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Short communication

Mixed-mode failure strength of implant–cement interface specimens with varying surface roughness

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ABSTRACT

Aseptic loosening at the implant–cement interface is a well-documented cause of failure in joint arthroplasty. Traditionally, the strength of the implant–cement interface is determined using uni-axial normal and shear loading tests. However, during functional loading, the implant fixation sites are loaded under more complex stress conditions. For this purpose, the strength of the implant–cement interface under mixed-mode tensile and shear loading conditions was determined in this study using interface specimens with varying interface roughness. For the lowest roughness value analyzed (R_a=0.89 μm), the interface strength was 0.40–1.95 MPa at loading angles varying between pure tension and shear, whereas this was 4.90–9.90 MPa for the highest roughness value (R_a=2.76 μm). The interface strength during pure shear (1.95–9.90 MPa) was substantially higher than during pure tension (0.58–6.67 MPa). Polynomial regression was used to fit a second-order interpolation function through the experimental interface strength data (R^2=0.85; $p<0.001$), relating the interface strength (S [MPa]) to the interface loading angle (α [degrees]) and interface roughness (R_a [μm]): $S(\alpha,R_a)=0.891R_a^2+0.001\alpha^2-0.189R_a-0.064\alpha-0.060$.

Finally, an interface failure criterion was derived from the interface strength measurements, describing the risk of failure at the implant–cement interface when subjected to a certain tensile and shear stress using only the interface strength in pure tensile and shear direction. The findings presented in this paper can be used in numerical models to simulate loosening at the implant–cement interface.

1. Introduction

Aseptic implant loosening is a well-documented cause of failure in both total hip (Malchau et al., 2002) and total knee arthroplasty (Sharkey et al., 2002). Loosening of implants may occur due to debonding at either the implant–cement or the bone–cement interface (Stone et al., 1989). Traditionally, the strength of such interfaces is determined using uni-axial normal and shear loading tests (Raab et al., 1981; Ahmed et al., 1984; Stone et al., 1989; Chen et al., 1998). However, during functional loading, the implant fixation sites are loaded under more complex stress conditions (Race et al., 2010). For accurate modeling of potential failure at the interface, the strength under mixed-mode loading conditions has to be known. Earlier experimental studies have focused on the mixed-mode strength of the bone–cement interface (Mann et al., 2001), but the strength of the implant–cement interface has not yet been studied under mixed-mode loading condition.

In previous finite element (FE) studies, debonding at the implant–cement interface has been simulated using stress-based (Verdonschot and Huiskes, 1997) or energy-based (Perez et al., 2005) interface failure formulations. The Hoffman failure criterion (Hoffman, 1967) is a well-known example of a stress-based failure formulation used to simulate failure at the implant–cement interface (Weinans et al., 1993; Huiskes and Van Rietbergen, 1995; Verdonschot and Huiskes, 1997), although it has originally been developed for failure in orthotropic brittle materials. The Hoffman criterion uses a failure index (*FI*) to describe the risk of material failure when exposed to a mixed-mode stress situation based on a quadratic relation between the strength in pure normal and shear direction, which has never been validated for application to the implant–cement interface.

The objective of the current study was to determine the strength of the implant–cement interface under mixed-mode loading conditions and to propose an experimentally supported failure criterion. For this purpose, implant–cement interface specimens, having a varying interface roughness, were subjected to a combination of tension and shear.

2. Materials and methods

2.1. Implant–cement interface specimens

Rectangular samples of stainless steel with three different (arithmetic) average surface roughnesses (R_a=0.89 ± 0.090, 1.49 ± 0.059 and 2.76 ± 0.21 μm) were used

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as a basis for the implant–cement interface specimens (Fig. 1a). The surface roughness variations were obtained by grit-blasting the samples with multiple grit sizes. Subsequently, the surface roughness was measured (Surftest SJ-201, Mitutoyo, Veenendaal, The Netherlands). No additional treatments were performed to enhance the adherence of bone cement to the steel specimens. The variation in surface roughness among the three groups of specimens was assumed to represent the roughness range used in joint arthroplasty (Verdonschot, 2005). The dimensions of the steel samples were $70 \times 23 \times 9$ mm^3 ($L \times W \times H$), resulting in an implant–cement interface area of 630 mm^2. Triangular undercuts were made in the steel samples to minimize stress intensities around the edges and to obtain a relatively uniform interface load.

Prior to testing, the specimens were cleaned with acetone and placed in a Teflon® mould. The low-viscosity bone cement used in this study (CEMEX RX, Tecres Medical, Verona, Italy) was stored at room temperature for 24 h before preparation. We hand-mixed the cement for 1 min before pouring it into the mould, which was closed slowly allowing residual bone cement to escape to obtain homogeneous steel–cement specimens. The size of the bone cement was identical to the steel samples. After 20 min of polymerization, the interface specimens were removed and stored in saline at 37 °C for 48 h to allow for further polymerization and fluid uptake.

2.2. Loading set-up

Mixed-mode interface loading experiments were performed using an MTS loading machine (MTS 458.20, MTS Systems Inc., Eden Prairie, MN, USA). The top and bottom part of the interface specimens were clamped in a custom-built circular loading jig (Fig. 1b), which allows to load the specimens at different angles (Wang and Suo, 1990). The interface specimens were subjected to a combination of tension and shear by varying the angle (α) between the applied load and the interface normal direction. The experiments were performed under displacement control with a loading rate of 0.5 mm/min. Due to the limited loading range of the MTS machine (max. 10 kN), the compressive strength of the specimens could not be determined as the strength exceeded the maximal load. Four loading angles were evaluated: pure tension (α=0°), pure shear (α=90°) and two combinations of tension and shear (α=30° and 60°). For each loading angle, five specimens were tested per roughness value (n=5).

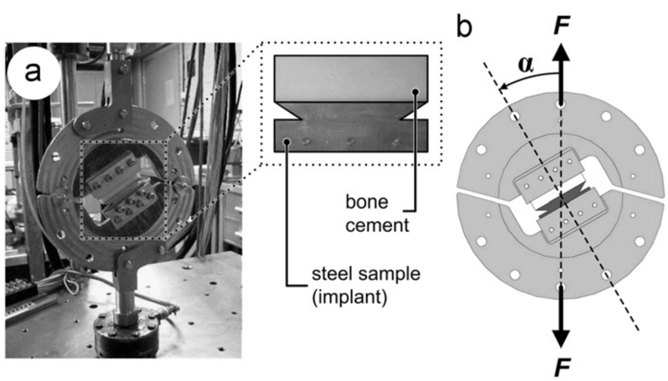

Fig. 1. Experimental set-up to determine the strength of the implant–cement interface using steel–cement interface specimens having a varying interface roughness (a). The implant–cement interface strength was tested for pure tensile (α=0°), pure shear (α=90°) and mixed-mode ($0° < \alpha < 90°$) loading conditions (b).

2.3. Statistical analysis

Linear and quadratic correlation coefficients (R^2) were determined between the interface strength and the loading angle and interface roughness analyzed. Polynomial regression was used to fit a second-order generalized interface strength function, depending on the loading angle and roughness, through the interface strength data using the least-squares method. A failure index (*FI*) was defined describing the risk of failure at the implant–cement interface when subjected to a mixed-mode stress condition, using the interface strength in pure tensile and shear direction.

3. Results

3.1. Mean results

The majority of the specimens failed by debonding of the entire steel–cement interface. In two specimens with a roughness of 2.76 μm, small cement remnants were seen at the metal surface, suggesting a locally intact implant–cement interface and fracture of the bulk cement. Table 1 summarizes the mean results. In general, enhancing the interface roughness increased the implant–cement interface strength. For the lowest roughness (R_a=0.89 μm), the interface strength was 0.40–1.95 MPa at loading angles varying between pure tension and shear, whereas this was 4.90–9.90 MPa for the highest roughness value (R_a=2.76 μm). The interface strength was substantially higher during pure shear loading tests (1.95–9.90 MPa) compared to pure tension tests (0.58–6.67 MPa). Quadratic correlations between strength and loading angle and strength and roughness (Fig. 2) resulted in R^2 values ranging from 0.82–0.90 and 0.54–0.76, respectively.

3.2. Generalized interface strength function

Based on the quadratic relations between interface strength and loading angle and roughness, a second-order interpolation function was defined (Eq. (1)) and fitted through the experimental data (R^2=0.85; $p < 0.001$), relating the interface strength (S [MPa]) to the interface loading angle (α [degrees]) and interface roughness (R_a [μm]).

$$S(\alpha, R_a) = 0.891R_a^2 + 0.001\alpha^2 - 0.189R_a - 0.064\alpha - 0.060 \quad (1)$$

Standardized coefficients corresponding to the variables listed in Eq. (1) were: 0.88, 0.96, −0.05 and −0.67. It should be noted that this equation only applies to a combination of tensile and shear loads (α=0°–90°) and is valid only within a specific interface roughness range ($R_a \approx$ 0.50–3.0 μm). A three-dimensional representation of the generalized interface strength function is shown in Fig. 3a.

Table 1
Implant–cement interface strength.

	Interface loading angle, α (deg.)				Correlations	
	0 (n=5)	30 (n=5)	60 (n=5)	90 (n=5)	*R^2 linear*	*R^2 quadratic*
Roughness (μm)	**Interface strength, σ (MPa)**					
R_{a1}=0.89 ± 0.090	0.58 ± 0.34[a]	0.40 ± 0.15[a]	0.45 ± 0.47	1.95 ± 1.16[b]	*0.24*	*0.54*
R_{a2}=1.49 ± 0.059	1.15 ± 1.12	0.88 ± 0.50	0.61 ± 0.29	3.27 ± 1.14	*0.27*	*0.59*
R_{a3}=2.76 ± 0.21	6.67 ± 1.68	4.90 ± 0.88	6.05 ± 0.97	9.90 ± 0.96	*0.32*	*0.76*
Correlations						
R^2 linear	*0.79*	*0.88*	*0.84*	*0.86*		
R^2 quadratic	*0.82*	*0.90*	*0.87*	*0.87*		

[a] Only 4 specimens were tested due to pre-testing interface failure.
[b] Only 3 specimens were tested due to pre-testing interface failure.

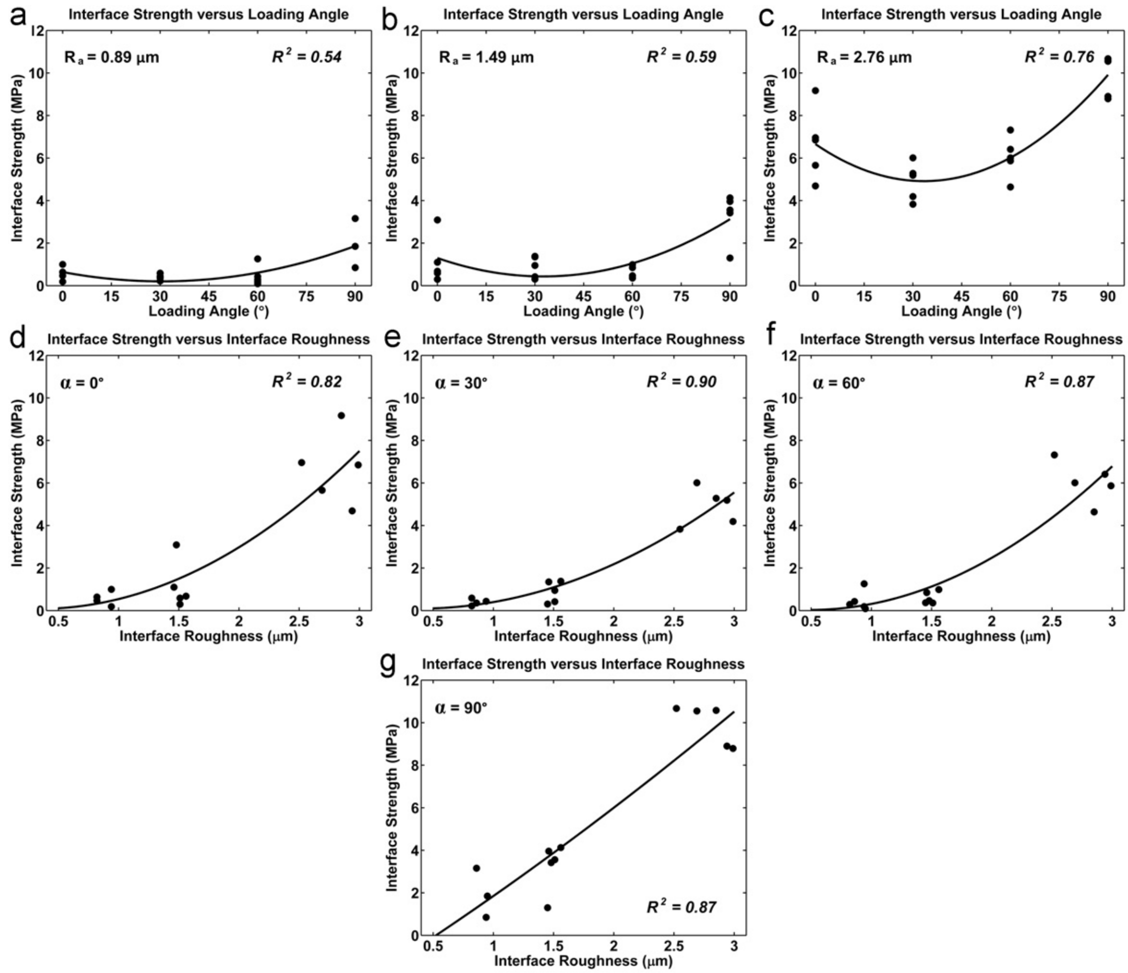

Fig. 2. Quadratic correlations between the interface strength and the interface loading angle (a–c) as well as between the interface strength and the interface roughness (d–g).

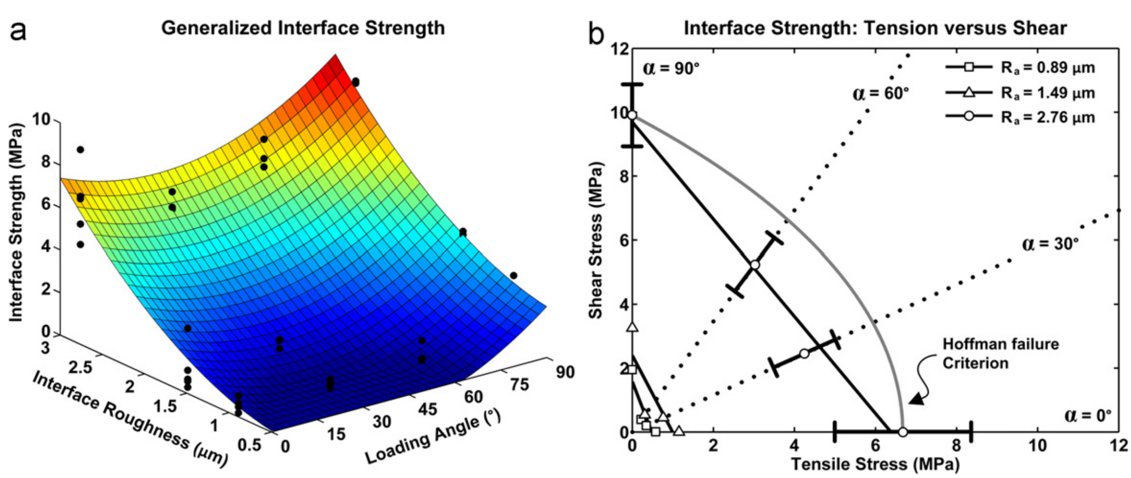

Fig. 3. Generalized interface strength function depending on the interface loading angle and roughness (a). Interface failure strength as a function of tensile and shear stresses for varying interface roughness (b). For each roughness, straight lines were fitted ($R^2=0.67$–0.98; $p=0.01$–0.18) through the average strength values at the four loading angles (black lines). Standard deviations are only shown for the highest roughness ($R_a=2.76$ μm). The Hoffmann failure criterion (Hoffman, 1967) adjusted to the uni-axial tensile and shear strengths found for this roughness is depicted as well (grey line).

3.3. Implant–cement failure criterion

The interface strengths measured were decomposed into pure tensile and shear components using the interface loading angles, and presented as a function of these uni-axial components (Fig. 3b). For mixed-mode loading conditions, the interface strength appeared to be linearly related to the strength in pure tensile and shear direction ($R^2=0.67$–0.98; $p=0.01$–0.18). Based on this finding, a linear interface failure criterion was formulated (Eq. (2)). Similar to the Hoffman failure criterion, a failure index (FI) was used to describe the risk of debonding at the interface when subjected to a certain tensile (σ_t) and shear stress (σ_s) using only the interface strength in pure tensile

(S_t) and shear (S_s) direction. Hence, for a given mixed-mode stress situation at the implant–cement interface static debonding is expected in case $FI \geq 1$.

$$FI = \frac{1}{S_s}\sigma_s + \frac{1}{S_t}\sigma_t \tag{2}$$

with:

$$S_t = S(\alpha = 0^\circ, R_a) = 0.891R_a^2 - 0.189R_a - 0.060,$$
$$S_s = S(\alpha = 90^\circ, R_a) = 0.891R_a^2 - 0.189R_a + 2.280$$

4. Discussion

The purpose of the present study was to determine the mechanical strength of the implant–cement interface under mixed-mode loading conditions. Our experiments show that the implant–cement interface strength is nonlinearly related to variations in loading angle and interface roughness (Eq. (1)). We moreover found that interface failure strength under mixed-mode loading conditions is linearly related to the strength in pure tensile and shear direction, which is different from the quadratic relation of the Hoffman failure criterion (Hoffman, 1967). The failure formulation derived from this finding (Eq. (2)) can be used in FE models to simulate interface failure and optimize implant longevity.

The uni-axial tensile (0.58–6.67 MPa) and shear strengths (1.95–9.90 MPa) determined with varying interface roughnesses (R_a=0.89–2.76 μm) are comparable to values reported in literature. For example, interface shear strengths have been reported in the range of 5.3–13.8 MPa for an interface roughness of R_a=1.1–8.6 μm (Raab et al., 1981; Chen et al., 1998). Although in our experiments the interface strength was considerably lower in pure tension than in pure shear, the lowest strength was found at a loading angle of 30°. The addition of a small amount of shear in this load-case appeared to worsen the stress situation at the implant–cement interface.

A limitation to our study was that the loading set-up was not as sensitive as hoped for. Initially, a low roughness specimen (R_a=0.40 μm) was included in the experiment, but its strength was too small to measure with our loading set-up. The low sensitivity of the measurement set-up might be an explanation for the relatively large standard deviations found for specimens with a low interface roughness (Table 1). Smaller scale interface experiments may be more appropriate to describe the failure response of low-roughness specimens. Furthermore, not more than one type of bone cement was considered (CEMEX RX). Due to the limited loading range (max. 10kN), the failure strength under compression could not be determined. Trial compression tests at 60° using the high roughness interface specimens (R_a=2.76 μm) showed a compressive strength of more than 15.9 MPa (10 kN/630 mm^2). The Hoffman failure criterion needs further evaluation for mixed-mode compression and shear loading conditions. Lastly, interface fatigue was not considered as only static experiments were conducted. Our results therefore mainly apply to short-term implant fixation analyses, although the fatigue strength of the implant–cement interface may be related to its static strength (Chen et al., 1998).

Conflict of interest statement

The authors declare that they have no competing interests.

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