CRACK BEHAVIOUR IN A 3D CONTACT MODELLING OF A KNEE JOINT REPLACEMENT UNDER RUNNING CONDITIONS

S. Plumet*, M.-C. Dubourg*

Explanted prostheses show several kinds of fatigue failure such as pitting and delamination in the tibial component made of Ultra High Molecular Weight Polyethylene (UHMWPE). The present model aims to simulate crack behaviour, and more particularly delamination in tibial component under running conditions. It is based on superposition of solutions corresponding to homogeneous body response to the load and to crack response. They are respectively obtained by a 3D model for total knee joint replacement (TKR) including two body contact solution and a fatigue crack model. Stress Intensity Factors (SIFs) in mode I (KI) and II (KII) are then computed at crack tips during a typical walk cycle.

INTRODUCTION

Current total knee joint replacements consist of a plastic tibial insert made of UHMWPE and a metallic femoral component. Wear and failure of UHMWPE and the generation of wear debris can contribute to loosening and failure of knee joints. Improved understanding of these mechanisms is required to extend clinical lifetimes of prostheses. A theoretical investigation is described to simulate knee kinematics and to analyse crack behaviour in tibial component. 3D linear elastic knee prosthesis model including contact problem solution and stress distribution determination within tibial part is presented. It is then combined with a 2D fatigue crack model. The former leads to the determination of the state of stress in the component in the absence of cracks called the 'continuous stress field'. The latter using the superposition principle gives the crack stress field. The total stress field satisfies the contact boundary conditions along crack line. In this paper SIFs are calculated and analysed during typical walk cycle.

* Laboratoire de Mécanique des Contacts, UMR C-5514, INSA, Bat 113,
20 Av. EINSTEIN, 69 621 Villeurbanne Cedex, France

THEORETICAL MODEL

3D total knee joint model

3D model was developed to predict contact area, stick and slip zone repartitions, normal and tangential contact pressure distributions and stress fields in total knee joint replacement where thickness of UHMWPE component is similar or less than contact half width. One femoral condyle is represented by an ellipsoid. Tibial insert is composed of a layer of UHMWPE and a metallic substrate (figure 1).

Contact model is based on linear elasticity theory, integral transform techniques and unilateral contact with friction. Relations between contact stresses and surface displacements are obtained in terms of influence coefficients, determined at arbitrary points in Fourier domain to reduce the dimensionality of the problem and computer time. Fourier inverse transform is applied to obtain influence coefficients in the spatial domain. Contact problem is then solved under normal and tangential (rolling/sliding) contact conditions using classical methods (Hertz and Kalker (3)). Continuous stress distributions are thus determined within tibial insert.

This model is able to simulate knee kinematics of any TKR geometry (finite thickness, contact conditions, boundary conditions at the bottom of the layer). Stress distributions within tibial insert are obtained. Satisfactory comparisons with classical models concerning contact solution and with Finite Element codes for stress distributions were performed. Differences do not exceed 5%.

Fatigue crack model

The next step is now to determine the crack response. It corresponds to displacement discontinuities along crack faces, opening and slip, generating "crack" stresses. Stress and displacement expressions are available along the whole crack whatever the number and distributions of these slip, stick and open zones. Continuous distributions of dislocations 'bx' and 'by' model these different zones. SIFs are controlled by total stress field. The latter is obtained from the displacement discontinuity determination. Suitable repartition of dislocation distributions is automatically the result of unilateral contact analysis with friction between crack faces (1). This analysis is conducted by considering the total stress field.

Any crack geometry (straight, inclined or not, kinked, embedded or not), various type of loading can be considered. Satisfactory comparisons with simple cases in the literature and with experimental results were performed.

Model combination

Stress distribution within tibial insert once calculated with 3D TKR model are then used as data for studying delamination in tibial component. A cross section containing cracks is therefore defined.

RESULTS AND DISCUSSION

Femoral part is modelled as an ellipsoid whose radii (Rx, Ry) are variable, depending on knee flexion. Tibial insert is modelled as one layer where no displacements are applied at its bottom. Its thickness is equal to 6 mm. UHMWPE Young's modulus (E) and Poisson's ratio (υ) are respectively equal to 800 MPa and 0.3. Femoral part is considered as rigid ($E \approx 210$ GPa, $\upsilon \approx 0.3$).

Seireg and Arvikar walk cycle (Figure 2) was chosen for its severe loading conditions. This cycle corresponds to minimal and maximal normal forces respectively equal to 120 and 3600 N. They lead to minima and maxima contact area lengths along rolling direction equal to 3.29 and 12.69 mm. Knee kinematics is composed of two main parts:

- pure rolling contact conditions for knee flexion angle ranges from 0 to 12°,
- rolling/sliding contact conditions hold next 12° of knee flexion with increasing of sliding conditions.

Rotation and sliding of the femoral component lead to maximal translation (10 mm) of this component relative to tibial component.

For each walk cycle percentage (WCP) (Figure 2), normal load, knee flexion angle and contact conditions are given to determine stress distributions within tibial plateau. Then a cross-section is defined. It represents a plane at the middle of contact area parallel to rolling direction (Figure 3) containing crack parallel to contact surface. Different parameters define this crack: its depth (h), length (d) and its position (p) relative to contact pressure distribution (Figure 3). SIFs at crack tips (a and b in fig 3) are determined every 2 or 3 WCP to analyse crack behaviour during walk cycle. Crack position (p) is defined relative to first step load location. Relative movement between femoral and tibial parts is taken into account by a translation of contact pressure distribution over cracked plane.

During a walk cycle, crack is submitted to variable normal and tangential stress distributions. It leads to SIF variations at crack tips. Several key parameters are identified:

- For one crack depth (h=500µm) and crack relative position (p=8mm) SIFs increase with crack length (Figure 4). For example an increase from 1 to 4 mm of crack length leads to an increase of 71 % of KIb (mode I SIF at crack tip b) at 18 WCP.

- For the most severe crack length (d=4 mm) and one crack relative position (p=5mm) SIF variations have been studied depending on crack depth location (Figure 5). Crack is more sensitive near the contact surface than for greatest depth (SIF increasing of 83 % at 40 WCP).
- For the most severe crack length and depth respectively equal to 4 mm and 500 μm, crack behaviour depends on crack relative position (p) with respect to the load translation (Figure 6). Two configurations hold: if p belongs to 0 and 5 mm (Case I) maxima SIFs are obtained for 40-60 WCP range. In case II (p range from 6 to 10 mm), maxima SIFs appear from 18-24 WCP range.

This simple parametric study shows clearly that embedded cracks parallel to the surface and situated at a small depth under the surface, with length exceeding 3 mm are the most dangerous during a walk cycle whatever p value. But no considerations concerning crack propagation can be formulated. Classical Paris 's law is not able to simulate crack behaviour in knee prosthesis where non proportional conditions and mixed mode exist. Therefore experimental data are needed to define crack criterion to simulate crack propagation in knee prosthesis.

CONCLUSION

A cracked total knee joint model has been presented to analyse crack behaviour in knee prosthesis under real running conditions (knee prosthesis geometry, contact conditions, crack locations, crack length, ...). This model is based on an original approach combining a 3D total knee joint and a 2D fatigue crack models. Key parameters influencing SIF increase have been identified during walk cycle.

REFERENCES

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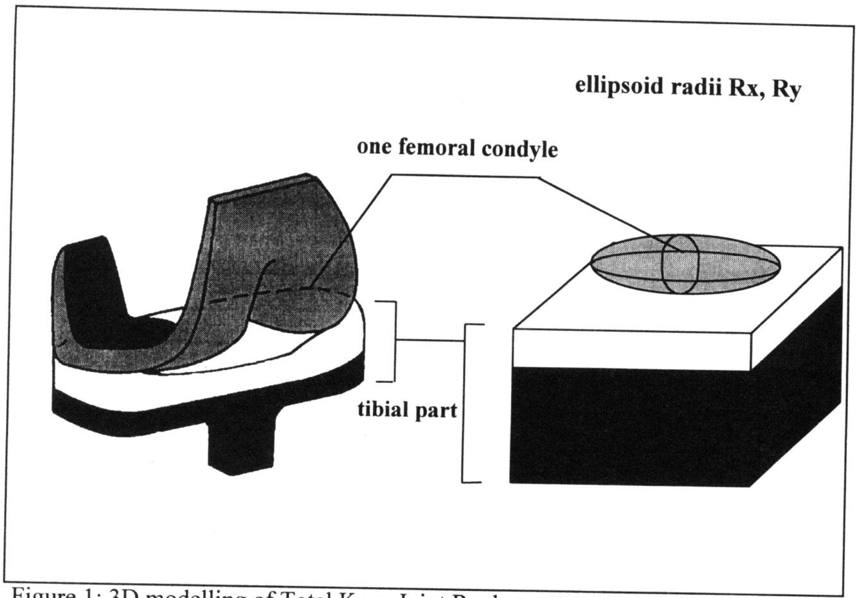

Figure 1: 3D modelling of Total Knee Joint Replacement

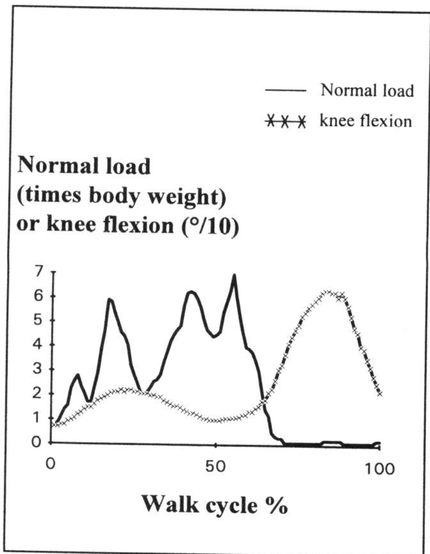

Figure 2: Seireg and Arvikar walk cycle

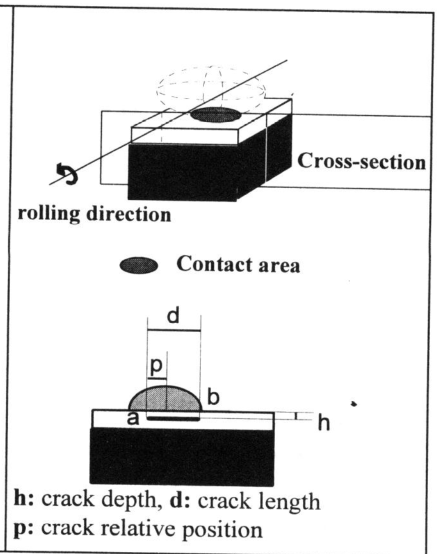

Figure 3: Cross section definition in 3D model

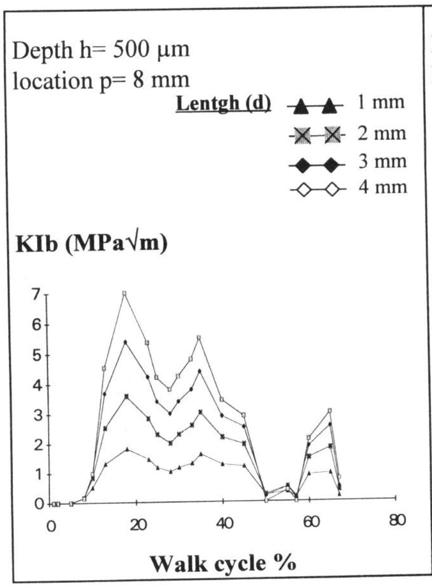

Figure 4 Crack length influence

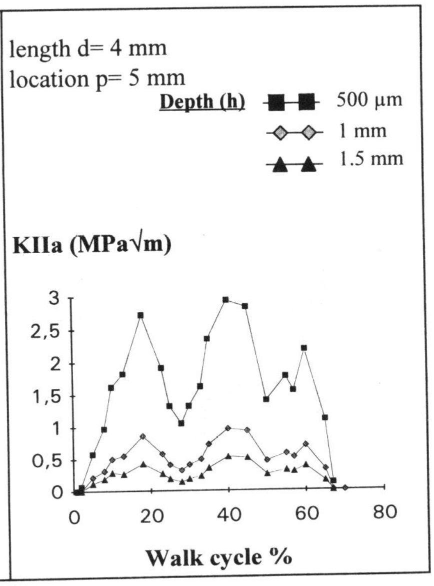

Figure 5: Crack depth influence

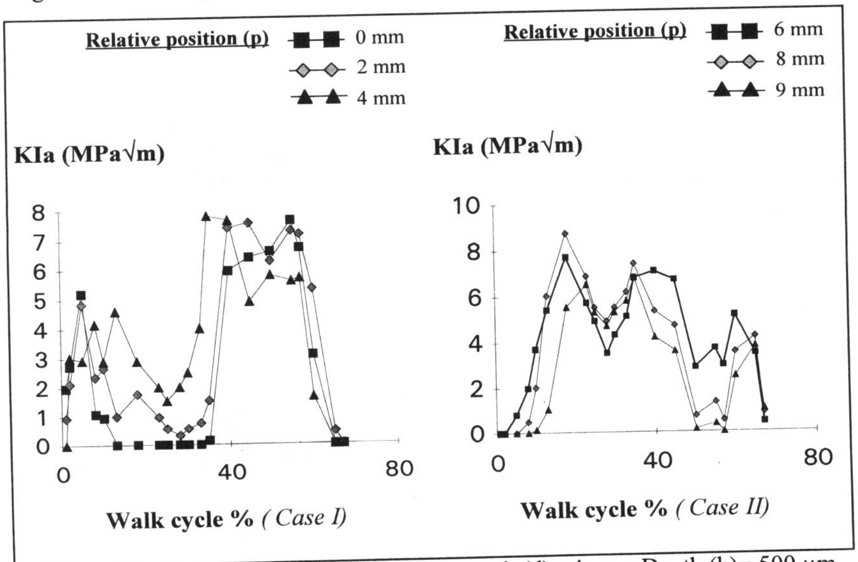

Figure 6 Crack relative position influence Length (d)= 4 mm, Depth (h)= 500 µm