MESH CONSIDERATIONS FOR ADAPTIVE FINITE ELEMENT ANALYSES OF CEMENT FAILURE IN TOTAL HIP REPLACEMENT

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INTRODUCTION

Failure of the cement mantle has been identified as a possible mode of failure of the implanted femur in total hip replacement (THR) [1]. Finite element (FE) analyses have been used to investigate the stresses experienced in the cement mantle [2] and to predict the life of the cement mantle when taking different factors into account [3]. The number of elements used, or mesh density, is an important consideration when creating a FE model. A model with an insufficient mesh density will not be able to fully capture the stress state in the area of interest, but increasing the mesh density dramatically increases the computational cost of the analysis.

The aim of this study is to determine the mesh density necessary to model creep and damage accumulation in the cement mantle of a cemented implanted femur. We compare the initial stress state and damage accumulation rate for different mesh densities and different element types.

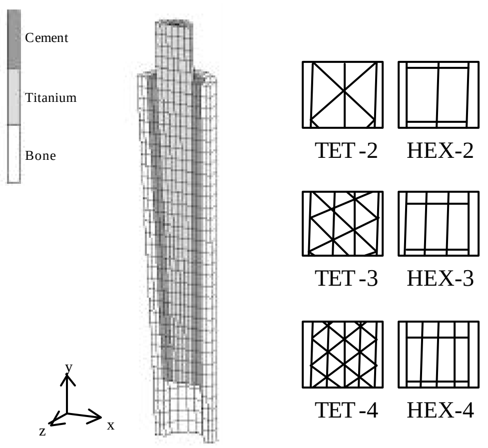

Figure 1. Finite element model (HEX -2) and different meshes used for the cement mantle

METHODS

The simplified implanted femur was generated and meshed in I-DEAS™ (figure 1). All the nodes at the distal end of the cortical bone were constrained in every direction. The nodes in the x - y plane were constrained in the z - direction, allowing displacements only in the x and y directions. All material interfaces were assumed perfectly bonded. The stem, bone cement and cortical bone were assigned Young's moduli of 110GPa, 2.8GPa and 15.5GPa respectively. The stem and cement were assigned a Poisson's ratio of 0.30 and the cortical bone was assigned a Poisson's ratio of 0.28. A load of 2100N at an angle of 16° to the y-axis in the x - y plane was applied to the proximal tip of the femoral stem [4]. Using the same geometry, material properties and loading conditions, six models in total were generated, as described in table 1.

Analysis Name	Element type (figure 1)	Number of elements through thickness of cement mantle (figure 1)
HEX-2	Hexahedral	2
HEX-3	Hexahedral	3
HEX-4	Hexahedral	4
TET-2	Tetrahedral	2
TET-3	Tetrahedral	3
TET-4	Tetrahedral	4

Table 1. Different FE analyses performed

Using the FE solver MARC™, the initial stress state within the cement on the lateral side was compared for each model. After comparing the initial stresses, the load described above was applied cyclically, simulating normal gait. Calculation of creep and damage at every loading cycle would have been both inefficient and unnecessary, so an iteration procedure was developed, based on a similar technique created by Verdonschot [3].

The iteration procedure consists of a number of iterations, each being capable of simulating a number of loading cycles. At the beginning of each iteration, the FE model is loaded, and the stresses calculated. The number of cycles to failure (N_f) for the highest stressed element is calculated using data from S-N curves. The number of cycles to be simulated in the iteration is essentially a predefined percentage of N_f. Once the number of cycles to be simulated within the iteration is determined, creep and damage for all elements can be calculated. If damage reaches a predetermined value the element is deactivated and the load transferred to the surrounding elements. As the creep data and S-N curves come from uniaxial tests; the equivalent Von Mises stress must be used to calculate creep and N_f.

The damage (**D**) of an element is calculated using the following linear Palmgren-Miner law:

$$D = \frac{n}{N_f} \quad (1)$$

where n is the number of cycles completed. When **D** is gt. 1 for any element, the element has failed and is deactivated. **D** is a scalar value, meaning that a deactivated element cannot transfer load in any direction, even though failure only occurs in one direction. The iteration process is repeated until bulk failure of the cement mantle.

RESULTS

The initial stress state through the length of the cement mantle on the lateral side is shown in figure 2. The values plotted here are nodal values, which are extrapolated from the integration point values where MARC™ calculates the stress. Therefore there may be a slight inaccuracy where the node is a distance from the integration point. This is found to occur commonly at outer surfaces, i.e. at either end of the cement layer. Figure 2 illustrates the rapid convergence of results for the static stress state.

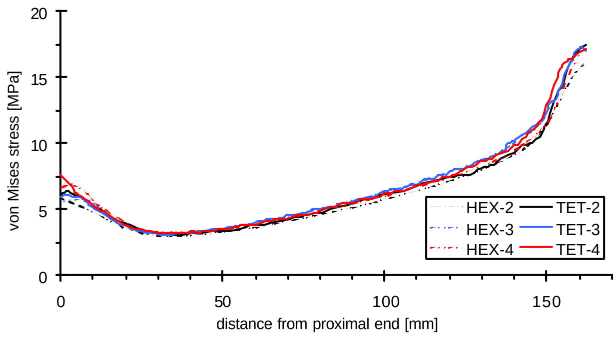

Figure 2. Initial stress state in lateral cement mantle

To monitor the damage accumulation in the cement mantle, the percentage of failure of the cement mantle is plotted against the number of cycles (figure 3).

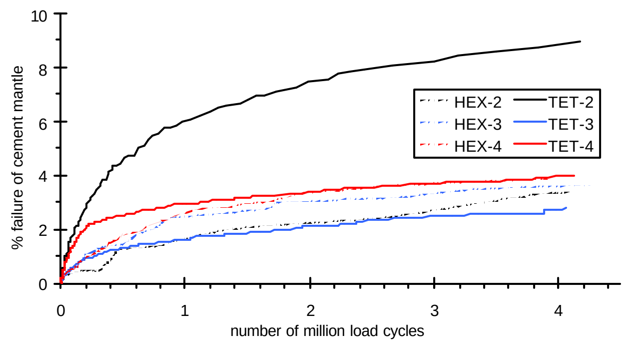

Figure 3. Element failure in cement mantle

The failure of elements can be seen over 4 million cycles. The TET-2 analysis gives a particularly high failure of elements, 9% after 4 million cycles. All other analyses report a failure of between around 3 and 4% for the same number of cycles.

DISCUSSION

The initial stress state is comparable for all analyses. Taking only the initial stress state into account, one could argue that all the analyses performed produce similar results and that the mesh that is least computationally expensive is adequate for an adaptive analysis that simulates creep and damage. This does not seem to be the case, as is demonstrated in figure 2. Even though the TET-2 analysis has a similar initial stress state to the others, the rate of damage accumulation is notably higher.

The HEX-4 and TET-4 analyses produce an almost identical damage accumulation rate from 2 million cycles; we can assume this is a reliable result. The HEX-2, HEX-3 and TET-3 damage accumulation rates all fall within a close range, but follow the same trend as HEX-4 or TET-4 and are certainly superior to the results from the TET-2 analysis. Even though the results for HEX-2, HEX-3 and TET-3 differ only by little more than 1% it must be noted that this is 1% in 3%, i.e. they differ by 30% at 4 million cycles.

The simplified implanted femur geometry used here is a gross simplification to the geometry of a real implanted femur, and given that for complex geometries a tetrahedral mesh is far easier to create than a hexahedral mesh, a tetrahedral mesh is preferred. This point becomes more relevant when it is considered that multiple implant geometries would ideally be meshed and compared. From this point of view the TET-4 mesh is the most advantageous, but when the computational cost of the analysis is taken into account, the TET-3 mesh must be considered. It follows the same trend as the TET-4 mesh and as long as it is used as a comparative tool the fact that it underestimates damage shouldn't pose a problem.

CONCLUSION

The initial stress is not a definitive guide to the performance of an FE mesh and must therefore be used with caution. Although the hexahedral mesh seems to perform better than the tetrahedral one, it is more difficult to use with anatomical models. A thickness of 4 elements through the cement mantle provides the most reliable results, but a tetrahedral mesh with three elements through the cement mantle offers the best compromise when computational cost is taken into account.

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