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THE APPLICATION OF CONTINUUM DAMAGE MECHANICS TO PRE-CLINICAL TESTING OF CEMENTED HIP PROSTHESES: THE EFFECTS OF CEMENT/STEM DEBONDING

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SUMMARY

Using the finite element method, combined with the theory of continuum damage mechanics, the damage process of the acrylic bone cement around a femoral hip prosthesis was simulated under variable stem/cement interface conditions. It was found that these conditions had a significant effect on the mechanical survival time of the system. The mechanical life time was about substantially longer for the prosthesis with the bonded interface. Damage was initiated at the prosthetic tip and in the proximal/medial region of the cement. The method used in this study is at a preliminary stage and is still under investigation. However, notwithstanding the limitations of this method, it can be a very useful pre-clinical testing tool. Locations where damage in the cement is initialized can be identified and the effect of various design parameters on the mechanical life time can be investigated.

1. INTRODUCTION

The average survival rates of total hip replacement (THR) are significantly affected by prosthetic design factors [1]. Traditionally, new designs will be tried in clinical patient series and survival rates will be established post-operatively. To avoid unnecessary clinical problems and costs, designs can also, to some extent, be tested pre-clinically, using advanced computer-simulation models, such as the finite element method (FEM) and scientific data on failure mechanisms. Traditionally, FE studies on bone/prosthesis systems were focused on calculating stresses and strains, and on how these quantities were influenced by prosthetic design parameters. However, these studies do not directly indicate their ultimate effects on the mechanical life time of the prosthesis.

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. [9] 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 mechanical life times.

To model the fatigue process of engineering structures under dynamic loading, Continuum Damage Mechanics (CDM) theories have been developed, and implemented in FE codes [5,10,14]. Although the theory itself is relatively simple, the application of this theory reveals many problems. Difficult problems concern the three-dimensional behaviour of damage accumulation, the dependency of the solutions on the FE model characteristics, and computer costs. The application of CDM to the cement material of an implanted hip prosthesis has some additional obstacles. One important unknown factor is the state of the cement/stem interface. A number of investigators have published articles concerning the strength of this interface [6,15]. The general finding was that the interface strength was relatively low relative to the stresses. Huiskes [7] showed that a variation of interface conditions can have a profound effect on the interface stresses, and on the stress and strain distributions occurring in the surrounding materials. This implies that these conditions might also have a significant effect on the mechanical survival times. Other problems concern the unknown fatigue damage parameters for bone cement (e.g. initial damage and the relation between damage and the mechanical properties). The purpose of this study was to investigate the effect of cement/stem interface conditions on the damage process of the cement mantle in a cemented bone/prosthesis system under dynamic loading.

2. MATERIAL AND METHODS

2.1 Finite element model

The simulations were carried out with a 3-D FE model symmetric relative to the mid-frontal plane, using 8-node isoparametric brick elements. The model comprised 1052 elements and 1600 nodal points. The materials used in the analyses were assumed to behave linear elastic, homogeneous and isotropic. Three different materials were assumed, with an elastic modulus of 17 GPa for bone, 2 GPa for bone cement, and 200 GPa for the prosthetic material. Poisson's ratio was taken as 0.3 for all materials. In the model, the prosthesis was completely surrounded by bone cement. The loading conditions acting on the system were taken from the literature [2,12]. The force on the prosthetic head was 2460 N, 23 degrees medial of the central axis and 6 degrees anterior to the mid-frontal plane. The total muscle force was 525 N. Angles were 25 degrees relative to the central axis, and 10 degrees posterior to the mid-frontal plane. These loading conditions represented the maximum load level of the dynamic load during normal walking [2,12].

The analyses were focused on the influence of the cement/stem interface conditions on the mechanical life time of a cemented hip prosthesis. Interface conditions were assumed to be perfectly bonded or frictionless loose. In the latter case special non-linear interface elements between both surfaces were added (MARC Analysis Corporation, Palo Alto CA).

2.2 Continuum damage mechanics

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 ($\bar{a}$) for stress transfer is less than a. Assuming a uniform distribution of cracks and cavities in all directions, the amount of damage can be characterized by a scalar D. This variable represents the reduction of effective area, and is defined as

$$D = \frac{a-\bar{a}}{a}. \tag{1}$$

When a structure is dynamically loaded, new cracks are initiated or existing cracks grow. This will lead to an accumulation of damage as the effective area ($\bar{a}$) to withstand the load decreases. This process continues until the effective area has reached a critical value and the element ruptures.

The amount of damage occurring in a material due to dynamic loading mainly depends on applied load, number of loading cycles, temperature and moisture content [8]. The applied load is determined by the shape of the load function, the frequency, and the load level (the amplitude). 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, which is called the "Palmgren-Miner" rule [13]. 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:

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

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

Using the elastic relations between stresses and strains, the amount of damage in an element can be coupled with the elastic properties. For a one-dimensional linear elastic structure [10]:

$$\begin{aligned} &E=E_0 && \textit{undamaged state,} \\ &E=(1-D)E_0 && \textit{damaged state,} \end{aligned} \tag{5}$$

E_0 being the initial Young's modulus, and E the effective Young's modulus. This formula describes the deterioration of the stiffness while the damage is accumulating. Analyses using this formula are called coupled analyses. Uncoupled analyses are performed to study the behaviour of brittle materials. These material hardly show any change in the mechanical properties prior to rupture. When the process of damage accumulation of these materials is simulated, degradation of the mechanical properties prior to complete damage may be neglected. In these analyses the elastic properties are not changed until the damage is complete (D=1.0):

$$\begin{aligned} &E=E_0 && \textit{if } D<1.0, \\ &E=0.0 && \textit{if } D=1.0. \end{aligned} \tag{6}$$

2.3 Iterative damage accumulation

To investigate the effects of a bonded versus an unbonded cement/stem interface on the mechanical life time, the loading conditions were applied to a FE model of a cemented hip prosthesis. Stresses and strains 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 1.

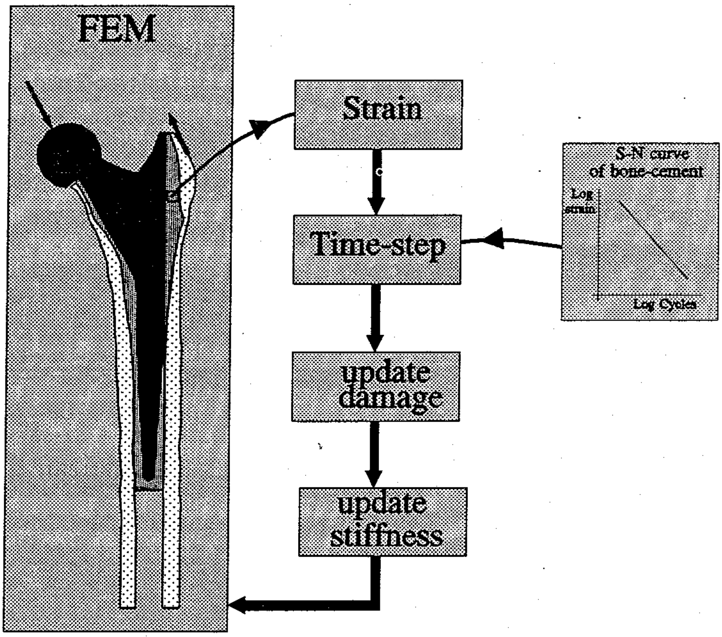

Fig. 1 Iteration scheme of the damage accumulation simulation.

After the strain tensor at the integration points was obtained, an equivalent strain using a "Modified von Mises" formula derived from static mechanical tests [16] was determined. As is shown in Figure 2 for the 2-dimensional case, the different behaviour of bone cement under tension and compression was accounted for. Subsequently, from these integration point values, the average equivalent strain for each element was calculated.

Carter et al. [3] presented *S-N* data from which the relation between strain level and number of cycles to failure in cement was estimated:

$$\log\epsilon=-0.19*\log N-1.57 \ , \qquad (7)$$

in which ϵ is the applied strain level, and N is the number of cycles to failure in the fatigue test. The fatigue experiments also revealed that the elastic properties of the bone cement were nearly constant for most of the loading history. For this reason an uncoupled damage analysis was performed using eq. (6).

Combining the strain values with (7), an estimate for the number of cycles to failure for each element could be made (N_ϵ). The damage was assumed to behave isotropically. Hence, the accumulated damage in each element could be represented by one damage parameter per element (D_ϵ).

In each iteration, the number of cycles to failure for each element for the current strain level in that iteration was calculated. The minimum of this value determined the time-step for the current iteration. Hence, in the next iteration, at least one element is wholly damaged (D_ϵ=1.0) and removed from the mesh. The other elements damaged only partly, which was accounted for in their value of D_ϵ.

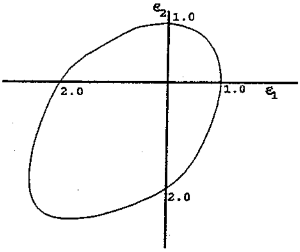

Fig. 2 Two-dimensional representation of a constant equivalent strain curve.

Obviously, when damaged elements were removed, the strain distribution for the remaining cement elements changed. This caused a multi-loading level fatigue process in these elements and equation (4) was used. The procedure continued until all cement elements were completely damaged. At that point the number of cycles to failure of the whole system was calculated.

3. RESULTS

The process of damage accumulation in the cement mantle can be divided in three stages (Figure 3). In the first stage, the damage growth was rather slow, and the overall stiffness of the cement mantle was hardly affected. When more elements became damaged, the mechanical integrity of the cement was reduced, which increased the damage rate (stage 2). In the final stage the cement mantle had lost its capacity to sustain any load and fractured completely.

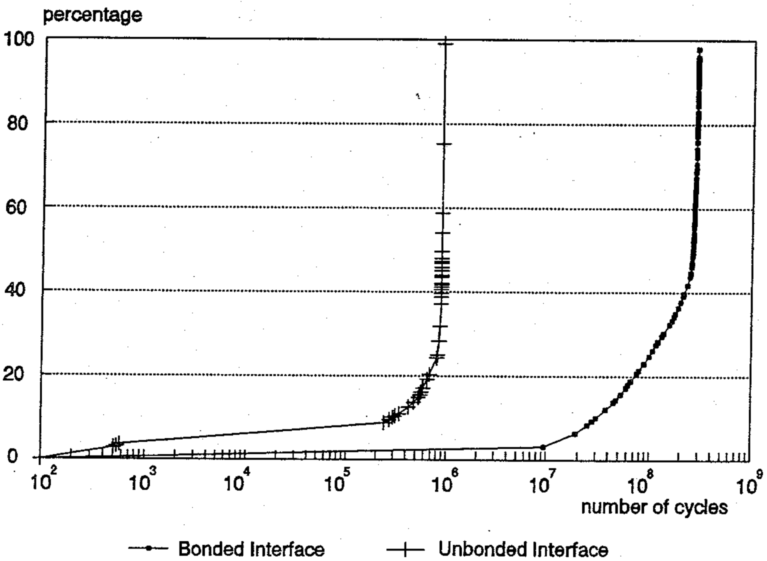

Fig. 3 Amount of damage accumulated in the cement mantle as a function of number of cycles.

Due to the different mechanism of load transfer [7], strain values in the cement mantle were significantly higher when an unbonded interface was assumed. The initial equivalent strain was about 2.5 times higher when an unbonded interface was simulated. Due to the double logarithmic scale of the *S-N* curve, this had a profound effect on the damage rate of the cement mantle. The predicted mechanical life time for a cemented prosthesis with a bonded cement/stem interface was about $2.7*10^8$ cycles. Simulating an unbonded interface, a mechanical life time of about 1 million cycles was found. The analyses also revealed the locations where damage of the cement mantle was initiated and how it progressed. For the bonded prosthesis, the damage-process initiated at the tip of the prosthesis and proximal-medially in the model (Figure 4). As time proceeded, damage developed particularly at the distal part of the cement mantle, until complete failure of the system occurred. In case of a loose interface, a more evenly distributed damage-field was obtained. It therefore often occurred that more elements were deactivated after one time-increment, resulting in less FE loading-increments. Here too, the damage initiated at the tip of the prosthesis and in the proximal-medial area of the cement mantle.

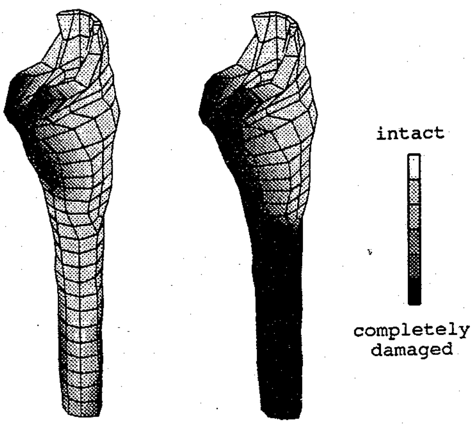

Fig. 4.a State of damage in the cement mantle after 176 and 267 million loading cycles assuming a bonded interface.

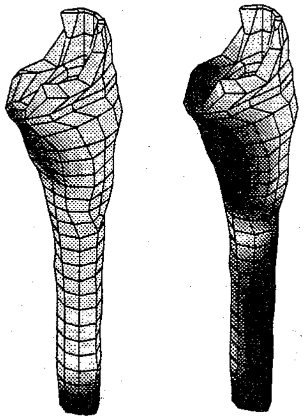

Fig. 4.b State of damage in the cement mantle after 546 and 874 thousand loading cycles assuming an unbonded interface.

4. DISCUSSION

In this paper an effort was made to analyze the effects of different cement/stem interface conditions on the damage process of bone cement in a hip replacement. It was found that these conditions have a profound effect on the survival time of the cement mantle. The predicted mechanical life time for a cemented prosthesis with a bonded cement/stem interface was about $2.7*10^8$ cycles, while a stem with an unbonded interface failed after about 1 million cycles. These numbers can be compared to daily activities assuming a number of loading cycles of about 1 million per year (about 4 kilometres walking each day). The bonded stem would function for about 270 years, the unbonded stem would fail one year post-operatively. The large differences in the survival times found in the two cases, already indicate that these results should only be interpreted on a relative basis due to the many uncertainties and inaccuracies of the damage model. Nevertheless, the differences in the results strongly suggest that debonding of the cement/stem interface may significantly reduce the endurance of a cemented Total Hip Arthroplasty.

In addition, the results are also affected by the characteristics of particular stem designs. With this particular design, damage initialized at the tip of the prosthesis and in the proximal/medial region for both the bonded and unbonded stems. This is very valuable information and can be integrated within the design process of cemented hip prostheses.

The application of the theory of damage to determine the mechanical life times of cemented hip prostheses involves a number of uncertainties and many problems remain to be solved. One important problem is the mesh-dependency of the strains calculated in the elements. The ultimate purpose of these simulations is to analyze different prosthetic designs and the effects of various design parameters with one another. This will result in different FE meshes. A small deviation of strain-values has a very significant effect on the survival time calculated. For this reason the calculations should be independent from the FE mesh. Many investigators are working on this problem [11], and many approaches have been studied, but there does not yet seem to be an adequate solution.

Another problem is the relationship between the state of damage, the number of cycles and the elastic properties of the bone cement. In this study the relation between the state of damage and the number of cycles is assumed to be linear, and the relation between the number of cycles and the elastic properties was uncoupled. These assumptions are probably not realistic and therefore should be adjusted. However, these relations are not clear yet, and should be determined in the future.

Deactivating elements from the cement-element set after complete damage of the element has occurred does not seem to be realistic either. It would be more elegant to incorporate the direction of the principal strains and use a tensorial description of the damage effect. Complete damage would then result in low stiffness in one direction but a retention of initial stiffness in another direction.

Finally, we should keep in mind that we are dealing with a lifeless degrading material in a living tissue. It is very well possible that after a small part of the cement has been damaged, the living tissue will respond and that from that moment on the system becomes unstable and the prosthesis will fail much quicker than calculated.

It is clear that many problems have to be solved and many parameters have to be established as yet. However, looking at retrieved specimens [9], it becomes obvious that cement fatigue is a very important mode of failure in cemented hip replacement and requires attention.

Knowing the limitations and the assumptions of this method, the application of the theory of damage mechanics combined with finite element modelling of cemented bone/prosthesis systems can be a useful tool in the design stage. Locations where damage in the cement is initialized can be identified and the effect of various design parameters on the mechanical life time can be investigated, before prototypes are made, and patients are put at risk.

REFERENCES

1. Ahnfelt L, Herberts P, Malchau H, Anderson G B J. Prognosis of total hip replacement. Acto Orthop. Scand. Suppl. 238, 1990.
2. Bergmann G, Graichen F and Rohlmann A. Instrumentation of a Hip Joint Prosthesis. from Implantable Telementry in Orthopaedics. Ed. Bergmann, G. Berlin, 1990.
3. Carter D R, Gates E I, Harris W H. Strain-controlled fatigue of acrylic bone cement. J of Biomed. Mat. Res. Vol 16, 647-657, 1982.
4. Chaboche J L. Continuum damage mechanics: Part I-General concepts. J of Appl. Mech. Vol 55, 59-64, 1988.
5. Chaboche J L. Continuum damage mechanics: Part II-Damage growth, crack initiation, and crack growth. J of Appl. Mech. Vol 55, 65-72, 1988.
6. Convery F R, Malcom L L. Prosthetic fixation with controlled pressurized polymerization of polymethylmethacrylate. Trans. ORS, febr. 5-7, Atlanta, 1980.
7. Huiskes R. The various stress patterns of press-fit, ingrown , and cement femoral stems. Clin. Orthop. and Rel. Res. No 261, 27-38, 1990.

8. Hwang W, Han K S. Cumulative damage models and multi-stress fatigue life prediction. J of Composite Mat. Vol 20, 125-153, 1986.
9. Jasty M, Maloney W, Bragdon C R, O'Connor D, Haire T, Harris W. The initiation of failure in cemented femoral components of hip arthorplaties. J.Bone and Jt.Surg, Vol 73B, 551-558, 1991.
10. Lemaitre J. How to use damage mechanics. Nuclear Eng. and Design Vol 80, 233-245, 1984.
11. Mazars J, Bazant A P. Cracking and damage; strain localization and size effect. New York, USA, 1989.
12. McLeish R D, Charnley J. Abduction forces in the one-legged stance. J.Biomech. Vol 3, 191-209, 1970.
13. Miner M A. Cumulative damage in fatigue. J of Appl. Mech. 159-164, 1945.
14. Paas M H J W, Schreurs P J G, Janssen J D. The application of continuum damage mechanics to fatigue failure mechanisms. From: Integration of theory and applications in applied mechanics. Ed. Dijksman J F, Dordrecht, 1990.
15. Raab S, Ahmed A M, Provan J W. Thin film PMMA precoating for improved implant bonecement fixation. J.Biomed.Mat.Res, Vol 16,679-704, 1982.
16. Rooijakers W M, Spierings P T J. Proefopstelling en bepaling van de schuifspanning van botcement. Internal report, Nijmegen, 1988.