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A 3D Fatigue Crack Growth Simulation Based on Free Front Shape Development that Takes Account of Overloading Effects

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ABSTRACT: Recent investigations have shown a major interest in the prediction of life-time for structures using a 3D crack growth analysis. These applications are very important in aeronautical field where one has to predict the crack growth behaviour in aicraft engine components during flights. These flights are generally represented by cycles where overloadings have an important influence on the component behaviour. The purpose of this paper is to point out the overloading effects on cracks propagation and to develop numerical methods able to simulate propagations in these conditions. A 3D Finite Element crack growth model using two different propagation laws with thresholds is presented. The case of crack growth in presence of residual stresses induced by shot-peening is also described.

Notation

σ_{max}	maximum stress in a cycle
σ_{min}	minimum stress in a cycle
σ_{op}	crack opening stress
K	Stress Intensity Factor
s	curvlinear abscissa along the crack front
$\Delta a(s)$	crack advance increment along the crack front
ΔN	cycle increment
ΔK_{eff}	effective SIF amplitude
$\frac{da}{dN}$	crack propagation rate

Introduction

The safety restrictions in aeronautical industry have led to a great development of Damage Tolerance notions the last twenty years. These notions consist currently in considering the presence of a defect in a structure and to check that the growth of this defect can not have disastrous effects during flights. In this case an inspection program is applied to track the crack growth and to avoid critical crack sizes. The Damage Tolerance concept is applied to a large number of jet engine components, most of them being part of the rotor. The applied stress is not a simple repeated fatigue loading but a pseudo stochastic loading depending of the flight conditions. Many studies have been done on the 3D fatigue crack growth using most often the classical PARIS equation (1). This paper proposes a 3D Finite Element crack growth model based on free front shape evolution that takes account of different effects :

- compressive shot-peening residual stresses
- overloads and spectral loading conditions

In order to take numerically shot-peening into account one has proposed a simple process to introduce experimental plastic strain due to shot-peening. The problem is actually to obtain the evolution of residual stresses field under the subsequent loading applied to the structure. For this purpose CHABOCHE & JUNG (2) have suggested a model based on multi-kinematic hardening rule that efficiently described residual stresses relaxation during cyclic loading. This relaxed residual stress field is then taken into account in the 3D Crack growth Analysis through the linear elastic Fracture Mechanics assumptions. Concerning the last point, we have compared two overloading crack propagation models - ONERA model (3) and PREFFAS model (4) - whose notions of thresholds are different. For the first one the threshold includes all the history of plasticity since the beginning of the loading. The other one is based on the notion of opening Stress Intensity Factor (SIF) developed by ELBER.

The 3D Crack Growth Model

In 1981, LABOURDETTE et al (5) have studied more precisely the behaviour of crack growth and have suggested a technique based on the thermodynamic theory developed by SON (6) to describe efficiently the 3D crack propagation. This theory allows us to integrate seperately the propagation law at each node of the crack front which can have consequently a free evolution during a part of the subsequent cyclic growth. This integration is done for each node defining the crack front with respect to its normal. Furthermore the method allows us to integrate the following general propagation law :

$$\frac{da(s)}{dN} = C\left(\Delta K_{eff}(s)\right)^{m} \qquad (1)$$

where s denotes the position of a point on the crack front. Besides the integration is made without reference to the F.E.M. calculation that gives energy release rate results. Moreover the number of cycles ΔN corresponding to the crack growth increment Δa is adjusted to a right number of F.E.M. calculations in order to save some CPU time. For each calculated crack advance a simple mapping is used to remesh the structure during the crack growth. With these assumptions we are able to build a 3D Finite Element crack growth model represented by the following general scheme :

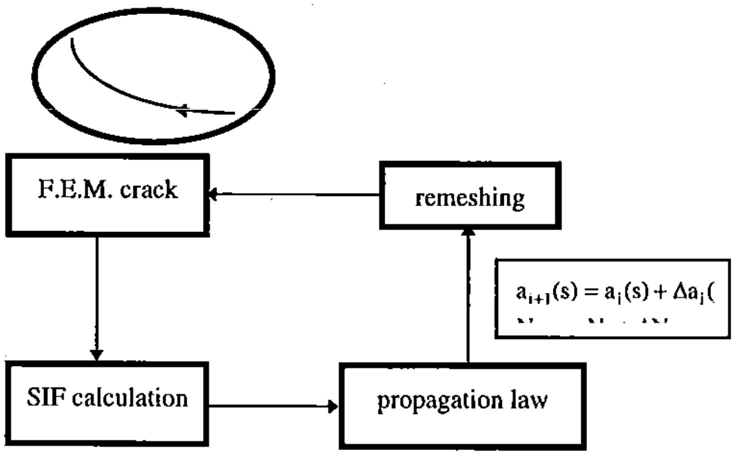

Fig. 1. The 3D FEM Crack Growth model scheme.

Effects of Shot-Peening Residual Stresses

In order to prevent crack initiation and propagation, a surface teatment - shot-peening - is used in aeronautical motor production aeras. It consists in projecting some shots on the external surface. The impact caused by shots generates hardening an compressive residual stresses that contribute to increase the life-time of aircraft engine components. Under cyclic loading of the structure we may expect a residual stress relaxation due to cyclic plastic straining. Then the first problem for life prediction of structures after shot-peening is to predict correctly the residual stress profile obtained after cyclic loading. Methods for the residual stresses of shot-peening and their relaxation have been developed previously (7). They are using the simplified method due to ZARKA (8) which couples several elastic analysis corresponding to several external loadings, with a stress decomposition (into elastic part and residual part) and a back-stress decomposition. Such a method allows quite an easy and inexpensive treatment and qualitatively correct results. However using mainly the linear kinematic hardening rule, or a multilinear model, the ratchetting properties or cyclic relaxation properties of the constitutive model are certainly underevaluated, leading to the risk to overevaluate the residual stresses after cyclic service loads. That's the reason why CHABOCHE & JUNG (2) have proposed an other approach based on the following three steps method :

- use measured residual stresses due to shot-peening or use calculated values by simplified techniques.
- determine initial values for the plastic strain field and the kinematic hardening state.
- perform the cyclic inelastic analysis of the near surface part submitted to service loads and deduce the stabilized residual stresses.

These points are more precisely described in (2). The proposed model used actually a multi-kinematic hardening rule with thresholds, already developed by CHABOCHE et al, in order to depict correctly the stabilized residual stresses. Such a method allows us to introduce the residual stress profile obtained in the Elastic Fracture Mechanics analysis. In this way JUNG & OUSSET (9) have compared two energetic methods - G-θ method (10) and Virtual Crack Extension (VCE) method (11) - in different cases of shot-peening. The basics of these methods consists in derivating the elastic potential energy P during a « virtual » crack growth. In G-θ method, this derivation is analytic whereas it is a numerically approximated in the other method. The residual stresses are actually introduced as an exterior loading in addition to the loading applied to the structure. In this case, numerical results have pointed out the compressive effect of the shot-peening residual stresses near the free surface on the numerical local energy release rate values. By this way these two methods were used to compute the energy release rate during the crack evolution. Figure 2 shows the evolution of an initially semi-circular surface crack in presence of shot-peening F15A with a Paris law. One notices the effect of compressive residual stresses on the form of the crack-front near the free surface. The predicted fronts are evaluated for number of cycles increments of 200 cycles (periodic loading). Figure 3 shows also the effect of shot-peening on the crack propagation rate in comparison with experimental data. The values were normalised for confidential reasons. One notices a good agreement between numerical results and experimental ones.

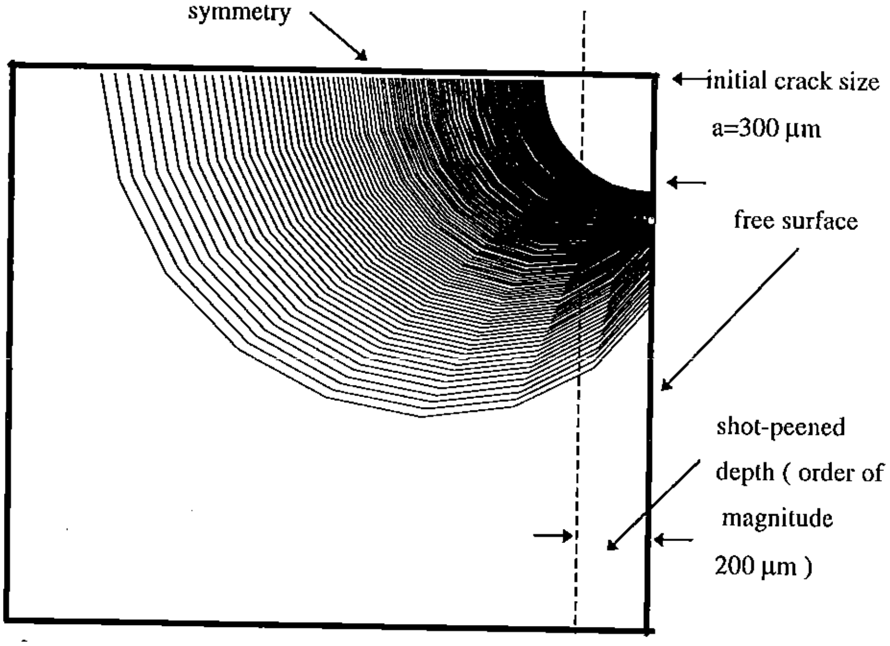

Fig. 2. Semi-circular surface crack evolution in presence of shot-peening F15A

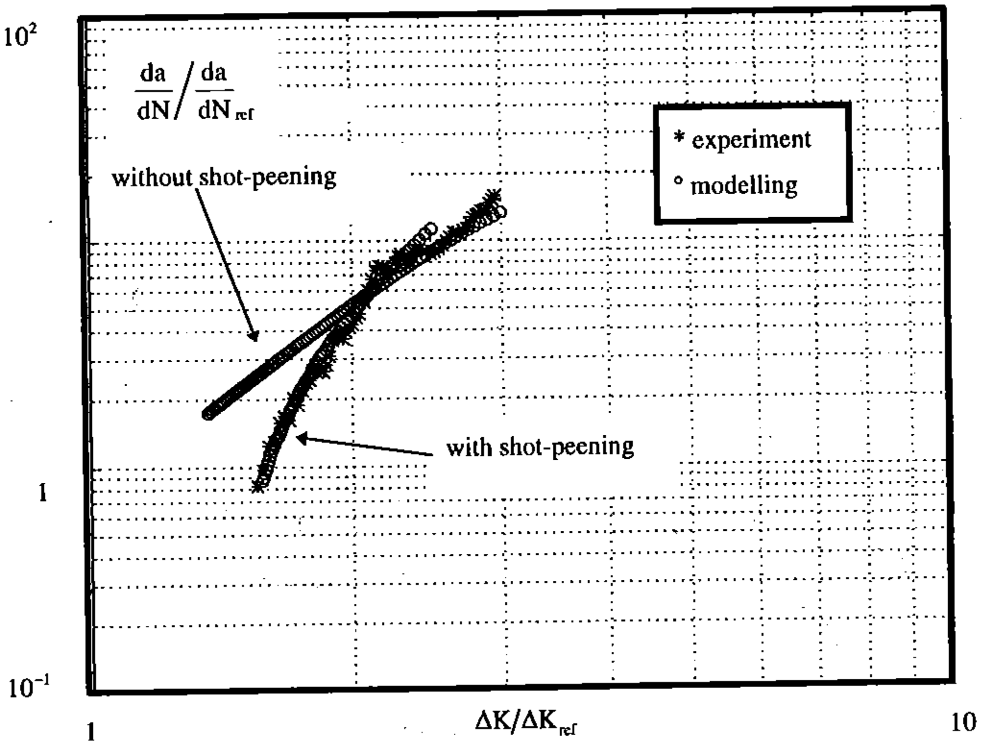

Fig.3. Effects of shot-peening on the crack propagation rate. Comparison with experimental data.

Overloading Effects

Two overloading crack propagation laws were implemented in the proposed 3D FEM fatigue crack growth model : ONERA model (3) and PREFFAS model (4). Both used the ELBER concept of opening SIF K_{OP}, which allows us to rewrite equation (1) as

$$\frac{da(s)}{dN} = C(\Delta K_{eff}(s))^m = C(K_{max}(s) - K_{OP}(s))^m \qquad (2)$$

In ONERA model, K_{OP} is replaced by the loading dependent threshold SIF K_S. In this model, two basic cases were particularly studied : the single overload and the Constant

Amplitude (CA) loading, the latter being considered as the upper limit of the multiple overload effect in the sense of the loading history effect. For a given material, these notions can be summarized using two empirical functions f1(R) and f2(R) expressing the crack arrest conditions after applying respectively one overload and a CA loading as a function of the load ratio R. Then the mechanical history due to any Variable Amplitude (VA) loading is expressed at a given cycle by the following three variables :

- K_S threshold SIF
- K_{Meq} maximum equivalent SIF
- K_{meq} minimum equivalent SIF

K_{Meq} and K_{meq} are related to overload and underload effects of the load history. K_s is actually interpolated between the two functions f1 et f2 described above through a parameter α. Then K_s is given by the following equation :

$$K_S = K_{Meq}\left[\alpha f1\left(R_{eq}\right) + (1-\alpha) f2\left(R_{eq}\right)\right]$$
$$R_{eq} = \frac{K_{meq}}{K_{Meq}} \qquad (3)$$

α stands between two particular values : α = 0 for CA loading case and α = 1 for single overload case. The value of α changes actually from cycle to cycle during a VA loading but, unfortunately, it is very difficult to give a simple evolution law of this parameter. That's the reason why α is considered as constant during a given repetitive sequence representative of the aeronautical spectrum. The role of K_{Meq} is precisely to memorise overload effects. Consequently, this variable is connected to the plastic zone size at crack tip. In particular the monotonic plastic zone size is considered significant for the vanishing of load effects. This main assumption is not considered in PREFFAS model where the classical crack closure equation is used, i.e.

$$\frac{K_{max} - K_{OP}}{K_{max} - K_{min}} = U(R) = aR + b$$
$$R = \frac{\sigma_{min}}{\sigma_{max}} \qquad (4)$$

a and b are two real coefficients independent of R. In this case each sequence is described by the Rain-Flow method and the crack opening stress σ_{OP} corresponding to K_{OP} is calculated for each cycle i using the mathematical rule depicted here (see also figure 4).

$$
\begin{aligned}
R_{ij} &= \frac{\mathrm{INF}\left(\sigma_{\min k}\right)_{k=j}^{k=i-1}}{\sigma_{\max j}} \\
\sigma_{OPij} &= \sigma_{\max j}\left(1-U\left(R_{ij}\right)\left(1-R_{ij}\right)\right) \qquad (5) \\
\sigma_{OPi} &= \mathrm{SUP}\left(\sigma_{OPij}\right)_{j=1}^{j=i-1}
\end{aligned}
$$

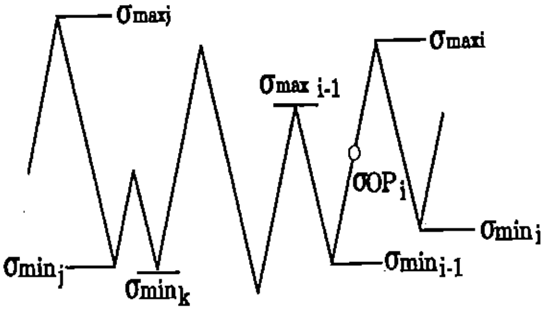

Fig. 4. PREFFAS modelling.

A lot of authors have shown a good agreement concerning life-time results between these two models in standard 2D cases. But we have previously shown that PREFFAS model doesn't take account of the plastic zone size during the simulated growth. This has a consequence in 3D cases particularly on the shape of the crack front which has a different evolution near the free surface due to the plane stress condition increased by the overloading effect. That's the reason why the use of a loading dependent threshold is necessary in 3D crack growths. Figure 5 shows the different crack fronts obtained with the two models. One notices that the crack grows more slowly near the free surface due to the plastic zone more important in this region with ONERA model although PREFFAS model doesn't simulate such a difference.

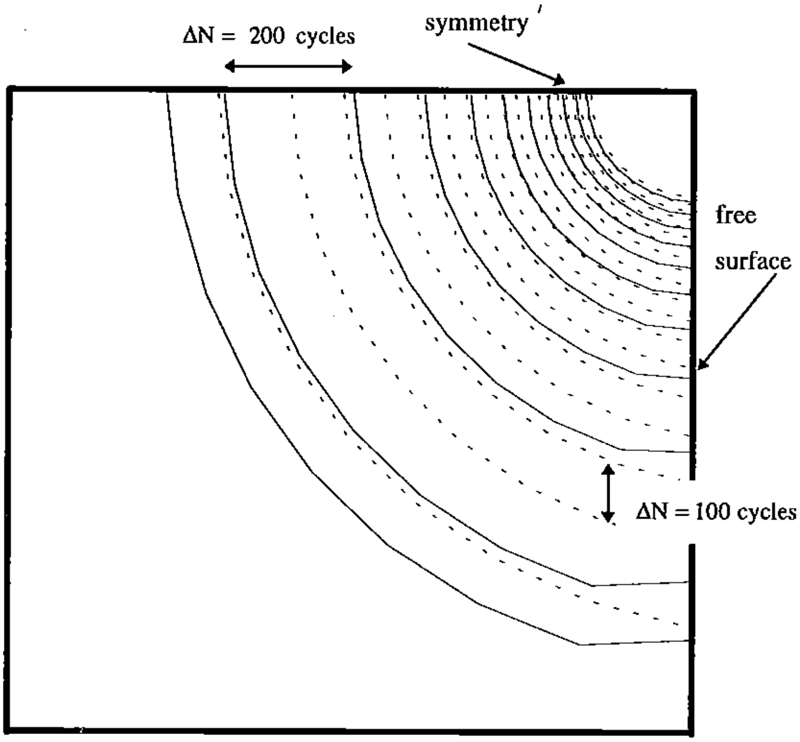

Fig. 5. Crack growth obtained with ONERA model (-) and PREFFAS model (--).

Conclusions

A 3D Finite Element crack growth model is presented allowing the crack front to have a free evolution during the simulated growth. Moreover different effects on the crack propagation are taken into account : effects of compressive shot-peening residual stresses and overloading effects. Concerning the first factor the low value of the crack propagation rate at the beginning of the growth is consistent with experimental data. Two crack propagation laws including the description of overloading effects were also implemented and these effects on the crack front shape are pointed out. In the future the computing procedure of crack growth described in this paper will allow to explicitely simulate the crack growth in large structures.

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