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A COMBINATION OF CONTINUUM DAMAGE MECHANICS AND THE FINITE ELEMENT METHOD TO ANALYZE ACRYLIC BONE CEMENT CRACKING AROUND IMPLANTS

N. Verdonschot[1] and R. Huiskes[2]

1. ABSTRACT

In this paper we present a method to simulate acrylic bone cement damage accumulation around implants. The method combines the Finite Element Method (FEM) with the theory of Continuum Damage Mechanics (CDM). Damage was considered a tensorial variable, resulting in anisotropic material behavior when the material was damaged. The method was applied to an axi-symmetric structure, consisting of a taper pushed in a cement mantle. Varying the taper/cement interface conditions revealed that these had considerable effects on the damage process. Not only the mechanical endurance of the structure changed, but also the way in which damage progressed was affected. Two mesh densities were considered, the to study the effects of mesh refinement.

It was concluded that, although further research is required to obtain more realistic survival times, the method can be used on a comparative, qualitative basis. It predicts, pre-clinically, sites where cement damage is initiated, how this process progresses, and the effects of design parameters of implants on the mechanical endurance of the structure.

2. INTRODUCTION

Failure rates of cemented total hip replacement (THR) are significantly affected by prosthetic design factors [1,2]. However, at this point in time, thirty years after the introduction of bone cement, the most favorable design characteristics are still uncertain and are a matter of continuous debate [3,4]. Recent articles concerning retrieved cemented prostheses indicate that an important role in the failure process of cemented THR is played by acrylic bone cement. Jasty et al. [5] investigated 16 retrieved specimens. They found a large number of cracks in the cement, originating at voids or at the cement/stem interface. Particularly at locations where the prosthesis had sharp edges, a high crack-density was found. Although the number of prostheses studied was small, they also found a tendency of increased crack-length and density when the prosthesis had been in-situ for a longer period of time. Hence, it can be assumed that the fatigue process of bone cement is an important cause of failure of a bone/prosthesis system, and it would be very valuable to be able to simulate this process and to predict its mechanical endurance.

Keywords: total hip replacement, bone cement, failure, damage mechanics

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To model the fatigue process of engineering structures under dynamic loading, Continuum Damage Mechanics (CDM) theories have been developed, and implemented in FE codes [6-9]. Although the theory itself is relatively simple, its can be problematic. Difficult problems concern the three-dimensional behavior of damage accumulation, the dependency of the solutions on the FE model characteristics, and computer costs.

Earlier, we presented a method that combined the FE method with CDM to analyze the effects of cement/stem debonding in a cemented femoral THR [10]. However, in that study, damage was assumed to be a scalar variable, hence, the orientation of the stresses in the cement material, and the subsequent post-damage anisotropy, was not accounted for.

The purpose of this study was to make the model more realistic by using a method that considers damage as a tensorial variable. This results in anisotropic material behavior of damaged sites. To allow for comparison with experimental findings, the method was applied to an axi-symmetric structure consisting of a taper pushed into a cement mantle under cyclic loading. Parameters varied in the damage accumulation simulations were interface friction conditions and cement mesh density, as these parameters are expected to affect the damage process.

3. METHODS

3.1 Finite element model

Two axi-symmetric FE models were used in the simulations (figure 1). The refined model (270 elements) was used as the reference model, whereas the coarse model (140 elements) was used to investigate the effects of a reduced mesh density. The taper/cement interface characteristics were varied. This interface was assumed to be either perfectly bonded or completely unbonded. In the latter case special non-linear interface elements between both surfaces were used (MARC Analysis Corporation, Palo Alto CA), and three coefficients of friction (μ=0.0, μ=0.05, μ=0.25) were assumed.

The materials modeled in the analyses were assumed to behave linear elastic, homogeneous and isotropic. However, when the bone cement was damaged, the material behaved anisotropically. Elastic moduli were assumed as 200 GPa for the taper material and 2.2 GPa for the bone cement. Poisson's ratio was taken as 0.3 for both materials. The top-center of the taper was loaded with a compressive force from zero to 7 kN, and the bottom of the bone cement mantle was constrained in the axial direction.

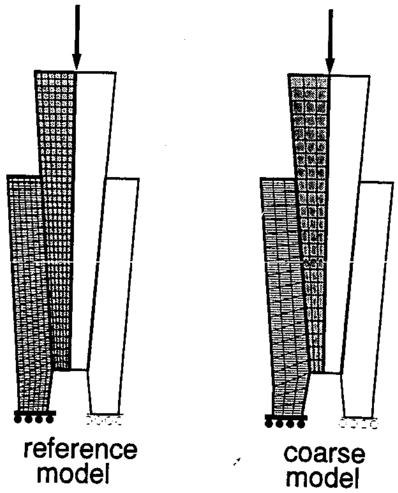

Fig. 1: Two axi-symmetric FE models were used in the simulations.

3.2 Continuum damage mechanics

When a material is dynamically loaded, micro-cracks may be initiated. When this occurs, the material is damaged. Consider an element of a damaged material. Let a be the area of a section through this element. Due to the presence of the micro-cracks and cavities, the effective area ($\tilde{a}$) for stress transfer is less than a. The damage (D) can be defined as:

$$D = \frac{a - \tilde{a}}{a} \tag{1}$$

Depending on the loading history, the damage (D) of the material may have a particular orientation. In that case, D is not a scalar but becomes a tensor [8].

The amount of damage occurring in a material due to dynamic loading depends on a large number of factors (e.g. applied load, number of loading cycles, environmental conditions). In this study, assuming constant environmental conditions, the amount of damage was assumed to be solely dependent on the applied load and the number of loading cycles.

Consider, for the sake of simplicity, the one dimensional case, where damage becomes a scalar variable. When only the load level is varied during the damage process, the amount of damage becomes a function the of number of cycles (n) and the load level (S):

$$D = F(n,S) = f(n/N), \tag{2}$$

with the restrictions: $D = 0.0$ when $n = 0$,
$D = 1.0$ when $n = N$,

where N is the number of cycles to failure for constant amplitude loading in a fatigue bench test of the same material. In these tests, specimens are exposed to a dynamic load with a constant load level and the number of cycles to failure is recorded. By repeating these tests with different load levels the relation between load level (S) and the number of cycles to failure (N) can be determined. Results of fatigue tests are often presented as S-N curves. The function $f(n/N)$ in equation (2), which is called the damage rule, defines the relation between the amount of damage and the ratio between the number of cycles of loading versus the number of cycles to failure. In the analyses a linear cumulative damage rule was chosen, that is called the "Palmgren-Miner" rule [11]. This damage rule, which itself is stress-independent, states that the damage is a linear function of the number of cycles of operations (n):

$$D = f(n/N) = n/N. \tag{3}$$

In reality, structures are often exposed to dynamic loads of which the load level varies in time. The damage sum accumulated during fatigue loading for a number of cycles of n_i at load levels S_i can be written as [12]:

$$D = \sum_{i=1}^{m} \Delta D_i\ , \tag{4}$$

where ΔD_i represents the amount of damage accumulation during fatigue at load level S_i and m is the number of load levels.

Using the elastic relations between stresses and strains, the amount of damage in an element can be coupled to the elastic properties [8]. However, dynamic experiments on bone cement have shown that bone cement fractures in a rather brittle way and that the elastic properties of the material are hardly affected by the number of loading cycle [13]. Therefore, it was assumed that the damage and the stiffness of the cement material were uncoupled. This means that the elastic properties of the cement were constant until the damage was complete (D=1.0).

In the two or three dimensional case, the damage (D) becomes a tensor. Due to cyclic loading in a particular direction, the material can be completely damaged in one direction, whereas it may be unaffected in another one. As a consequence, the elastic properties of the material become anisotropic after damage has occurred in one or two directions.

3.3 Iterative damage accumulation and implementation in the FEM

Initially, the damage at every integration point is set to zero. After loading the taper, stresses in the cement were calculated and, depending on the values of these quantities, the damage process in the cement started and progressed. The damage iteration scheme is illustrated in figure 2.

The FE method calculates the stresses occurring in the cement mantle. It provides the stress tensors in the global reference system $(\sigma_{ip})^{global}$ at every integration point within the cement elements. Subsequently, the principal stresses$(\sigma_{ip})^{local}_{principal}$ are calculated, which results in stress tensors in a local coordinate system. The orientation of these coordinate systems are stored in the R_{ip} rotation matrix variable. In the case that the principal stress directions are tensile (usually one or two components are) damage is assumed to occur perpendicular to that plane. The rate of damage is determined by using fatigue data reported by Davies et al., (1987). Using uni-directional fatigue experiments, they described the relation between the stress level (σ) and the number of cycles to failure (N) at stress level (σ):

$$\log N = -4.68 * \log\sigma + 8.77 \ , \qquad (5)$$

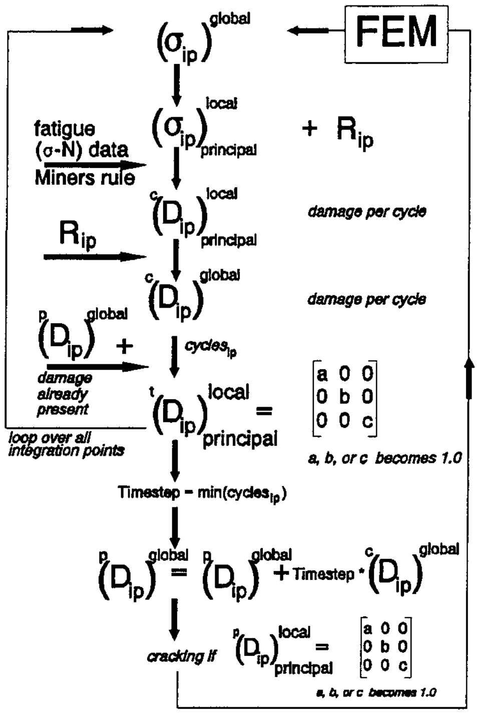

Fig. 2: Damage simulation scheme.

Using Palmgren-Miners rule (Miner, 1945), the damage per cycle in each principal stress (or damage) direction is known:

$$\Delta D_{loc} = \begin{bmatrix} \Delta D_i & 0 & 0 \\ 0 & \Delta D_j & 0 \\ 0 & 0 & \Delta D_k \end{bmatrix}_{loc} = \begin{bmatrix} \frac{1}{N_i} & 0 & 0 \\ 0 & \frac{1}{N_j} & 0 \\ 0 & 0 & \frac{1}{N_k} \end{bmatrix}_{loc} \qquad (6)$$

where N_i, N_j, and N_k are the numbers of cycles to failure in the principal directions, and ${}^{c}(\sigma_{ip})^{local}_{principal}$ the local matrix indicating the damage per loading cycle at the integration point. To be able to add this cyclic damage tensor to the tensor which indicates the damage that already exists, the local cyclic damage tensor is rotated to the global coordinate system, using the R_{ip} matrix. This produces ${}^{c}(\sigma_{ip})^{global}$, which identifies the damage tensor per loading cycle, oriented in the global coordinate system. In the next step, this cyclic damage tensor is added $cycles_{ip}$ times to the damage which was already present (${}^{p}(\sigma_{ip})^{global}$) until a temporary damage indicates how many times the cyclic damage tensor should be added to the already existing damage in order to obtain complete damage in a new direction. After this procedure has been performed for all integration points, the *timestep* used in the current increment is set to the minimal value of *cycles*$_{ip}$. Subsequently, the damage tensors ${}^{p}(\sigma_{ip})^{global}$ are updated by adding *timestep* times the cyclic damage tensors $({}^{c}(\sigma_{ip})^{global})$ for all integration points. This approach makes sure that damage becomes complete in a direction in at least one integration point during every calculation increment. To omit very small *timesteps* and to reduce computer costs, damage was assumed to be complete when the damage in a direction was more than 0.95.

The effect of damage was incorporated by using a cracking option available in the MARC finite element code (MARC Analysis Corporation, Palo Alto CA). This option allows the user to initiate a crack in a user-defined orientation. In the simulation, cracks were initiated perpendicular to the direction where the material had completely damaged. The cracking option ensures no stiffness in tensile and shear direction, whereas full stiffness is restored in the case that the crack would be forced to close due to compressive stresses. This results in non-linear, anisotropic material behavior of the cement material after damage has occurred.

4. RESULTS

In general, the damage process can be divided in three stages. In the first stage, high-stressed areas in the tip region are damaged and the maximal stress level in the cement mantle is reduced. At this stage, the damage rate decreases with the number of loading cycles. Figure 3 shows how the maximal tensile stress in the cement mantle was reduced from 20 MPa to about 5 MPa in the early stage for a bonded taper. This is caused by the fact that high stressed areas were damaged, and lost their mechanical stiffness leading to a stress re-distribution and a stress reduction in the damaged areas. The stress reduction mechanism was more pronounced in the bonded case as compared to the unbonded ones. The explanation for this phenomenon is that the unbonded tapers have the possibility to subside during the damage process. Hereby, stress levels increase, resulting in an only moderate decrease of maximal stress levels in the initial damage stage.

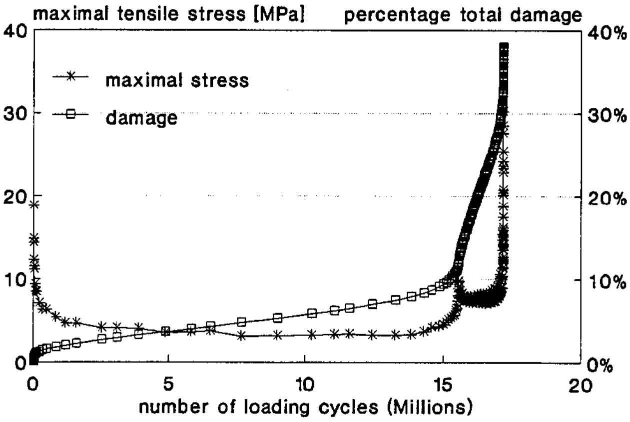

Fig. 3: Maximal tensile stress and total damage in the cement mantle as a function of the number of loading cycles in the bonded stem configuration.

In the second stage, the maximal stress level is relatively constant, resulting in a damage rate which is fairly constant as well. In the final stage, the cement mantle looses its mechanical integrity, the stress levels increase, and the damage rate increases rapidly.

In all cases, the damage process was initiated in the tip region. However, the progress of damage differed considerably between the bonded case and the unbonded ones (figure 4). In the bonded case, the damaged zone expanded in all directions, whereas in the unbonded cases, damage propagated along the interface. This can be explained by the fact that the bonded stem generates relatively low loads along the taper, but high ones in the tip region. The unbonded tapers, however, generate high stress levels along the whole interface. The orientation of the cracks was also different for the bonded and unbonded cases. In the former case, damage was built up in the plane of symmetry, resulting in cracks perpendicular to these directions. In addition, a relatively large number of multiple cracks perpendicular to

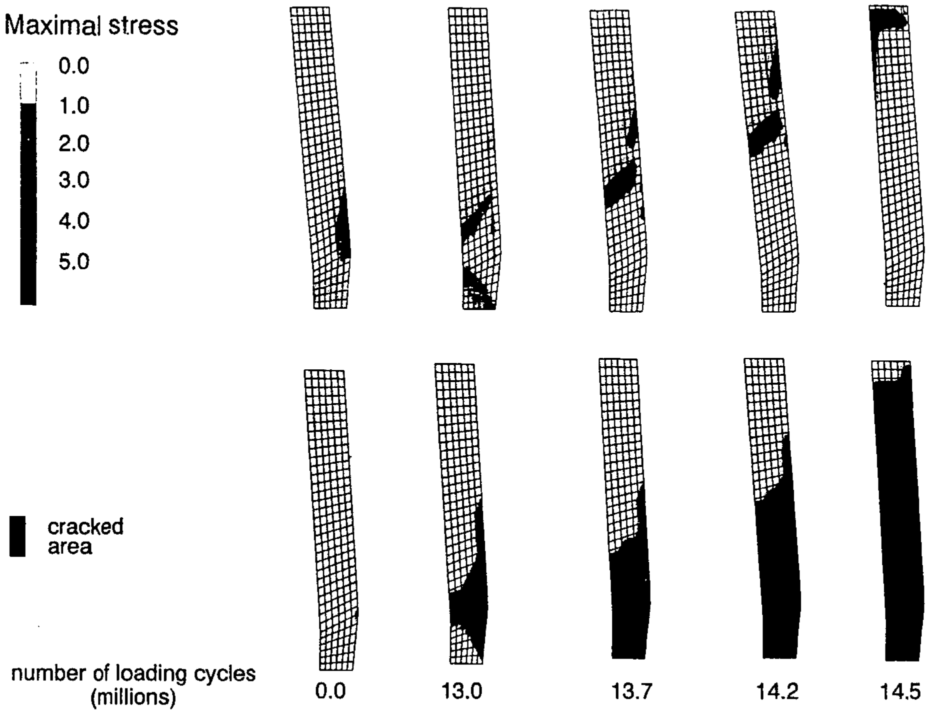

Fig. 4.a: Tensile stress (top) and damage (bottom) distribution (top) in the cement mantle around the bonded taper.

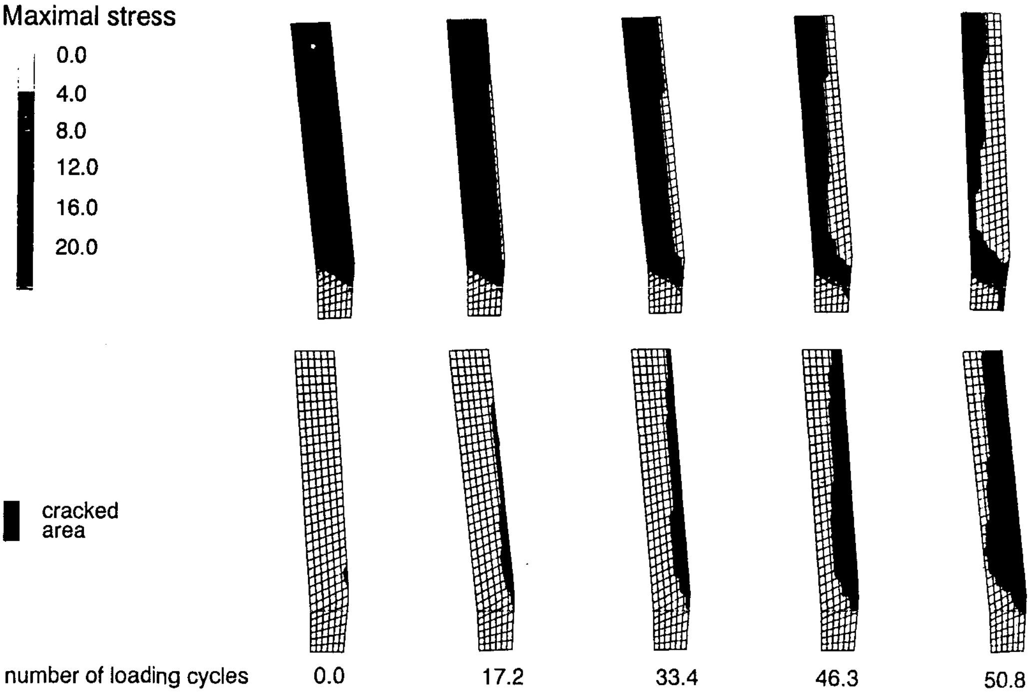

Fig. 4.b: Tensile stress (top) and damage (bottom) distribution (top) in the cement mantle around the unbonded taper (no friction was assumed).

each other developed at the end of the damage process. In the unbonded cases, cracks were generated perpendicular to the circumferential direction, and the number of multiple cracks was negligible. At locations where the material was assumed to be damaged, the changes in mechanical properties led to a significant reduction of stresses (figure 4). These damaged areas were usually surrounded by areas of higher loads which were the future damage sites.

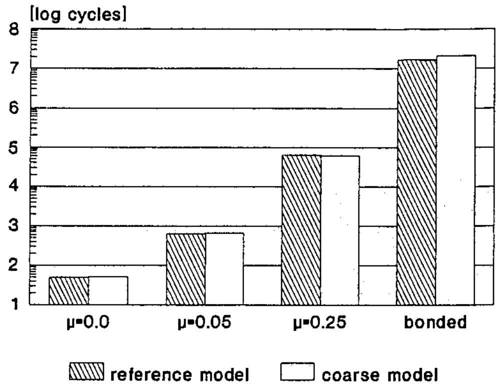

Fig. 5: The effects of interface characteristics and mesh density on the mechanical survival time of the structure.

The interface characteristics had a profound effect on the endurance of the structure (figure 5). The frictionless configuration survived for only 50 loading cycles, whereas the bonded one endured almost 20 million loading cycles. Higher friction at the interface resulted in lower stress levels and a lower damage rate of the cement mantle. The effects of mesh density on the damage process were very small (figure 5). The maximal stress levels and the total survival times in the two models were very similar. Obviously, as the number of integration points participating in the damage process decreased in the coarse mesh, the number of iterations in the damage simulation decreased as well. However, the reduction was not with a factor of 4 as one might have expected regarding the 4 times reduction of integration points, but on the order of 1.5 to 2.5 times. This is explained by the fact that, in general, the stress levels at neighboring integration points are more similar in the reference mesh as compared to the coarse one. As a result of this, the damage rate at these points is similar, and cracking of these points is switched on in the same iteration. This mechanism reduces the number of iterations required for the damage simulation.

5. DISCUSSION

In this study we tried to simulate the damage process occurring in bone cement. It appeared that the procedure was stable, even when non-linearities such as friction at the interface were assumed in the model. This method facilitates the study where damage is initiated, how it progresses, and what kind of effects various parameters have on the damage process. Taper/cement interface characteristics appeared to have a profound effect on the damage process and mechanical survival time of the cement mantle. Only a small amount of friction (μ=0.05) extended the survival time by a factor of about 12 relative to the frictionless case. The completely bonded case showed the longest survival time of almost 20 million loading cycles.

In order to determine whether these numbers are realistic, we performed an experiment where we used the same experimental set-up as simulated with the FE model. A highly polished taper was dynamically loaded with a sinusoidal load ranging from zero to 7 kN for a period of 1.7 million loading cycles at a frequency of 1 Hz. It appeared that the cement mantle was hardly damaged after this number of loading cycles. A few, radially oriented cracks were found in the cement by SEM investigation. By measuring the strains on the exterior of the cement mantle, it appeared that the highest dynamic strains were generated in the tip region and that the dynamic, cyclic strain amplitudes were considerably smaller as compared to the maximal strains levels. This was explained by the occurrence of friction at the interface which caused the taper to stuck in the cement mantle at unloading. Comparing the experimental findings with those of the simulation, it must be concluded that the FE simulation results in an underestimation of the survival time of the structure.

A simulation like this is based on many uncertainties and inaccuracies in the model and therefore a large number of reasons can be put forward to explain the differences between

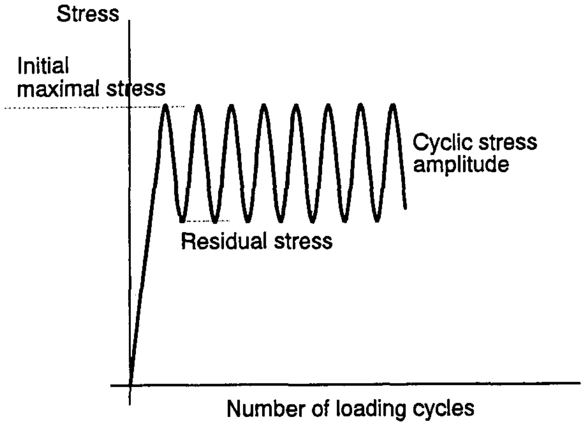

Fig. 6: Schematic representation of the stress levels in the cement mantle around an unbonded stem with friction at the interface.

experiment and simulation. One important factor is the visco-elastic behavior of bone cement. It has been shown that bone cement creeps under physiological conditions [13]. This will reduce the stress levels in the cement mantle, slow down the damage process, and expand the endurance of the cement mantle. A second important aspect is the stress amplitude used to determine the rate of damage. For this purpose, the stress level at maximal loading was used in the damage simulation. However, as indicated by the laboratory experiment, the dynamic stress amplitudes are considerably smaller than the maximal ones generated at loading. This is clarified in figure 6 where a schematic representation is shown of the hoop stresses occurring at the exterior of the cement mantle at loading and after unloading. It is clear that the dynamic stress amplitude is much smaller than the stress level at maximal loading. As a result of this, the damage rate may be significantly lower and the survival time longer. In the simulation, it was assumed that compressive stresses did not damage the cement material. Although, bone cement is much stronger under compression than under tensile loads, the material may fail under high compressive loads, resulting in higher damage rates than predicted in the model. The simulation is focussed on the damage accumulation in the cement mantle. Around an implant, the damaged material may provoke adverse reactions of the living tissue [15]. This means that not only the mechanical properties of the cement mantle are affected by the damage accumulation, but also those of the surrounding materials. This also applies for the interface characteristics that may be affected by the damaging process. The cement particles generated by the damage process may completely alter the friction characteristics at the stem/cement interface. Based on these assumptions and limitations, it must be emphasized that the results of the simulation should be used in a relative sense and not in an absolute one.

The laboratory experiments indicated highest stresses in the tip region, which was also found in the simulation, where damage was initiated in this region. The radially oriented cracks as found in the experiments were also reproduced in the simulation of the unbonded stems.

The method appeared to be rather insensitive for mesh density. The survival times found in the reference models were almost identical as compared to those found in the coarse ones. This is probably caused by the fact that the coarse mesh was sophisticated enough to produce the same stress intensities as found in the reference model. Therefore, it can be concluded that in this study, the coarse mesh was adequate. However, the effects of mesh density remains a topic of concern for other configurations and loading modes.

In general we conclude that this method is a promising tool to analyze the damage process of bone cement around implants. The results warrant further research to tune the method in order to obtain realistic survival times. At present, the method can be used only on a qualitative basis and to assess the character of the damage process. It predicts, pre-clinically, sites where cement damage is initiated, how this process progresses, and the effects of design parameters of implants on the mechanical life-time of the structure, on a comparative basis.

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