# EXPERIMENTAL AND NUMERICAL ANALYSIS ON FATIGUE CRACK PROPAGATION ON THREE MEDIUM-STRENGTH STEELS

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Fatigue crack growth of aircraft materials tested in laboratory air has been studied. The experimental fatigue crack growth rate data, obtained utilizing CT specimens with T-L orientation, have been analyzed by means of the Paris, Modified Forman and Collipriest models. A numerical simulation has been done by a computer program to estimate the threshold SIF range with more accuracy. For the steels studied, it has been made clear that the Collipriest relationship seems to predict with satisfactory confidence the safe-life of structure subjected to fatigue.

## INTRODUCTION

The assesment of susceptibility to the brittle fracture or of the fatigue crack growth dependence on the load amplitude and the crack length is of paramount importance for determining the fail-safe strength of any materials to be utilized in structures subjected to cyclic loads.

It is known that a valid approach to these evaluations is accomplished applying some concepts of the LEFM that allow to relate parameters such as yield strength, structure geometry, applied stress or cyclic loading amplitude, etc., to the crack growth rate by determinations of the stress intensity factor (1). However, relationships deduced from various proposed models interpret the fracture phenomenon in merely mechanical terms, whereas the fatigue crack growth rate is proved to be more or less affected by the interaction between mechanical and microstructural phenomena (2).

Moreover the appearance of various fracture modes observed by microfractographes gives evidence of different operating mechanisms

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for a given metal-environment system (3). Accordingly it appears opportune that data obtained under determined experimental conditions are carefully analyzed in order to check up the suitable model fitting the studied system. On these bases, the present work was developed considering that it is important i) to determine $\Delta K_{th}$ and $K_{Ic}$ with satisfactory confidence for valueing the fatigue behaviour of any metal particularly where the environmental effect is considerable, ii) to interpret the constants of the suitable model in terms of the fracture modes observed (4), (5).

## Materials and Experimental Methodology

Chemical composition and mechanical properties of the steels studied are listed in Table 1 and 2 respectively. These steels, commercially produced as hot rolled and normalized plates, are hardened by precipitation process. CT specimens ($B = 5 * 10^{-3}$m; $W = 25 * 10^{-3}$m),

TABLE 1 - Chemical composition and structure

| Steel | C | Mn | Si | P | S | Cu | Ni | Cr |
|---|---|---|---|---|---|---|---|---|
| FeE420-KT | 0.18 | 1.31 | 0.31 | 0.010 | 0.007 | 0.12 | 0.27 | 0.08 |
| A 710-A | 0.05 | 1.36 | 0.30 | 0.003 | 0.006 | 1.20 | 0.92 | 0.65 |
| NICUAGE/R | 0.04 | 0.83 | 0.28 | 0.010 | 0.007 | 1.02 | 0.88 | 0.07 |

| | Sn | Mo | V | Nb | Al | Structure |
|---|---|---|---|---|---|---|
| | 0.02 | 0.01 | 0.07 | 0.04 | 0.05 | Ferrite-Pearlite |
| | 0.02 | 0.02 | 0.07 | 0.03 | 0.01 | Ferrite |
| | – | 0.19 | – | 0.06 | 0.04 | Ferrite Bainite Martensite |

TABLE 2 - Mechanical properties

| Steel | 0.2% YS (MPa) | UTS (MPa) | El. (%) |
|---|---|---|---|
| FeE420-KT | 430 | 580 | 30 |
| A 710-KT | 730 | 880 | 20 |
| NICUAGE/R | 490 | 605 | 28 |

utilized in the experiments to determine the fatigue crack growth rate, were machined with T-L orientation, in order not to change the original steel structure. The test, performed according to ASTM E647-81 and E399-81 designations, were conducted at room temperature (20 ± 1 °C) in laboratory air. Crack length was measured by means of two optical microscopes closely placed at both the sides of the specimens which had reference marks at predetermined locations along the cracking direction. The average values of these two measured crack lengths was used in the calculations. The maximum value of $\Delta K$ reached has been limited by the measurement requirements. Test variables were the following:

i) $R = 0.17$

ii) $P_{max} = 2.75$ KN

iii) Cyclic frequency = 4Hz (sinusoidal wave)

## Matematical Models

At present the more useful fatigue crack growth models are the Paris', Forman's, Mod. Forman's and Collipriest's equations. All these models, valid only within the LEFM, allow to evaluate the crack growth rate as a function of some typical parameters as: stress intensity factor amplitude $\Delta K$, loading ratio $R = \sigma_{max}/\sigma_{min}$, material's constants etc. Therefore these models have been developed for fatigue crack growth in not strongly aggressive environments.

The first and simpler model is that by Paris:

$$\frac{da}{dN} = C(\Delta K)^n$$

This formula is valid within so-called medium-amplitude range of fatigue kinetic diagram and generally it gives conservative predictions of the fatigue life.

The Forman's equation is a refinement of the Paris one and it introduces two new parameters i.e. $K_C$ and R:

$$\frac{da}{dN} = \frac{C\,\Delta\,K^n}{(1-R)K_C - \Delta K}$$

This formula is considered to be useful to investigate the propagation process near the critical conditions i.e. for $\Delta K \sim (1-R)\,K_C$.

To study the crack growth near the threshold conditions, Forman proposed a modified formulation of the previous eqn.:

$$\frac{da}{dN} = \frac{C\,\Delta\,K^n[\Delta K - \Delta K_o]^p}{[(1-R)K_C - \Delta K]^q}$$

where

$$\Delta K_0 = (1 - C_0 R)K_0$$

This equation gives a significant improvement for describing either threshold or subcritical conditions (low and high $\Delta K$ values).

The Collipriest's model (6) describes the crack growth in all the $\Delta K$ range:

$$\frac{da}{dN} = C_0(K_C \Delta K_0)^{n/2} \exp \left\{ \ln \left[ \frac{K_C}{\Delta K_0} \right]^{n/2} \operatorname{arctgh} \left[ \frac{\ln(\Delta K^2/[(1-R)K_C \Delta K_0])}{\ln[(1-R)K_C/\Delta K_0]} \right] \right\}$$

As can be seen in this formula there are just two material's constants.

The environment effects the material constants and furthermore new parameters, as frequency of cyclic loading and the waveform, must be considered.

The Paris', Mod. Forman's and Collipriest's equations have been implemented in a computer program.

The constants required by the three equations have been obtained with a least square method from the experimental data.

## Results

The following graphics present experimental and numerical results for FeE420-KT, A 710-A and Nicuage/R steels.

Fig. 1 shows the results for FeE420-KT steel. As it can be seen, Paris' model gives a satisfactory fitting as do the mod. Forman's equations, the latter with $\Delta K_{th}$ supposed equal to 11. Collipriest's model gives a good approximation of experimental data only with $\Delta K_{th} \simeq 5$.

The most probable value for $\Delta K_{th}$ is closer to 5 than 11. This conclusion can be justified considering that mod. Forman eqn. requires to find four constants instead of the two constants required by Collipriest.

So it is simpler for Forman's model to fit the experimental data, even considering $\Delta K_{th}$ and $K_C$ values affected by some uncertainty. From this consideration it is possible to say that in any case the most probable $\Delta K_{th}$ value is closer to the value for which the Collipriest's eqn. gives the best fitting to the experimental data.

To confirm these results we have made a numerical-experimental comparison of the number of cycles necessary to reach a crack length close to the maximum length compatible with the measurement requirements (Table 3).

The same comparisons have been made also for the two other steels.

As it can be seen from Fig. 2, refering to A710-A steel, the Paris' model doesn't fit very well the experimental data, while modified Forman's and Collipriest's models provide a good fitting with the same $\Delta K_{th}$ = 11. This can be seen also in Table 3.

Also for the last steel, NICUAGE/R, the best fitting is obtained by modified Forman's and Collipriest's eqn. (Fig. 3).

For this material an extrapolation has been attempted for $\Delta K$ values that haven't been reached in the experimental tests. This has been made both with Forman's and with Collipriest's models.

As can be seen in Fig. 4 the former doesn't allow, for the studied steels, to carry out extrapolations as the curve decreases near the $K_c$. Collipriest equation, instead, gives reasonable results in the whole range of $\Delta K$.

It can be argued from the graphs and Table 3 that Paris' eqn. gives less accurate results (even if always conservative) in any case but for FeE420-KT steel. This fact is probably linked to the lower value of $\Delta K_{th}$ for this alloy.

TABLE 3 - Comparison between numerical and experimental results for crack growth vs. number cycles of FeE420-KT, A710-A and NICUAGE/R steels.

| FeE420-KT | Exper. | Paris | Collipriest | | Mod. Forman |
|---|---|---|---|---|---|
| | | | ($\Delta K_{th}$ = 5) | ($\Delta K_{th}$ = 11) | ($\Delta K_{th}$ = 11) |
| Δa(m) | 0.0132 | 0.0132 | 0.0161 | 0.0131 | 0.01305 |
| Cycle | 151000 | 141500 | 144000 | 156000 | 142500 |
| A 710-A | | | | | |
| | | | ($\Delta K_{th}$ = 11) | | ($\Delta K_{th}$ = 11) |
| Δa(m) | 0.0161 | 0.0160 | 0.0161 | | 0.0156 |
| Cycle | 120618 | 97000 | 117000 | | 123000 |
| NICUAGE/R | | | | | |
| | | | ($\Delta K_{th}$ = 11) | | ($\Delta K_{th}$ = 10) |
| Δa(m) | 0.0136 | 0.0136 | 0.0134 | | 0.0137 |
| Cycle | 123130 | 104500 | 119000 | | 115000 |

For relating the behaviour of the mathematical models to the fractu re mechanism, an interpretation of the fracture crack growth in terms of the metallographic structures can be attempted by observating the fracture surfaces by SEM.

For the FeE420-KT ductile striations for the whole range of $\Delta K$

and evident secondary cracking (both of intergranular and vertical type) have been visible as shown in Fig. 5.

Morphological characteristics, similar to those of FeE420-KT steel, have been showed by the fracture surface of NICUAGE/R steel. The description of the fracture morphology of A710-A steel, Fig. 6, is more difficult probably owing to the more complex metallographic structure of this alloy.

Ductile striations with intervening regions of brittle fracture have been observed as well as intergranular secondary cracking. From these observations it might be deduced that Collipriest's model is able to describe the crack growth even with more fracture mechanisms operating in complex metal structures.

## CONCLUSIONS

This paper has allowed us to pick out the peculiar features of each of the proposed models, in order to obtain the best results according to the problem to work out.

In the considered case (test carried out on ferrous materials and in laboratory air) the following remarks have been made:

1) Paris' equation can be used with good results only with stress intensity factors far enough from $\Delta K_{th}$ and $K_c$.
2) Collipriest eqn. has showed good precision for all the considered materials. These results have showed a strong sensibility to the threshold value. For this reason this eqn. has been used to find an approximate value for $\Delta K_{th}$.
   Taking into account likely values for $\Delta K_{th}$ and $K_c$, Collipriest model has given reliable results even for S.I.F. values greater than those reached in the experimental tests.
3) Forman's modified eqn. has given, in this case, some trouble since the experimental data referred to S.I.F. values $\ll K_c$. For this reason we have obtained for the four constants some value, Fig. 4, that is hardly theoretically justifiable. This fact has involved the impossibility to use this eqn. for the whole range of $\Delta K$.
   On the other hand, starting from experimental data ranging from values little greater than $\Delta K_{th}$ to values little lesser than $(1 - R)K_c$, it can be reasonably foreseen a good fitting, even without exact informations about $\Delta K_{th}$ and $K_c$.

As regards the metallurgical interpretation of the mathematical models, better correlation among crystal metal structures, type of observed fracture and the crack growth rate could be found only with more data for a statistical analysis.

## SYMBOLS USED

| | |
|---|---|
| $\Delta a$ | crack length growth |
| $c$, $n$, $p$, $q$ | constants in the semiempirical equations |
| $C_0$ | slope factor |
| $N$ | number of fatigue cycles |
| $K_0$ | fatigue threshold S.I.F. |
| $K_c$ | critical S.I.F. for fracture |
| $\Delta K$ | stress intensity factor range |
| $\Delta K_{th}$, $\Delta K_0$ | fatigue threshold S.I.F. range |

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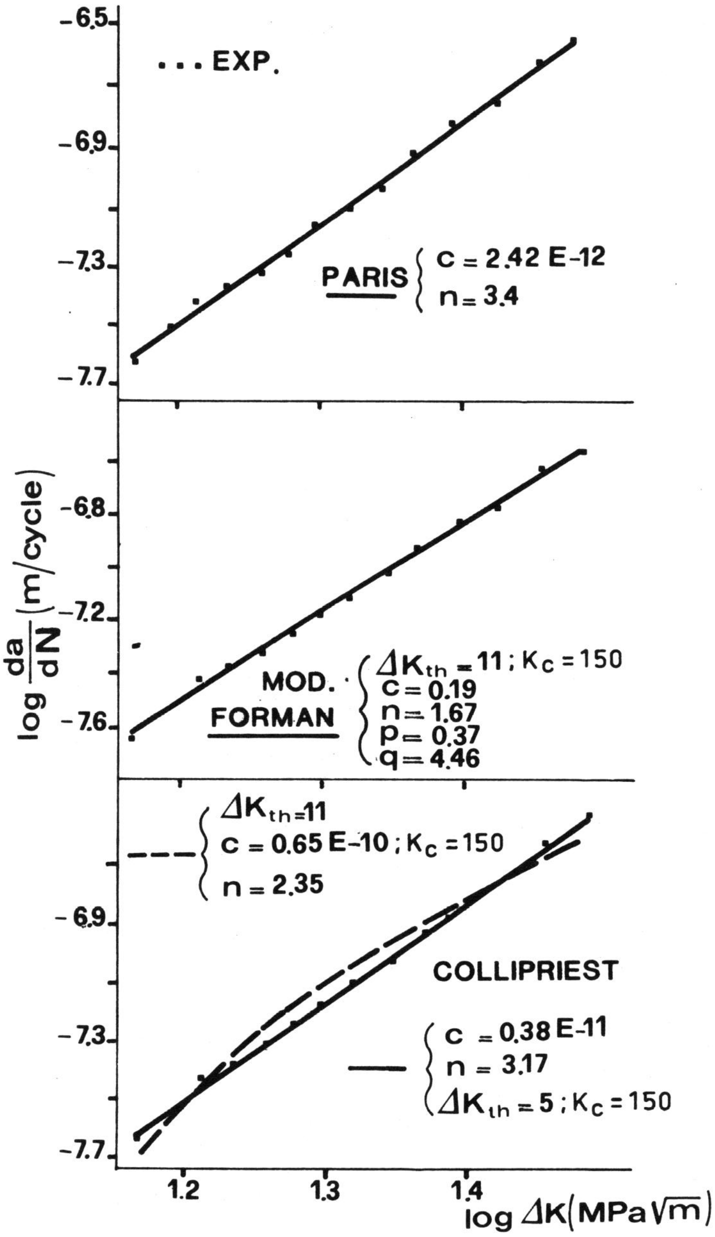


Figure 1 Curve fit of Paris, Mod. Forman and Collipriest equations to crack growth rate data for FeE420-KT steel (laboratory air).

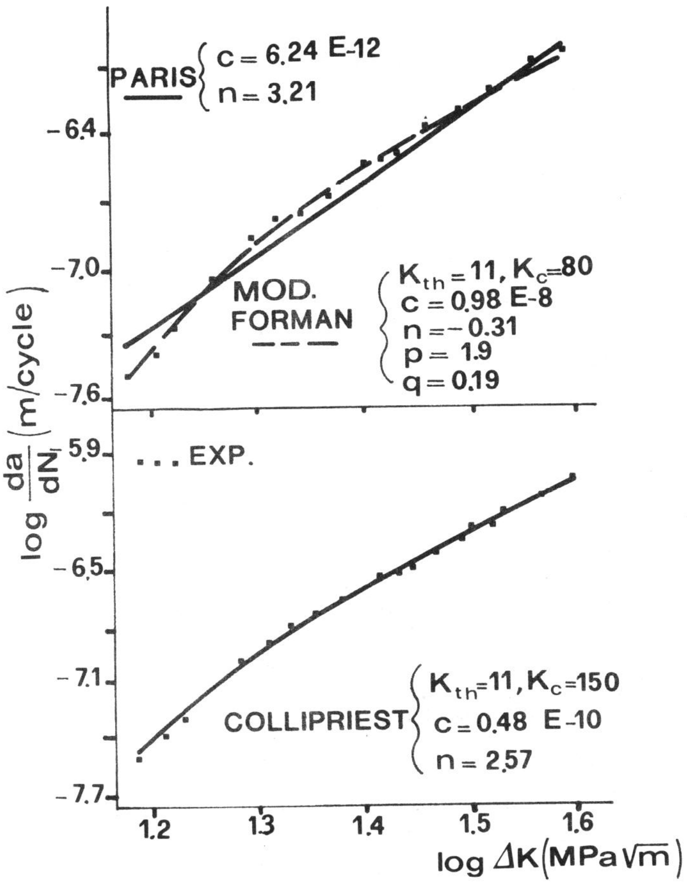


Figure 2 Curve fit of Paris, Mod. Forman and Collipriest equations to crack growth rate data for A710-A steel (laboratory air).

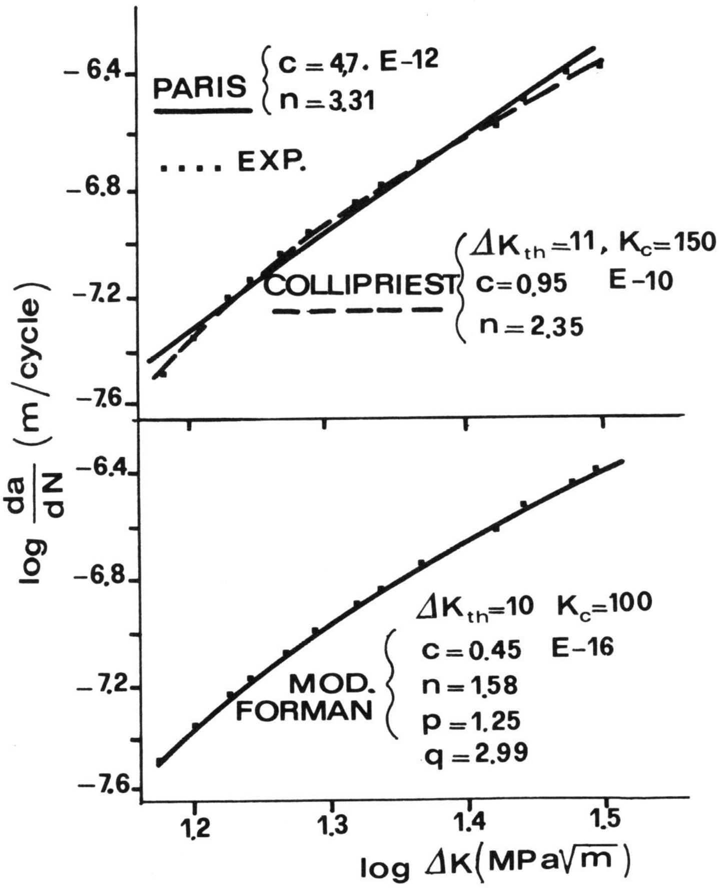


Figure 3 Curve fit of Paris, Collipriest and Mod. Forman equations to crack growth rate data for NICUAGE/R steel (laboratory air).

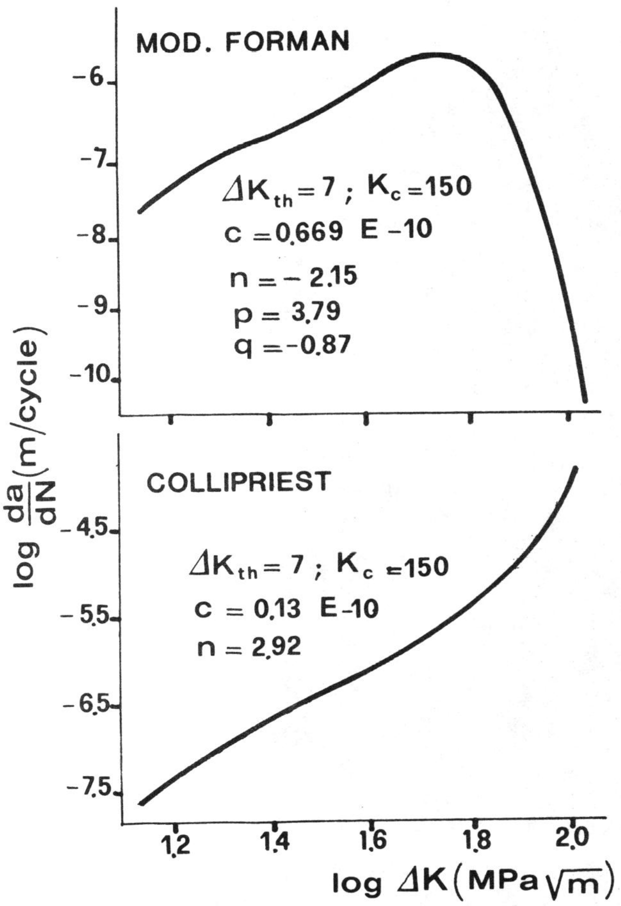


Figure 4 Crack growth rate prediction from Mod. Forman and Colli-priest equations for overall range of ΔK (NICUAGE/R steel).

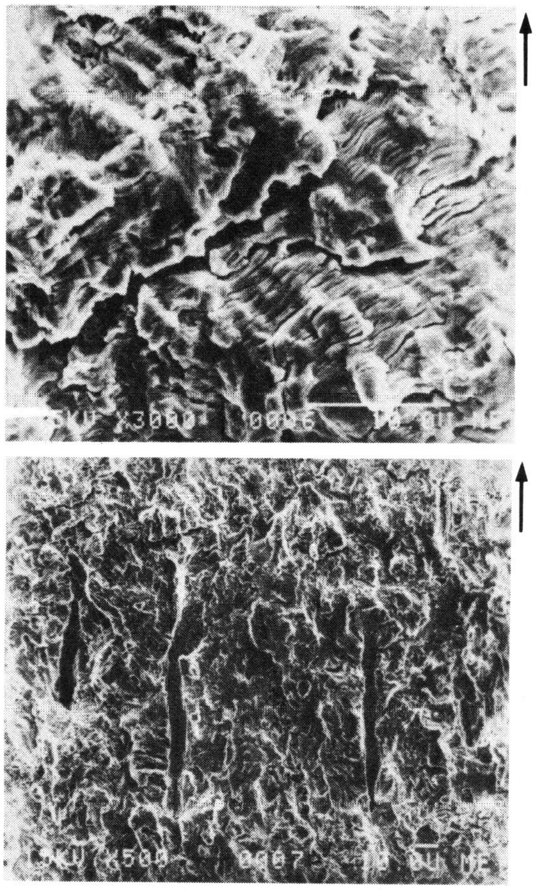

Figure 5 Micrograph of FeE420-KT steel (x3000 and x 500): $\Delta K$ = 29.60 KN $\sqrt{m}$, a = 0.008 m (↑ crack growth direction)

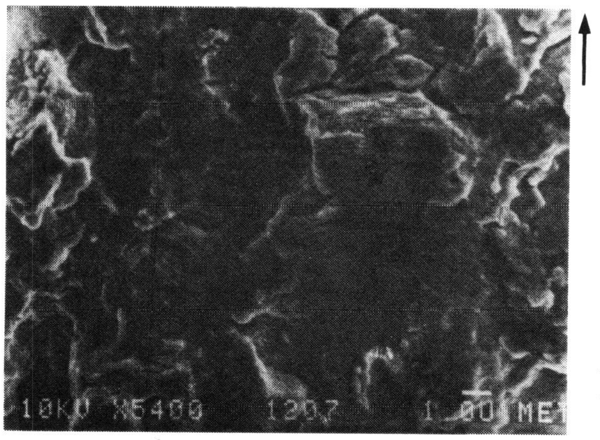

Figure 6 Micrograph of A710-A steel (x 5400): $\Delta K$ = 29.60 KN $\sqrt{m}$, a = 0.008 m (↑ crack growth direction)