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Interfacial fracture toughness of synthetic bone-cement interface

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Abstract

Conventionally, the bonding strength of bone-cement interface is obtained by mechanical strength testing which tends to produce large variability between specimens and test methods. In this work, interfacial fracture toughness of synthetic bone-cement interface has been determined using sandwiched Brazilian disk specimens. Experiments were carried out under selected loading angles from 0 to 25 degrees to achieve full loading conditions from mode I to mode II. Solutions for complex stress intensity factors as well as strain energy release rates were obtained for a sandwich disk with a finite interlayer using the finite element method. Phase angles were obtained at a fixed distance to the crack tip. The fracture loads were obtained from the load displacement curves and the values of interfacial fracture toughness were calculated from the fracture loads and the finite element J-integral solutions. The implication of this information on the assessment of fixation in acetabular replacements was discussed in the light of in-vitro fatigue testing of implanted acetabula.

Keywords

Bone-cement interface; Brazilian disk specimen; mixed mode fracture; interfacial fracture toughness; orthopaedic biomaterials

Introduction

The bonding strength of the interfaces within the cemented arthroplasty system has been evaluated using conventional mechanical testing such as reported in [1-6]. The most comprehensive study of bone-cement interface to day was carried out by Mann and his associates [1,4-6], including modelling the tensile behaviour of the cement-bone interface [4], mechanical strength of the bone-cement interface under shear and tension [5], mixed mode [1] and creep-fatigue loading conditions [6]. Although of considerable value for orthopaedic research, the measured strength of the interface is usually very sensitive to material combination, specimen geometry and fixture conditions [1,7]. There is a large variation in the results between specimens due to the difference in the amount of cement infiltration into bone and variations in the human cadaver bone tissues [1]. A variety of failure mechanisms have also been observed [7] during the separation process of the interface, such that the failure characteristics cannot be uniquely quantified by a bonding property.

A fracture mechanics approach seems to be more appropriate since micro-defects may form during the process of cement application and subsequent physiological loading conditions in

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routine activities. Both material mismatch and mixture of the loading modes may be

characterised by a phase angle, $\psi = \tan^{-1} \left[\left(\frac{\sigma_{12}}{\sigma_{22}} \right) \right]$ at a fixed distance to the crack tip, and the interfacial fracture toughness of a given bimaterial system is known to vary significantly with ψ . There has been a number of specimen geometries developed as suitable candidates for the measurement of interfacial fracture toughness [8-11]. Sandwiched compact tension specimens [8] were used to produce predominantly mode I loading conditions with a phase angle $\psi \approx 0^\circ$; while four-point bend arrangements provided results within the mid-range $\psi \approx 35^\circ$ - 60° [9]. Interfacial fracture toughness between cortical bone and cement was studied by Swain et al [10], using a four-point bend test arrangement.

Ideally, a test specimen should cover a range of phase angles so that a variety of material mismatch and mixed mode loading conditions may be characterised. Brazilian disk specimen [11] is such a convenient arrangement that allows continuous measurement of fracture toughness as a function of loading angle θ to achieve loading conditions from mode I to mode II. The homogeneous specimen is mode I when $\theta = 0^\circ$, and mode II when $\theta \approx 25^\circ$. A sandwich specimen may be obtained by using an interlayer to glue two identical halves of substrates, as shown in Fig. 1. The specimen has been successfully used in the determination of interfacial toughness between substrates including aluminium, brass, steel and plexiglass and interlayer epoxy [12], although the stress intensity factor solutions for homogeneous disk were used in that case, under the assumption that the interlayer was much smaller than other characteristic dimensions.

Sandwiched Brazilian disk specimens were chosen for the present study to represent the nature of loading at the bone-cement interface within the acetabular prosthetic system, which is a mixture of compression and shear [13], as opposed to primarily bending in the femoral components. The objectives of this work were to explore the feasibility of Brazilian disk specimens in the determination of interfacial fracture toughness of cancellous bone-cement interface, and to develop a methodology that may be used in the assessment of the integrity of acetabular fixation based on fracture mechanics concepts. Due to the appreciable thickness of the cement, numerical solutions for stress intensity and strain energy release rate of the sandwich disk were obtained. Experiments were carried out using solid polyurethane foams as a cancellous bone analogous material to reduce the inter-specimen variability [14]. The results were examined in the light of in-vitro fatigue testing of implanted composite sawbones.

Materials and methods

Specimen preparation

Solid rigid polyurethane foams were used as an alternative medium for human cancellous bones. The solid foam blocks have a density of 0.64 grams per cubic centimetre and are “graded” foams per ASTM standard F-1839 [15]. A commercial bone cement PMMA (CMW) was used for the study. The cement was mixed manually according to the recommended procedures, as in normal surgical operations. A rectangular foam block was marked as the pre-determined initial crack length, $2a = 10$ mm, and the area was then protected using a piece of thin tape before the application of the cement between this and another identical sized foam block. Pressure was applied and metal pins were used to ensure equal thickness of the cement of 2 mm until the cement set. The disks were then machined to the final sizes with radius $R = 19 \pm 0.1$ mm and thickness $B = 10 \pm 0.1$ mm.

Experimental methods

The experiments were conducted at room temperature using a Hounsfield material testing machine (H20k-W). The load was applied under displacement control at a rate of 0.025 mm/s. Compressive force was applied at angles of 0, 5, 10, 15, 20 and 25° with respect to the crack plane. All disks were measured for R and B prior to testing and measured for crack length $2a$ post testing. The experiments were repeated for two additional crack lengths, $2a = 15$ and 20 mm, with a thickness of $B = 10$ mm.

Results

The deformation behaviour experienced in all the disks appears to be similar, as shown in Fig. 2, where some typical load-displacement curves are presented as a function of loading angle. Fracture occurred catastrophically and cracks propagated dynamically. The load at fracture increases as the increase of the loading angle, and the values of peak load/thickness ratio, P/B , remained comparable for all three different crack lengths. Microscopic examination showed that most of the fracture surfaces were clean-cut at the bone-cement interface, with very limited adhesion of cement to the foam. During the experiments, it was observed that the polyurethane foam was “flattened” in the vicinity of the loading point, and the flattened area was marked and subsequently considered in the calculation of the fracture stress, from which the stress intensity factors and the interfacial fracture toughness were obtained.

Finite element analysis

A homogeneous circular disk of radius R , with a centre crack of length $2a$, was presented by Atkinson et al [11], where explicit formulae for stress intensity factors K_I and K_{II} as functions of the loading angle θ were given:

$$\begin{aligned} K_I &= \frac{P}{\pi BR} \sqrt{\pi a} f_I, \\ K_{II} &= \frac{P}{\pi BR} \sqrt{\pi a} f_{II}, \end{aligned} \quad (1)$$

where B is the thickness of the disk, and f_I and f_{II} are functions of the loading angle and relative crack size (a/R).

Finite element analyses were carried out to evaluate the effect of a finite interlayer of dissimilar materials on the solutions of stress intensity factors of a Brazilian disk. A finite element model was developed using ABAQUS 6.5, with 13804 nodes and 3964 elements of 8-noded quadratic plane strain elements. The crack tips were refined with collapsed 8-noded elements and an average size of the crack tip elements was $10\mu\text{m}$. The radius of the disk was taken as 20 mm, and crack length $2a$ was 10 mm. Contact elements were placed on the crack faces to prevent possible penetration of the crack flanks at large loading angles. The sawbone was taken as material 1 with the Young's modulus of 393 MPa and Poisson's ratio of 0.35 [14], while the cement was taken as material 2, with a Young's modulus of 2 GPa and Poisson's ratio of 0.33. The disk was maintained horizontally while the load and the constraints were altered to achieve loading angles of 0, 5, 10, 15, 20 and 25 degrees.

J-integrals were obtained for both left and right crack tips and the phase angles were calculated at a fixed distance to the crack tip, $L_0 = 5\mu\text{m}$, using:

$$\psi = \tan^{-1} \frac{\text{Im} [KL_0^{ie}]}{\text{Re} [KL_0^{ie}]} = \tan^{-1} \left[\left(\frac{\sigma_{12}}{\sigma_{22}} \right)_{L=L_0} \right]. \quad (2)$$

Due to the inherent oscillation of the stress fields near the interface crack tip, the shear and normal components of the stress intensity were not well defined. The complex stress intensity factors were extracted at the same fixed distance to the crack tip using an interaction integral method [16]. The normalised real and imaginary parts the stress intensity factors, f_I and f_{II} , as defined in Eq.(1), were obtained and the results are presented, together with those of an isotropic disk, in Fig. 3. The main difference seems to be that a mixed mode condition arises due to the material mismatch in the sandwich disk at $\theta = 0$, as opposed to pure mode I in the isotropic disk case. Otherwise, only moderate deviations from the results of isotropic disk were found as a result of the present interlayer. The relation between the phase angle and the loading angle may be readily obtained but omitted here due to space limitations. A simple transformation reveals that, at $L = 8.7 \mu\text{m}$, the phase angle is zero, corresponding a zero loading angle.

The interfacial fracture toughness of bone-cement may be calculated using modified stress intensity factors:

$$G = \frac{I}{2} (1 - \beta^2) \left[\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right] |K|^2, \quad (3)$$

$$\text{and } |K| = \sqrt{K_I^2 + K_{II}^2}.$$

Considering the relation between the phase angle and the loading angle, the interfacial fracture toughness may be presented as a function of phase angle, as shown in Fig. 4. Although there are some scatters in the results from three otherwise identical tests, particularly at larger loading angles, the general trends depicted seem to be similar. The minimum value of the interfacial fracture toughness, $\sim 0.43 \text{ J/m}^2$ (at $\psi \approx 0^\circ$), may be regarded as representative of the intrinsic interfacial fracture toughness of this bone-cement interface.

Discussion

The numerical analyses and experimental results presented in this study demonstrate that interfacial fracture toughness of bone and cement can be evaluated using sandwich Brazilian disk specimens. The magnitude of the overall strength of the interface is given by G_{IC} , while the phase angle ψ describes the ratio between the shear to tensile stress components acting at a fixed distance to the crack tip. Full range of phase angles from -90° to $+90^\circ$ can be achieved using a sandwich Brazilian disk loaded at angles from 0 to $\pm 25^\circ$. This is clearly advantageous compared with other specimen geometries with far more limited ranges of phase angles, such as $\psi \approx 0^\circ$ for double-cantilever beam specimen [9]; $\psi < 18^\circ$ for compact tension specimens [8] and $\psi \approx 45^\circ$ for four-point bend specimens [10]. There is a lack of material symmetry as the fracture toughness for a negative value of phase angle differs slightly from that at the same positive value of the phase angle. This illustrates the importance of determining interfacial fracture toughness as a function of a full range of phase angles. The values of interfacial toughness should not be compared unless they are referred to the same phase angle. For the current material system, the pure mode I state $\psi = 0^\circ$ may be obtained at $L = 8.7 \mu\text{m}$. Here L may be estimated as the size of the process zone under mode I loading condition.

Although there have been no publications on the interfacial fracture toughness between polyurethane foam and PMMA, there have been publications [1,8,10] on the bonding behaviour of PMMA to bone. Mann et al [1] reported that the bonding strength between human femur and cement depended on the amount of interdigitated with PMMA cement,

with the mean fracture energy measured as 350 J/m² for mode I and 1000 J/m² for mode II, although no defects were introduced in these tests. Wang and Agrawal [8] reported interfacial fracture toughness between bovine cortical bone and PMMA to be between 38 to 52 J/m² for phase angles $-18^\circ < \psi < 16^\circ$; while [10] reported 44 to 53 J/m² for bovine cortical bone and two different cements at $\psi \approx 45^\circ$. There are significant discrepancies in the last two sets of results, as the values of the fracture toughness measured appear to be independent of the phase angle, which is known to be untrue. The present results are in general lower than the published results. These lower values are partly the results of modification of the fracture loads by considering the “flattened” area. The discrepancy between the current and previous results may also be due to the difference in foam materials, as opposed to cortical bones, as well as the testing methods adopted.

Although polyurethane foams are limited in their representations of features of human cancellous bone, they have been shown to be a suitable analogous material with similar mechanical properties to those of cancellous bones, with inter-specimen variability 20 to 200 times lower than that for cadaveric specimens [17]. Interestingly, work currently carried out at Portsmouth [18] shows that preferential interface crack growth occurs in cemented acetabular replacements under fatigue loading conditions. Composite sawbones were used for these fatigue tests and the samples were reamed to receive the cement as in standard operations. The interfacial features between the synthetic cancellous bone and cement in the reconstructed acetabulum resemble the bone-cement interface used in the sandwich Brazilian disk tests. Further work is to evaluate the interfacial fracture toughness between bovine cancellous bone and cement, so that the values of interfacial fracture toughness obtained may be more relevant to clinical situations.

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Fig. 1.
Schematic of a sandwiched Brazilian disk specimen.

Fig. 2.
Typical load-displacement curves at selected loading angles.

Fig. 3.
Normalised stress intensity factors for isotropic and sandwich disks.

Fig. 4.
Interfacial fracture toughness of the bone-cement interface.