Simulation of the debonding process of cement-prosthesis interfaces in total hip arthroplasties

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Introduction
Clinical follow-up studies of joint replacements indicate that debonding of the implant is probably the most important mechanical cause of loosening. In cemented prostheses, this effect is mainly due to cyclic loads that produce creep damage in the cement. This may leads to the microrupture of the interfaces, increasing the local stress state in the fracture neighbourhood and, in some cases, its propagation and the progressive separation of the interfaces till the stem is completely debonded. Usually, the cement-prosthesis interface is the most problematic (Harrigan et al, 1991).

The main goal of this study is to develop a damage model based on the principles of Continuum Damage Mechanics, able to simulate the separation process of the cement-prosthesis interface. As it is well known, Continuum Damage models characterise the mechanical resistance loss at each point by an internal damage variable, normalised between zero and one in such a way that 0 means the undamaged situation (fully bonded surfaces) and 1 means local fracture (fully debonded).

This constitutive damage model has been implemented into an interface finite element joining cement and prosthesis.

Methods
Damage models (brittle or cohesive) assume that the undamaged state remains intact until a certain stress level is reached (damage criterion). If this stress level is crossed, damage appears and the element starts to loose part of its stiffness and strength. The evolution of the damage variable is ruled by a certain damage flow equation producing an irreversible process. An unloading constitutive law has also to be provided usually resembling the initial intact behaviour but with a reduction in the stiffness according to the value of the damage variable (if isotropic linear behaviour is assumed the relation between the elasticity modulus and the damage variable has to be provided). These are the main elements that compose a complete damage model.

In this work, we have followed the model initially proposed by Camacho et al (1996), that establishes all the previous elements in terms of a unidimensional stress and strain (elongation) effective state. The effective stresses and effective elongation are defined as:

\[
\begin{align*}
t_{\text{eff}}^2 &= t_3^2 + \beta^2(t_1^2 + t_2^2) \\
\delta_{\text{eff}}^2 &= \delta_3^2 + \beta^2(\delta_1^2 + \delta_2^2)
\end{align*}
\]

with \( \beta = \frac{\sigma_c}{\tau_c} \)

where \( \sigma_c \) the tensile strength of the interface, \( \approx 8 \) MPa in our case (Keller et al, 1980)
\( \tau_c \) shear strength of the interface, \( \approx 6 \) MPa in our case (Stone et al, 1989)
The damage evolution is expressed in terms of a relation between these two variables, earlier proposed by Rose (Rose et al, 1981) as:

\[
t_{\text{eff}} = A \cdot \delta_{\text{eff}} \cdot e^{-\frac{\delta_{\text{eff}}}{\delta_c}}
\]

where \( A \) and \( \delta_c \) are material constants.

The unloading relation is assumed to follow the path between the current stress-strain state in the previous curve and the origin as shown in Fig. 1.a. Damage starts to increase after the damage curve is reached again in a new loading step.
Fig. 1: (a) Loading/unloading law; (b) Damage law.

An equivalent approach may be written from an energetic point of view. In this sense, the effective stress may be rewritten as

$$t_{eff} = \frac{\partial \phi}{\partial \delta_{eff}} \quad \text{with} \quad \phi = A \cdot \delta_{c}^2 \left(1 - e^{-\frac{-\delta_{eff}}{\delta_{c}}} \right) - A \cdot \delta_{c} \cdot \delta_{eff} \cdot e^{-\frac{-\delta_{eff}}{\delta_{c}}}$$

(5)

an effective strain energy, such as $\phi(\infty)=G_c$, with $G_c$ the so-called critical energy release rate. The damage variable may therefore be defined as:

$$D = \frac{\phi_{max}}{G_c} \quad \in [0,1]$$

(6)

with $\phi_{max}$, the maximum value of $\phi$ achieved along the load history. This expression clearly represents an irreversible process.

The expression above is valid for a static loading case, but the aim of this study is to simulate the debonding process due to cyclic failure of the cement-prosthesis interface. Hence, it is necessary to find a rule, which relates the evolution of the damage accumulation as a function of the number of loading cycles. Damage of the interface can be eventually consider as a "crack" which progresses. Thus, the rate of crack development was determined from fatigue experiments on uncentrifuged bone cement specimens (Davies et al., 1987), which provide a relation between the stress amplitude $\sigma$ and the number of cycles to failure $N$ at that stress level, as described by

$$\log N = -4.86 \cdot \log \sigma + 8.77$$

(7)

We considered that this expression gives the number of cycles at which the crack initiation is produced under a constant stress. So $D_{1c}$ is the critical value of the damage at a crack initiation, as can be shown in the Figure 1b. The critical damage value was obtained when elongations reached the value of $\delta_c$ (Fig. 1b).

While damage is lower than $D_{1c}$, damage accumulation is evaluated using a modification of the Palmgreen-Miner’s rule (Lemaitre, 1990), as follows:

$$D_{N,N_{min}} = D_c + D_{sd} \cdot \frac{N_{min}}{N_c}$$

(8)

where $N_c$ was the number of cycles up to failure at each Gauss point and $N_{min}$ was set to the minimal value of cycles up to reach the critical damage at any point of the interface.

Once damage has exceeded the critical damage, the model incorporates the stiffness reduction that appears in the interface. We proposed a damage accumulation law, which depends on the new damage produced, $D_{sd}$, by the applied effective stress on a static loading case (Fig. 1b), described as

$$D_{N,N_{min}} = D_c + D_{sd} \cdot N_{min}$$

(9)

This model has been implemented in a finite element commercial code (ABAQUS). Before applying this model to the analysis of a prosthesis, it has been validated, using the experiments presented by Verdonschot and Huiskes (Verdonschot et al., 1996).

After this validation, a 3-D finite element model was established, to simulate a hip joint reconstruction with a femoral cemented Exeter stem. The mesh was generated using the I-DEAS CAD system and was composed by 5314 elements and 5628 nodes. This model was analysed by the finite element package ABAQUS including a special user element routine also implemented in 3-D to compute the stiffness.
properties of the previously detail interface element (an eight-noded element composed by two bilinear quadrilaterals separated by a certain depth). Bone tissue was considered anisotropic and evolutive as a result of the application of an anisotropic remodelling formulation (Doblaré and García, in press). The implant was modelled as a linearly elastic isotropic material with an elastic modulus of $E=2\times 10^5$ MPa and a Poisson ratio of 0.28, bonded by a polymethylmethacrylate bone cement layer with $E=2200$ MPa, $\nu=0.3$ and $G=2.5$ MPa.mm. In addition, a 0.1 mm layer of interface elements was included to take into account the cement-prosthesis interface.

The analysis process was made in two steps: first, the actual bone density distribution was computed from the application of three loads that simulate the gait cycle; and a second step in which different loads were applied independently for different typical situations (gait cycle and stair climbing).

Results & Discussion

Subsidence of the taper and experimental results from Verdonschot has been represented in Fig. 2. Our model reproduced experimental results, adjusting the parameter $\alpha$ that appears in (9). The results are quite good, considering that our model presents important limitations, like the need of incorporating the friction between the two surfaces when the interface has debonded. This effect is very important, as many authors have demonstrated, obtaining very different results depending on the friction coefficient value considered (Verdonschot et al, 1996). Furthermore, the mechanical properties of the interface, as the critical energy release rate $G_c$, depends directly on the roughness surface and this effect has not been considered in this work. Another improvement that should be taken into account is the addition of the cement viscoelastic properties.

Even all of this, we can conclude that this model a first step in the complex development of a damage model interface able to simulate the debonding in cemented prostheses.

![Fig. 2. Taper subsidence.](image)

References

Doblaré M. and García J.M., J. Biomechanics, in press.
Lemaitre J., A Course on Damage Mechanics, 141-142, Springer, 1990