-cement interface model followed a protocol reported elsewhere [4]. The elastic modulus, Poisson's ratio and yield stress of cement were assumed as 3GPa, 0.33 and 40MPa, respectively [5], while the corresponding values for AlSi7Mg alloy were assumed to be 70GPa, 0.3 and 150MPa, respectively [3]. The interaction between the surface of the foam and that of the cement was modelled with a friction coefficient of 0.4. All the simulations were performed on the FE solver ABAQUS 6.10 (Dassault Systèmes, USA).

RESULTS AND DISCUSSION

The average apparent strength for the foam-cement samples ranges from 0.53MPa in tension to 5.34MPa in shear, compared with 1.48±0.85MPa and 4.09±3.66MPa for the bone-cement interface under tensile and shear loading conditions, respectively. The FE predictions seem to have captured the essence of the experimental responses, although not all the details, resulting in an overestimation of the mean experimental stiffness for tensile and in particular for shear conditions.

Fig.1(I, II) presents some of the progressive microdamage during the step-wise compression for both foam-cement and bone-cement composites [2]. The predominant deformation was found to initiate in the foam region (Fig.1(I)) and virtually no load transfer occurred at the interface, as opposed to the bone-cement case (Fig.1(II)). In the latter case the main load transfer resulted in progressive bending and buckling of trabeculae adjacent to the interdigitated region.

The compressive strength for the foam-cement was estimated as 0.90±0.05MPa and the predicted stress-displacement behaviour compares reasonably well with the experimental data. The value differed considerably from the 4.93±1.10MPa reported for the bone-cement [2].

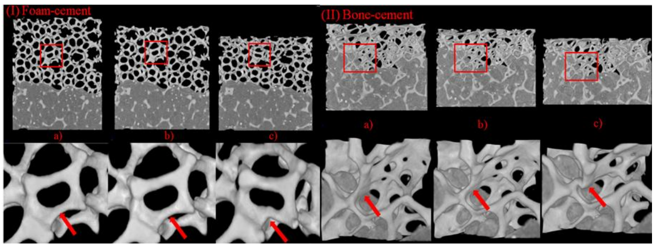

Figure 1: Microdamage evolution of the foam-cement (I) and bone-cement (II) interface samples tested under step-wise compression and selected sub-volumes (rectangles): (a) unloaded; (b) at the ultimate stress; (c) failure state and details of the local damage as indicated by the arrows. The bone-cement case (II) was adopted from Tozzi et al. [2].

Fig.2 shows the von Mises stress distribution in the foam/bone and cement of the two models under (a) compression, (b) tension and (c) shear when a displacement of 0.3mm was applied. Similarly to the bone-cement case, the foam region sustained most of the load under tension and compression. Under shear loading condition, the two models appear to be more influenced by the loading mode than by the material characteristics.

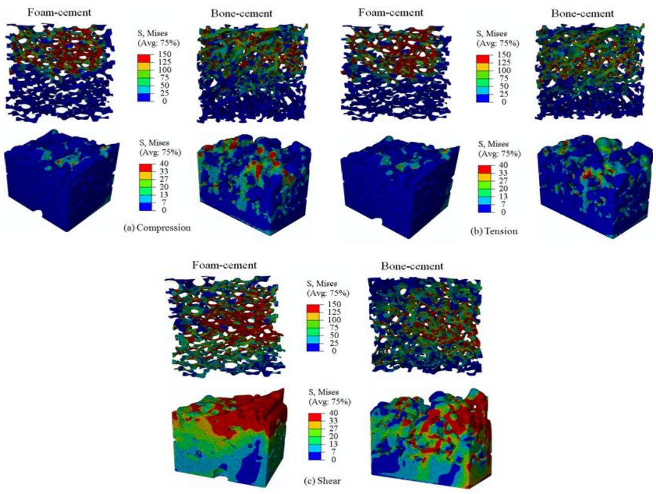

Figure 2: The local FE predicted stress distribution on the cellular and cement parts of the bone-cement and foam-cement samples under (a) compression, (b) tension and (c) shear loading conditions.

The apparent tensile strength obtained in the present study (0.53MPa) is in the lower range for lab-prepared bovine [1] and also human cadaveric bone-cement interface (1.28±0.79MPa) reported by Mann et al. [6]. For shear the present result of 5.34MPa is well within the experimental corridor obtained by Wang et al. [1] but higher than the cadaveric result 2.25±1.49MPa [7].
When shear is the predominant component an increase in the interfacial strength for both foam and bone cement interfaces was observed, suggesting that shear action may not be very sensitive to foam/bone material properties.

Under compression, however, the interfacial strength of the foam-cement interface is found much lower than that of bone-cement interface (<1MPa for foam-cement vs 3.5–6MPa for bone-cement). This may be attributed to the higher contribution of the foam material on the overall response of the interface. 3D volume visualisation of damage evolution shows that the foam region sustained almost the deformation, and the main damage resulted in progressive damage of struts mainly due to bending and buckling (Fig.1(I)). This is in contrast to the damage mechanism for trabecular bone-cement interface [2], where a more effective load transfer to the bone-cement interdigitated regime (Fig.1(II)) was observed.
Although the simulated interfacial responses under different loading conditions agreed reasonably with the experimental results, the FE model predicted higher initial stiffness of the foam-cement specimen than the correspondent experimental values. This difference might be attributed to the end and side artefacts of the experimental model [8], as well as difficulties in mimicking the actual loading and boundary conditions as those in the experiments.

CONCLUSIONS

The foam-cement mechanical performance under tension (0°), shear (90°) and mixed-mode (22.5°; 45°; 67.5°) loading conditions was found to be compatible with those obtained from the bone-cement specimens under the same conditions; whilst under compression, the foam-cement interfacial strength was found to be much lower than the corresponding bone-cement cases. Step-wise imaging showed virtually no load transfer in the foam-cement samples, unlike the bone-cement samples where the load transfer occurred mainly in the interdigitated contact region. Despite these differences, a similar pattern of microdamage evolution due to struts/trabeculae bending and buckling was observed.

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