

Analysis of the Fatigue Crack Propagation in Case of Extended Plasticity Conditions

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1. INTRODUCTION

Previous studies conducted on the fatigue crack propagation under extended plasticity conditions (Bhandari et al. - 1984 (a), 1984 (b)) have shown the existence of a parameter K_γ which correlates better the experimental data than the classical stress intensity factor (SIF) K based on linear elastic fracture mechanics (LEFM). Without going too much in theoretical details of the K_γ parameter, the objective of this paper is to verify its validity on some experimental results undertaken in the framework of a joint GIS-programme (Bhandari - 1982) between three french parties : NOVATOME, CEA (Atomic Energy Commission) and CREUSOT-LOIRE, on the propagation of cracks at the edge of circular notches in a wide plate or in a CT-type specimen. In order to compute the value of K_γ in such geometries, a separate study (Bhandari et al. - 1990) was made to establish weight-functions for analysis of cracks emanating from the base of a surface notch. The results of this study along with that conducted on evaluation of SIF for cracks at the edge of holes (Bhandari and Dubeaux - 1983), will be used to analyse the fatigue crack propagation data obtained in the experimental programme mentioned above.

2. BRIEF RECALL OF THE K_γ -CONCEPT

The parameter K_γ is based on the stress and the strain-field in the uncracked structure, in the region where the crack is to be introduced. It is evaluated elastically so that the numerous results from the LEFM-field can be used since the superposition-principle simplifies the resolution of the problems.

To illustrate this point, consider an elastic medium subjected to a certain boundary conditions. If the stress in the uncracked structure at the prospective crack region is given by $\sigma(x)$ and if a weight function $G(x, a)$ for the given configuration exists, then the SIF $K\sigma(a)$ for a crack of length a can be written as :

$$K\sigma(a) = \int_0^a \sigma(x) G(x, a) dx \quad [1]$$

In the case of a strain-hardening material, to the stress-field $\sigma(x)$ in the structure, corresponds a strain-field $\varepsilon(x)$ which cannot be deduced linearly but which can be computed using the stress-strain curve associated with a certain plasticity criterion. Now if we consider a fictitious elastic-stress corresponding to the strain-field $\varepsilon(x)$ $\left\{ \approx E \varepsilon(x) \right\}$ one could compute the strain-intensity-factor $K\varepsilon$ by replacing σ by ε in equation [1]. The parameter $K\gamma$ is the quadratic mean of $K\sigma$ and $K\varepsilon$ i.e. $K\gamma = (K\sigma K\varepsilon)^{0.5}$. It is already been shown (Bhandari et al. - 1984 (a), 1984 (b)) that the parameter $K\gamma$ correlates well with the SIF K_J based on the J-integral (Rice - 1968). On the other hand, it is now well established (El Haddad et al. - 1980, Dowling - 1983) that the parameter K_J correlates well the fatigue crack propagation under extended plasticity conditions. However, K_J is not simple to evaluate. Thence the usefulness of the parameter $K\gamma$. In this paper, the objective is to interpret the results of fatigue crack propagation obtained in the framework of a three party French GIS-programme (Bhandari - 1982), in terms of the parameter $K\gamma$ to show that it is more appropriate than other parameters based only on elastic considerations.

3. BRIEF DESCRIPTION OF THE GIS-PROGRAMME

3.1. Specimen Geometry

The experimental programme was conducted on 3 types of specimens with two configurations in each type thus requiring analysis on six different kinds of specimens :

- * Wide plate with circular central holes of radius 6 mm (CP1) or of radius 3mm (CP2)
- * Wide plate with circular edge notches of radius 6 mm (CP3) or of radius 3mm (CP4)
- * CT-type specimens : In this cas the standard CT-specimens were modified to introduce circular holes so that the cracks propagate at the edge of the hole. Two types of holes are considered : hole of radius 10 mm (CT1), of radius 1.2 mm (CT2)

3.2. Experimental Conditions

- * CP-specimens : These tests were conducted at Laboratoires de CREUSOT-LOIRE at UNIEUX (Amzallag - 1983) under fixed load conditions with a maximum load $P_{max} = 10000$ N and an R-ratio (P_{min}/P_{max}) of 0.1. The material used is a 316L-type stainless steel with the properties : $\sigma_y = 205$ MPa, $\sigma_u = 523$ MPa, $E = 192.2$ GPa.

The test programme consists of : 2 tests with each of specimen CP1 (CP11, CP12) and CP2 (CP21, CP22) and one test with each of specimen CP3 (CP33) and CP4 (CP45).

- * CT-specimens : These tests were carried out at Laboratoires du SRMA at CEA-SACLAY (Stromboni - 1984) with different imposed load but with $R = 0.1$. The material used is also a 316L-type stainless steel but with slightly different material properties : $\sigma_y = 220$ MPa; $\sigma_u = 550$ MPa; $E = 192.2$ GPa.

The test programme is as follows :

- * CT1 was subjected to three different maximum loads : 6000 N (CT11), 7000 N (CT12), 9000 N (CT13).
- * CT2 was subjected to six different maximum loads : 4000 N (CT21), 4400 N (CT22), 5000 N (CT23), 5500 N (CT24), 7000 N (CT25), 8000 N (CT26).

3.3. Finite Element Computations

Elasto-plastic computations were carried out at NOVATOME (Forgeron - 1983) on uncracked specimens of each of the six configurations tested to determine the stress and strain field corresponding to the applied loads. These results were analysed particularly to determine the polynomial representation of stress and strain field, necessary for the application of the weight function methods (Bhandari et al. - 1983, 1990) for the evaluation of stress and strain intensity factors K_{σ} and K_{ϵ} respectively and thus to compute the parameter K_{γ} .

4. ANALYSIS OF RESULTS

The experimental results obtained in this programme were analysed using :

- . weight function approach of (Bhandari et al. - 1990) for the case of test series CP3 and CP4 and also for the test series CT1 and CT2 simulating them as edge notched specimens,
- . weight function method of (Bhandari and Dubeaux - 1983) for the test series CP1 and CP2.

In this way, K_{γ} -concept is tested under different types of geometrical and loading conditions. All the results presented below in figures representing crack-growth rate as a function of SIF, contain also those obtained on standard specimens in the form of Paris law, $da/dN = C (\Delta K)^n$ obtained on the specific material as a mean curve (CP-series) or as a scatter band (CT-series).

* Series CP3, CP4 - Specimens with a lateral notch : Experimental results are available on two specimens (CP33, CP45) with respect to crack length as a function of number of cycles. Using weight function method (Bhandari et al. - 1990) and results of elasto plastic computations (Forgeron - 1983) on these specimens, the parameter K_{γ} (K_{FP} in fig. 1) is evaluated as explained earlier. An elastic SIF (K_L in fig. 1) is also computed using Bowie's analysis (1956) concerning cracks at the edge of a hole.

* Series CP1, CP2 - Specimens with a central hole : In this case 4 specimens were tested. In order to compute K_{γ} for cracks at the edge of an interior hole, reference (Bhandari and Dubeaux - 1983) is used where influence function was determined in an analytical form. Results are shown in figure 2.

* Series CT1, CT2 - Modified CT-specimens : Strictly speaking the analysis in (Bhandari et al. - 1990) is not applicable to evaluate K_{γ} for such type of specimens. However, considering small cracks, K_{γ} was computed as in the case of CP3, CP4 specimens, using elasto-plastic computations of stress and strain field for the uncracked specimens (Forgeron - 1983). Moreover other analyses were made using LEFM :

- . ASTM LEFM formula (see Stromboni 1984)
- . ASTM formula for SIF : $KL = P * f(a/w)/B.(w)**0,5$
 where $f(\lambda) = 29.6(\lambda)^{1/2} - 18.5(\lambda)^{3/2} + 655.7(\lambda)^{5/2} - 1017(\lambda)^{7/2} + 638,9(\lambda)^{9/2}$
 a being the total crack length including the dimensions of the hole
 (a = diameter of hole D + length of slit l)
- . Jergeus formula (1978) : The relation proposed here is of the type :
 $KS = 1'.KL/(1 + D)$

where $1' = 1 + D \left\{ 1 - \text{Exp.} \left[\frac{-4(1 + \sqrt{D/r}) \cdot 1}{\sqrt{D \cdot r}} \right] \right\}$, r = notch radius.

As an example fig. 3 shows the comparison of results for 3 specimens (CT2.2, 2.3 and 2.5).

5. DISCUSSION OF RESULTS AND CONCLUSION

One of the major objectives in the application of fracture mechanics to the analysis of fatigue cracks is to obtain conservative data with respect to fatigue crack propagation. The results presented here concern three types of specimen. The weight function method proposed in (Bhandari et al. - 1990) is applicable to specimen series CP3/CP4 and fig. 1 shows sufficient evidence of the conservatism of the $K\gamma$ -approach to predict crack growth behavior in extended plasticity conditions. It can be observed that the SIF based only on LEFM concepts could give non-conservative results.

The weight function method of (Bhandari and Dubeaux - 1983) is applicable to CP1/CP2 series and one will find that $K\gamma$ gives better (conservative) correlations than those obtained by LEFM-parameter evaluated using Bowie's solution (1956).

As for the CT1/CT2 series, analysis was conducted by simulating CT specimens as edge notched specimens. Results obtained by $K\gamma$ approach seem to give slightly better correlations than the LEFM evaluated SIF (KL and KS), although Jergeus proposed K parameter (KS) seems to correlate better than that evaluated using adapted ASTM formula (KL).

In general therefore, the $K\gamma$ -concept seem to present better correlations. It is evident, however, that more tests are needed to confirm the tendencies shown by the present results.

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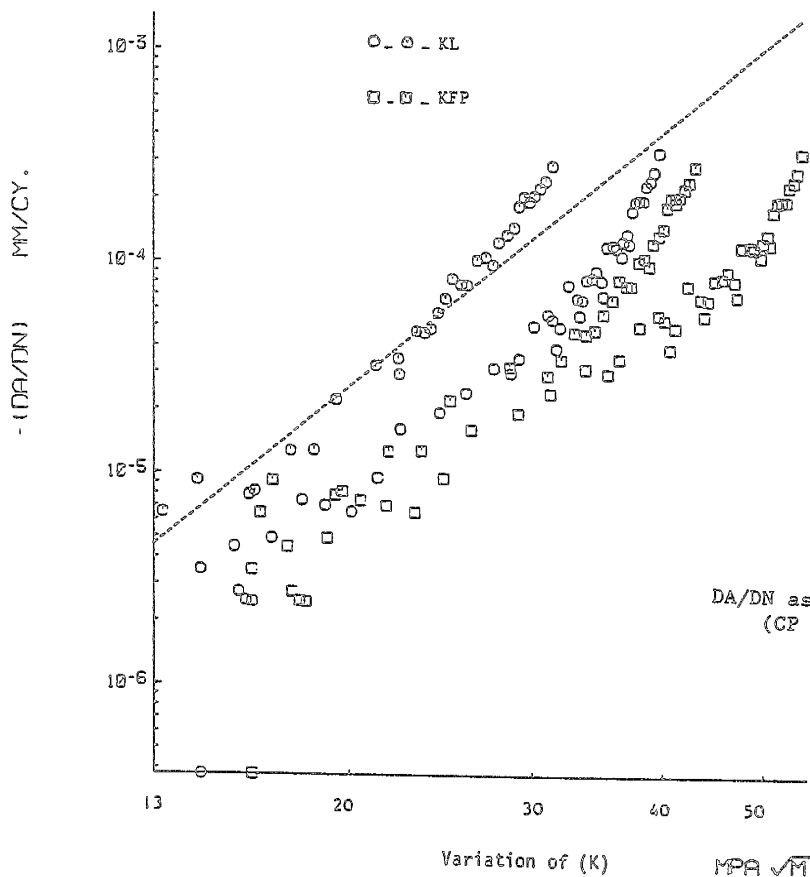


Fig. 1
 DA/DN as a function of ΔK
 (CP 3.3 - CP 4.5)

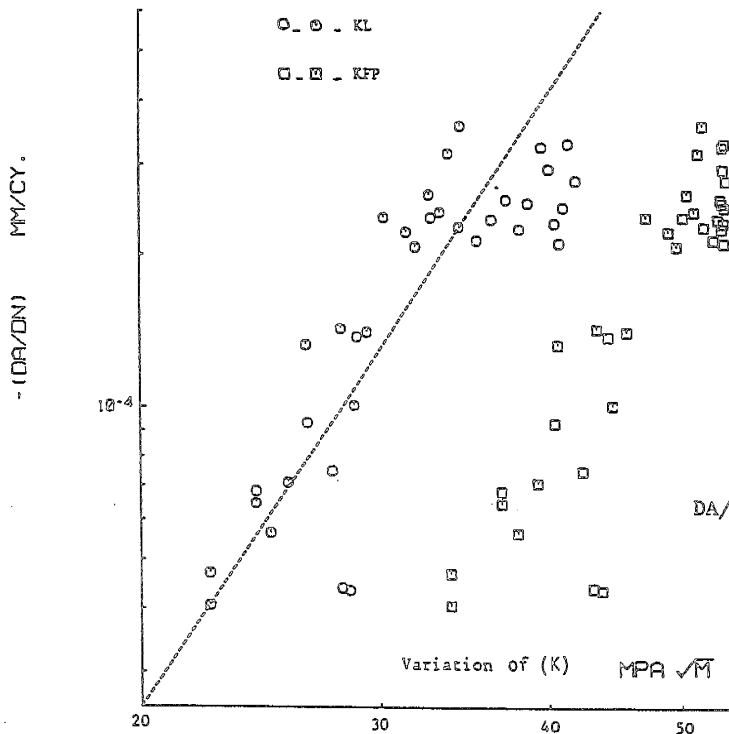


Fig. 2
 DA/DN as a function of ΔK
 (CP 1.1 - CP 1.2)

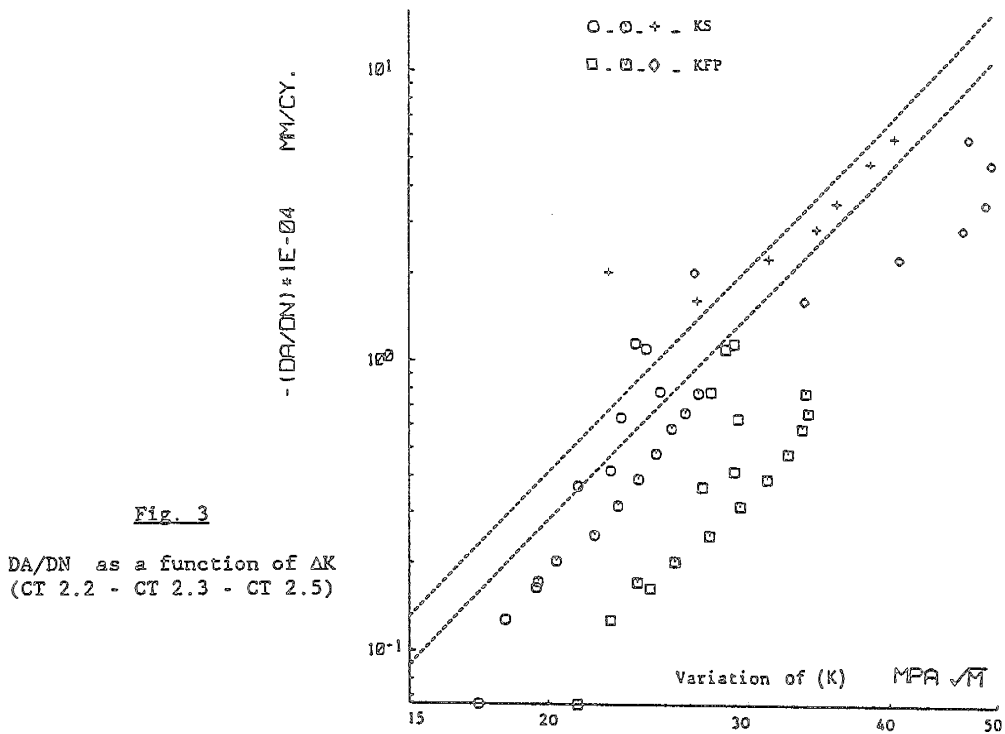


Fig. 3
 DA/DN as a function of ΔK
 (CT 2.2 - CT 2.3 - CT 2.5)