PREDICTION OF FATIGUE CRACK GROWTH UNDER MIXED MODE I AND MODE II OVERLOADS

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The prediction of fatigue lifes or crack growth rates in complex loaded components and structures represents one of the basic problems of engineering science. In case of variable amplitude loading, especially after single interpearsed overloads delay effects can appear, which decisively influence the crack growth rates. According to that, models have been developed to consider these delay effects for mode I loading conditions. The present investigations have shown, however, that after mixed mode or mode II overloads the crack growth retardation is considerably lower than after a comparable mode I overload. Elastic–plastic Finite Element calculations prove that the residual compressive stresses in front of the crack tip, which determine the effective stress intensity, are mainly caused by the mode I share of the overload. The delay effects can be calculated by using an effective overload value.

INTRODUCTION

Despite careful design and manufacturing fatigue crack growth in complex loaded components and structures often causes failure or damage. A reason for this damage are in general cracks which grow as a result of operating stresses and consequently lead to failure of these components. In order to give an accurate prediction of fatigue lifes or inspection intervals it is necessary to know the dependance of the crack speed on any kind of loading condition.

Based upon fatigue crack growth under mode I loading several models have been developed to estimate the fatigue lifes of cracked components as well for constant as for variable amplitude loading (survey in SCHWALBE (1), KANNINEN (2) and HENN (3)). The theories which account for the nonlinear effects of load interactions are either empirically obtained or based on theoretical reflections. The influence of mixed mode or mode II crack opening, however, is not taken into account in these models.

The submitted report deals with the investigation of the propagation behaviour of fatigue cracks subjected to mode I loading with single interpearsed overloads of variable loading directions. For this purpose fatigue tests and elastic-plastic Finite Element calculations have been carried out.

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FATIGUE CRACK GROWTH AT VARIABLE AMPLITUDE LOADING

One of the characteristic features of fatigue crack growth under VA loading is, that the incremental crack propagation per cycle does not only depend on the actual load case, but also on the load history endured by the cracked component. These effects of nonlinearity that occur in case of load interactions can be most clearly seen from the crack growth retardation that follows the imposition of a single peak overload in a constant amplitude load series, Figure 1. The simpliest way to calculate the working life of a cracked body is to neglect the effects of nonlinearity and to sum up the incremental crack lengths cycle by cycle using a fatigue law obtained from constant load tests

$$\frac{da}{dN} = f(\Delta K, R) \tag{1}$$

This corresponds to a linear damage accumulation, which can lead to non satisfying results.

In order to simulate the nonlinearities of fatigue crack growth under VA loading several models have been developed. They are predominantly based on two physical explanations for the retardation effects, which are the residual compressive stresses in front of the crack tip on the one hand and the crack closure phenomenon caused by residual plastic deformations in the wake of the crack on the other hand.

The models belonging to the first group, for example those by WHEELER, WILLENBORG, GRAY & GALLAGHER, etc. proceed from the assumption that the crack growth retardation following an overload is effective as long as the actual plastic zone is contained within the overload plastic zone. In the second group the authors (e.g. BUDIANSKI & HUTCHINSON, NEWMAN, PROBST & HILLBERY, etc.) try to calculate the amount of crack closure caused by the peak load using a modified DUGDALE model. A detailed description of these concepts can be found in References (1), (2) and (3).

EXPERIMENTAL INVESTIGATIONS AND RESULTS

Experimental setup and procedure

In order to obtain further knowledge concerning the effects of mixed mode and mode II overloads on subsequent mode I fatigue crack growth tests have been carried out on 7075 aluminum alloy (AlZnMgCu 1.5) by means of CTS–specimens in combination with a special loading device developed by RICHARD(4). Figure 2 shows the experimental setup (also in HENN(5) and HENN(6)). The crack length was measured indirectly with the d.c. potential drop method.

The specimens were fatigue cracked at constant ΔK_I and R–ratio

$$\Delta K_I = 8\ \text{MPa}\sqrt{m}\ , \quad R = 0.1 \tag{2}$$

The test frequency amounted 40 Hz.

To assure a comparative height of the peak load at any mixed mode or mode II overload the comparative stress intensity factor concept proposed by RICHARD(4) was used

$$K_V = \frac{1}{2} K_I + \frac{1}{2}\sqrt{K_I^2 + 6\ K_{II}^2} \tag{3}$$

With the constant overload ratio

$$R_{ol} = \frac{K_{V,ol}}{K_{I,max}} = \frac{K_{V,ol} \cdot (1-R)}{\Delta K_I} = 2.8 \tag{4}$$

the overload stress intensity value can be calculated to

$$K_{V,ol} = 24.89\ MPa\sqrt{m} \tag{5}$$

By using the dimensionless geometric functions Y_I and Y_{II} for the CTS–specimen, Reference (4), the required overload force to be set on the traction machine yields to

$$F_{ol} = \frac{K_{V,ol} \cdot w \cdot t}{\sqrt{\pi a} \cdot (\frac{1}{2}\ Y_I + \frac{1}{2}\ \sqrt{Y_I^2 + 6\ Y_{II}^2})} \tag{6}$$

Here w and t represent the width and thickness of the used CTS–specimens.

The overloads were applied during a short interruption of the fatigue loading and turning of the loading device (load angle $\alpha = 0^0$(mode I), 15^0, 30^0, ...,90^0(mode II)).

Results

The tests show that the retardation effects are considerably reduced when mixed mode or mode II overloads occur. The retardation time is decreased from 7 hours after a mode I overload to about 2 minutes after a mode II overload. An increasing mixed mode ratio obviously causes a smaller crack growth delay, Figure 3. Since the earlier mentioned models do not account for these effects, this can lead to non conservative fatigue life predictions.

The slope of the curve in Figure 3 shows that the decrease of the delay effects is mainly determined by the decrease of the K_I share of the overload. So this leads to the conclusion that the K_I share alone is responsible for the crack growth retardation. The number of delay cycles following the corresponding mode I shares of the mixed mode overloads were obtained in further fatigue tests and they are, as can be seen in Figure 3, in good agreement with the earlier presented results.

Further extensive test series with varying overload values subjected to different basic loading patterns (different ΔK_I– and R–values) have shown that the amount of crack growth retardation is mainly determined by the effective overload value R_{ol}^{eff}, which regards only the mode I share of the overload, and the crack growth rate $(da/dN)_{ol}$ at the time when the overload is applied, fig.4.

By use of the following equation one is then able to predict the number of delay cycles caused by an overload:

$$N_d = (A \cdot R_{ol}^{eff})^B \cdot \left(\frac{da}{dN}\right)_{ol}^C \qquad (7)$$

where A = 0.7151, B = 5.961 and C = –0.8136 are empirically obtained constants for the 7075 aluminium alloy.

NUMERICAL INVESTIGATIONS

In order to prove the influence of mode I or mode II peak loads on the residual stress distribution in front of the crack tip, elastic–plastic Finite Element calculations have been executed with the program system ADINA 5. The plastic zone sizes and stress distributions were computed for several time steps during a mode I and a mode II overload cycle (up– and unloading). A elastic–ideal plastic material law was assumed with the yield stress σ_y = 410 N/mm² (7075 allloy) under plane stress conditions.

The stress distributions in figure 5 show the plastic zones in front of the crack tip after the uploading to $K_{v,ol}$ = 24.89 MPa√m. During the unloading part of the load cycle a residual compressive stress field which can affect the subsequent mode I fatigue loading is formed only ahead of the crack that was subjected to the mode I overload. In the crack plane ahead of the tip of the mode II crack no residual compressive stresses perpendicular to the crack axis can be detected.

The results prove, that the effective stress intensity factor ΔK_{Ieff}, which determines the crack growth rate is almost not influenced by a interpearsed mode II peak load.

SYMBOLS

K_v : comparative stress intensity factor (MPa√m)

$K_{v,ol}$: overload comparative stress intensity factor (MPa√m)

N_d : number of delay cycles

R_{ol} : overload ratio

Y_I, Y_{II} : dimensionless geometric functions for the CTS–specimen

ACKNOWLEDGEMENT

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FIGURES

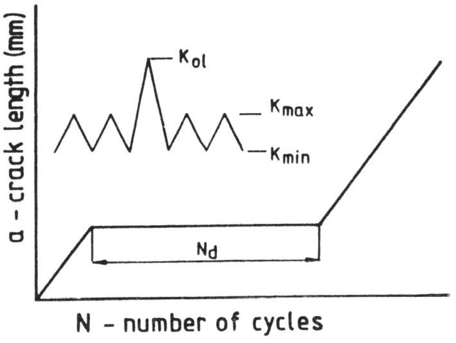

Figure 1 : Crack growth delay caused by a single peak overload.

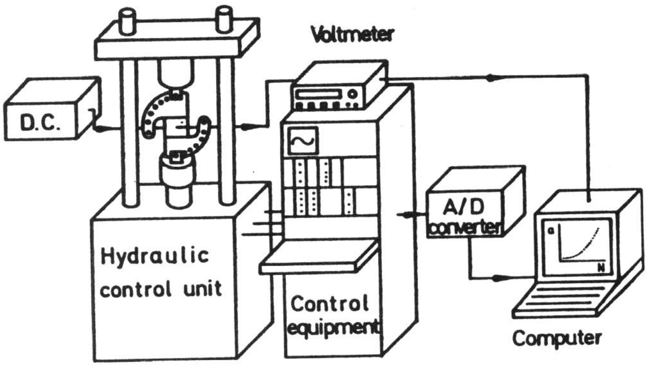

Figure 2 : Schematical experimental arrangement.

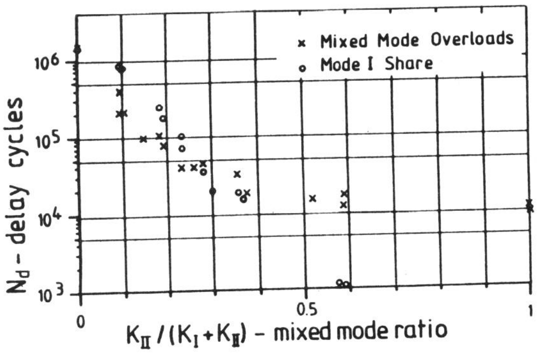

Figure 3 : Delay cycles N_d for various mixed mode ratios

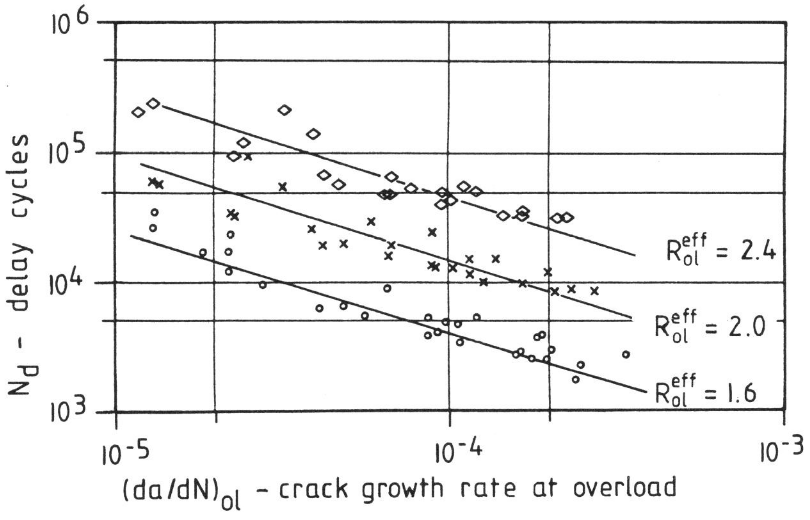

Figure 4 : Delay effects for different overload values and crack growth rates.

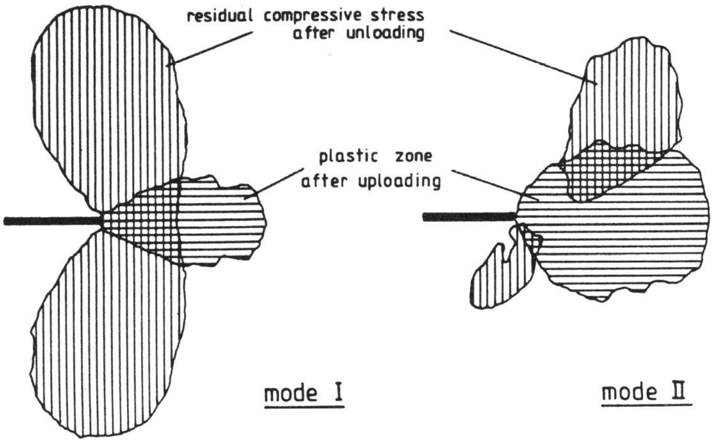

Figure 5 : Plastic zones and residual compressive stress distribution ahead of a mode I and a mode II crack.