INVESTIGATIONS ON THE CRACK GROWTH RETARDATION BEHAVIOR AND FATIGUE LIFE PREDICTION IN STRUCTURAL MATERIALS

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ABSTRACT

A brief survey over some recent investigations on the crack growth retardation behavior and fatigue life prediction by several semi-empirical models and their modifications is presented. The Wheeler, Willenborg, Matsuoka and Maarse models were chosen for evaluating the ability to predict the fatigue life in a Ti-6Al-4V alloy. Modifications of the Willenborg and Maarse models and their application to life prediction under single or a series of tensile overloads and spectrum loading were described. The mechanism of fatigue crack growth retardation behaviors under tensile overloading was discussed.

I. INTRODUCTION

In the early 1970's, the retardation behavior of fatigue crack growth caused by overloading and the prediction of lives based upon various retardation models have been drawn great attention by many investigators. A number of crack growth retardation models have been proposed (1-11). However, the retardation behavior in fatigue crack growth depends not only on the mode and sequence of overloading, but also on the fatigue damage produced by the plastic deformation and fracture characteristics under various loading conditions. Since the retardation effect is a rather complex phenomenon, the mechanism and its effect on fatigue life prediction have not been fully revealed.

In this paper, some recent progresses of studies conducted in the Institute of Aeronautical Materials, Beijing related to this area is

reviewed. Such studies may have some contributions to the basic understanding of the above mentioned topics and to the estimation of service lives in aircraft structures and components.

II. RETARDATION BEHAVIOR UNDER VARIOUS MODES OF OVERLOADING

The materials used in these investigations were two sheet alloys, an Al-Cu-Mg alloy, LY12-CZ (comparable to 2024-T4), and a mill-annealed Ti-6Al-4V alloy. The chemical compositions and mechanical properties as well as the experimental procedure have been reported in Reference [6]and[12].

For a LY12-CZ aluminium alloy, it was found that a single or a series of compressive overloads does not yield any appreciable retardation effect as compared with that of constant amplitude cyclic loading. A compressive-tensile overload, just like a single tensile overload, exhibites the greatest retardation effect on da/dN, while a tensile-compressive overload has much less effect than that of a single tensile overload.

According to the experimental results of Ti-6Al-4V under a single tensile overload, the retardation process may be divided into the following five stages [12] :

(a) acceleration of crack growth at an overload
(b) delayed retardation stage,
(c) maximum retardation stage,
(d) recovery stage, and
(e) retardation removed gradually.

Fig.1 illustrates some results of half crack length, a, versus number of cycle, N, under various overload ratio, Q_{01}, for a Ti-6Al-4V alloy. As shown in Fig.1, no retardation effect was observed at $Q_{01} = 1.3$ and nearly complete arrest of crack growth occurred at $Q_{01} = 2.8$.

III. EVALUATION OF CRACK GROWTH RETARDATION MODELS

In regard to the engineering application, two types of retardation models were evaluated:(a) the Wheeler model [2] and the Willenborg model [3] based upon residual compressive stresses and (b) the Maarse model [4] and the Matsuoka model [5] based upon the crack closure concept.

3.1 Retardation Behavior under A Single Tensile Overload

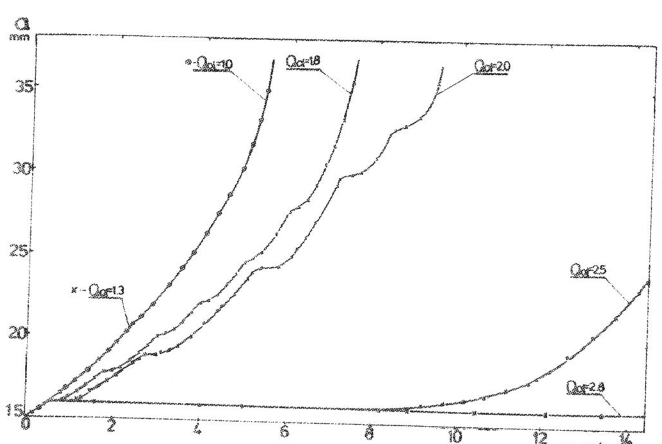


Fig.1 Crack growth behavior for different values of Q_{01}

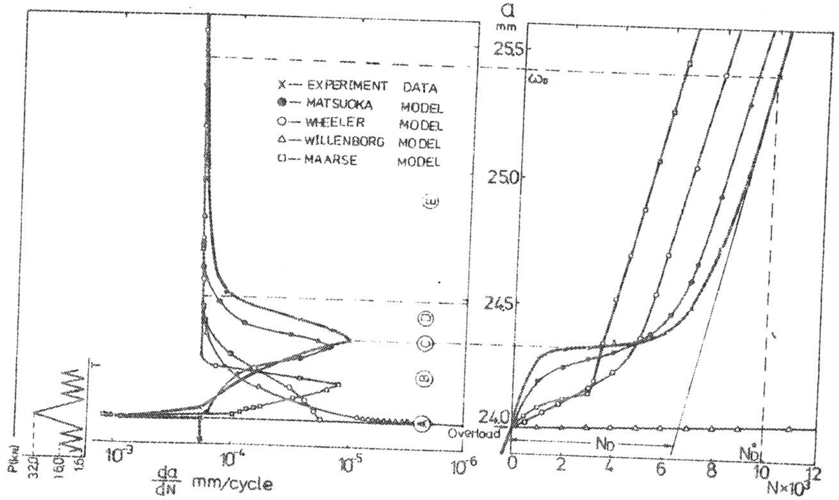


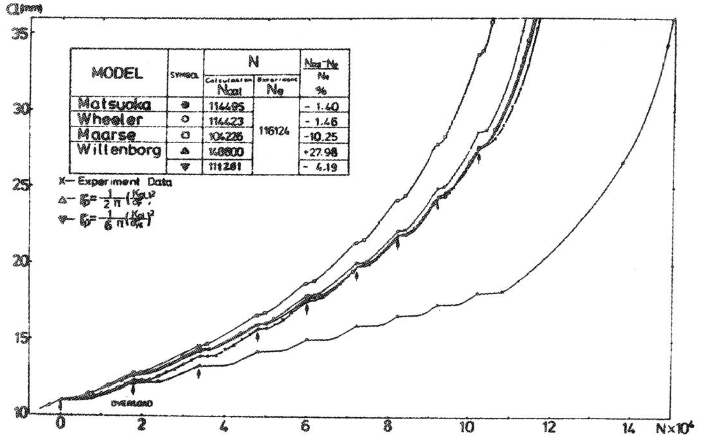
Fig.2 Comparison of experimental data with model predictions after a single overload, $Q_{01} = 2.0$

The retardation behavior of Ti-6Al-4V under a single overload at $Q_{01} = 2.0$ is shown in Fig.2. In which, the da/dN vs a and a vs N of the experimental curves and the calculated curves corresponding to the above mentioned models are illustrated.

In Fig.2, it is obvious that the Maarse and Matsuoka models based on the crack closure concept can describe the retardation process relatively well, in which the curve calculated by the Matsuoka model appears to be fairly consistent with the experimental curve.

3.2 Ability to Predict Fatigue Life

Fig,3 illustrates a vs N curves of a series of single overloads at different crack length (from 11 to 35 mm) at $Q_{01} = 1.8$. The calculated curves by these retardation models are also shown in the same figure.



MODEL	SYMBOL	N		$\frac{N_{cal}-N_e}{N_e}$ %
		Calculation N_{cal}	Experiment N_e	
Matsuoka	●	114495	116124	- 1.40
Wheeler	○	114423		- 1.46
Maarse	□	104226		-10.25
Willenborg	▲	148800		+27.98
	▼	111281		- 4.19

Fig.3 Comparison of experimental data and model predictions of the relationship between crack growth behavior and number of cycles when $Q_{01} = 1.8$

It was also found that the experimental value of the effective PZS are considerably greater than the calculated values suggested by these models, as shown in Fig.4. At a given overload ratio, Q_{01}, the number of delayed cycles, N_D, caused by an overload decreases with an increase of K_{01} in the initial stage and then increases gradually. This change may be regarded as a transition from a plane strain to a plane stress condition[12].

IV. MODIFICATION OF THE WILLENBORG AND MAARSE MODELS AND THEIR APPLICATION TO LIFE PREDICTION

As stated in the previous section, the calculated fatigue lives by the Willenborg and Maarse models exhibite greater deviation from the expermen-

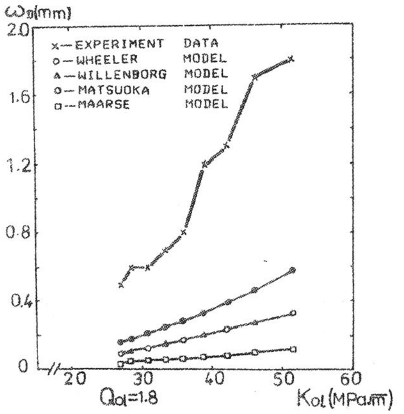


Fig.4 Comparison of experiment with models on the relationship between effective overload zone size and K_{01}

tal results than those by the other models. Hence, some modifications of the Willenborg and Marrse models are necessary.

4.1 Modification of the Willenborg Model

It is known that the overload PZS is an important factor to control the retardation effect and the PZS, γ_p, is generally expressed by,

$$\gamma_p = \frac{1}{\alpha\pi}\left(\frac{K}{\sigma_{ys}}\right)^2 \qquad (1)$$

where $\alpha = 2$ for pure plane stress condition and $\alpha = 6$ for pure plane strain condition.

Since the stress/strain condition of a specimen varies with ΔK (or crack length a) and stress ratio R, the coefficient α in the formula (1) used in the Willenborg model can be expressed by,

$$\alpha = \frac{6}{1 + 2S} \qquad (2)$$

where

$$S = \frac{\Delta K - \Delta K_{th}}{(1 - R)\ K_c} \qquad (3)$$

The parameter S may be regarded as the fraction of the plane stress region occupied in the fracture surface [12,13].

4.2 Modification of the Maarse Model

The formula used in the Maarse model based on the crack closure concept [4] was described as

$$\frac{da}{dN} = C^*(\Delta k_{eff})^{n^*} = C^*(K_{max} - K_{Op})^{n^*} \qquad (4)$$

where K_{Op} is the stress intensity factor corresponding to the crack opening load, P_{Op}; C^* and n^* are the experimental constants.

If we assume that the crack closure effect ratio, $C_f = P_{Op}/P_{max} = K_{Op}/K_{max}$, Then the Eq. (4) can be rewritten as follows:

$$\frac{da}{dN} = C^*[K_{max}(1-C_f)]^n \qquad (5)$$

According to the results reported by Bell and Greager [14], the slope of different values of R are approximately parallel to each other which imples that the variance of the experiment exponent n is rather small. For a first approximation, we may assume that

$$n^* = n \qquad (6)$$

and

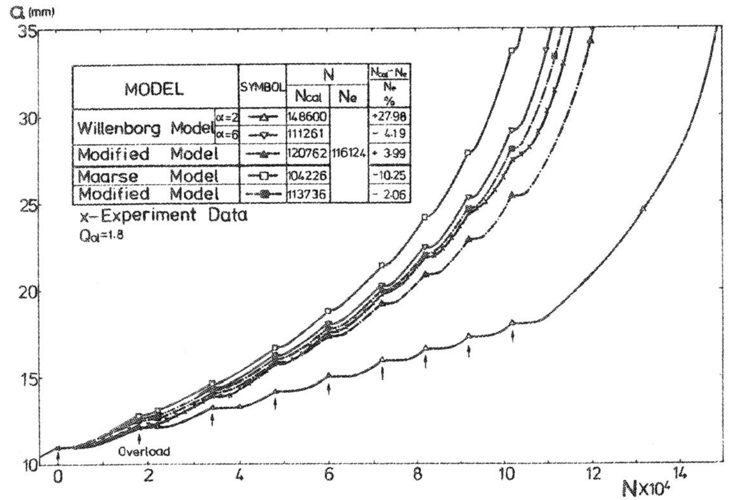
$$C^* = C\left(\frac{1-R}{1-C_f}\right)^n = C\left(\frac{1-R}{1-(\frac{P_{Op}}{P_{max}})}\right)^n \qquad (7)$$

where n and c are material constants obtained by the Paris' law under constant amplitude cyclic loading.

Meanwhile, the crack opening load, P_{Op}, and the ellipse equation used in the Maarse model can be also modilied by introducing the coefficient α [13].

4.3 Assessment of the Ability to Predict Fatigue Life

A comparison between the experimental a-N curve with the corresponding curves calculated by the original and modified models under a series of single tensile overloads (Q_{01} = 1.8) for Ti-6Al-4V is shown in Fig.5. In this figure, the number of cycles determined experimentally, N_e, the number of cycles calculated by different models, N_{cal}, and the relative errors



MODEL		SYMBOL	N: N_{cal}	N: N_e	$\frac{N_{cal}-N_e}{N_e}$ %
Willenborg Model	α=2	—△—	148600	116124	+27.98
	α=6	—▽—	111261		- 4.19
Modified Model		—▲—	120762		+ 3.99
Maarse Model		—□—	104226		-10.25
Modified Model		—■—	113736		- 2.06

Fig.5 Comparison of experiment data and model predictions of the relationship between crack growth behavior and number of cycles when Q_{01} = 1,8

$(N_{cal}-N_e)/N_e$, corresponding to these models are illustrated. It can be seen that the relative errors of modified models are much less than that of origional ones.

The retardation behavior and the crack opening load, P_{Op}, for a Ti-6Al-4V alloy under single tensile overload at Q_{01} = 2.0 were investigated, as shown in Fig.6. It was found that the modified Maarse model gives longer retardation period and exhibits less deviation from the experimental curve than the original model[13].

4.4 Life Prediction under Spectrum Loading

From an evaluation of life predictions for LY12-CZ Al alloy by two count methods and four types of simplified testing spectrums, it was found that the life predicted by the variable mean value and the two-wave method are in good agreement with the random spectrum loading [15].

In order to assess the ability to predict life by the present modified model, the linear accumulation method and the Matsuoka model [5] are employed for comparison.

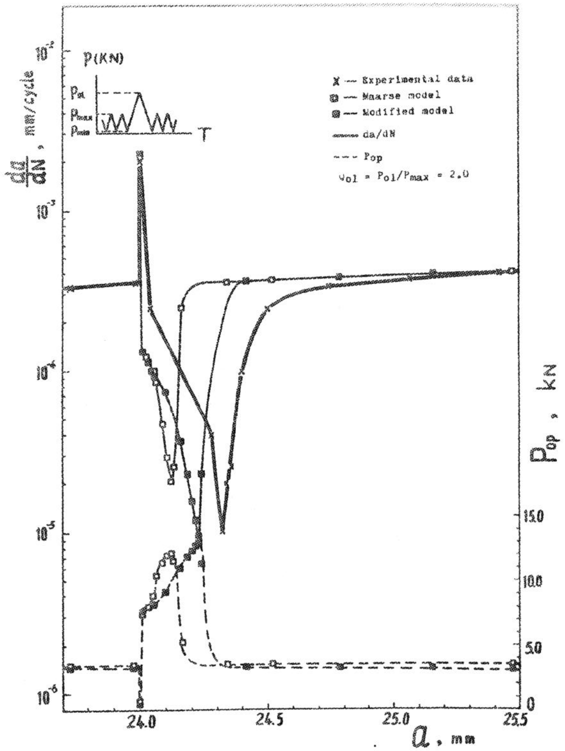


Fig.6 Comparison of da/dN and P_{Op} between the calculated and experimental results after a single tensile overload in a Ti-6Al-4V alloy, (Q_{01} = 2.0)

It was found that the linear accumulation method without considering the retardation effect, exhibits the greatest deviation from the experimental results. The life predicted by the Matsuoka model is not so promising as well. However, the results of two types of test spectrum calculated by the present modified model are fairly consistent with that of the 50 hrs random spectrum loading[15]. It is also worth noting that all the material constants used in the present modified model can be derived from the constant amplitude cyclic test, hence this model is relatively easy to be manipulated and could be used to predict life for engineering purpose.

V. MECHANISM OF CRACK GROWTH BEHAVIOR UNDER OVERLOADING

During the past decades, the following mechanisms have been proposed to explain the retardation behavior for fatigue crack growth under overloading [12]:

(1) crack tip blunting,

(2) crack closure effect,

(3) residual compressive stresses in front of the crack tip,

(4) strengthening by lattice flaws within plastic zone, and

(5) a synthetic retardation mechanism caused by a number of factors.

Recently, from some studies of fatigue crack tip region, fracture surfaces and dislocation structures within plastic zone in Al-Cu-Mg and Ti-6Al-4V alloys [16,17], it was found that the main causes of the retardation behavior and delayed growth may be ascribed to the following factors: (a) the closure stress behind the crack tip, (b) the compressive residual stresses in front of the crack tip and (c) the strain hardening effect in the overload plastic zone. The first two factors considerably reduce the effective stress intensity. The closure stress in the wake of the crack tip prevents the crack from opening and the compressive residual stresses ahead of the crack tip resist the crack from further extension. The strain hardening by lattice flaws within the plastic zone raises the stress intensity level for further deformation, consequently decreases the crack growth rate.

It was also recognized that the plastic zone size, r_p, the magnitude of the plastic strain, ε_3, and the number of delayed cycles, N_D, increase in an exponential function with the overload ratio, Q_{01}. The number of delayed cycles could be described by the following empirical expression [26]:

$$N_D = \ln N_0 \exp (m Q_{01}^2) \qquad (8)$$

A general mechanism of fatigue crack growth retardation behaviors under a tensile overload was also proposed in a separate paper [17].

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