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Numerical and experimental study on the optimization of overload parameters for the increase of fatigue life

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A R T I C L E   I N F O

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A B S T R A C T

Fatigue life and crack growth retardation due to periodic tensile overloads, which are superposed on constant amplitude cycles, have been investigated in the present study. In the numerical analyses, the Walker equation with the generalized Willenborg model has been used. The analyses and experiments have been performed on $C(T)$ specimens made of 7075 aluminium. The periodic overloads have been induced at two different periodicities and the effect of overload ratio and overload periodicity on the fatigue life has been studied. The results of the experiments and analyses reveal that the normalized fatigue life versus overload ratio curve has a maximum point, which indicates that there are greater retardation effects in the intermediate overload ratio values. Also, the numerical and experimental results indicate that at the occurrence ratios (the ratio of the number of overload cycles to the number of constant-amplitude cycles between overloads) of 1/50 and 1/500, the maximum interaction occurs at the overload ratios of 1.5 and 2.0, respectively.

1. Introduction

It has been estimated that 50 to 70% of machine and structure failures are due to fatigue [25]. Researches have shown that the fatigue failure of the critical locations of aircraft structures such as upper fuselage parts is the main cause of service life reduction in aircrafts [21]. An increase in the fatigue life of components can reduce the overall cost of a machine or an aircraft.

The study of the single overload case has two important aspects: first, the significant finding that the superposition of single tensile overload on the base loading results in crack growth retardation [2,4,12–14,19,24] or a full crack arrest [16] which leads to an increase in service life; and second, the study of the single overload effect on the crack propagation rate of subsequent cycles forms the basis for the study of the variable amplitude loading (VAL). It should be mentioned that the fatigue failure of common engineering components and structures is generally caused by the variable amplitude rather than the constant amplitude (CA) loading.

Fatigue crack behaves differently as the loading conditions of the single overload (SOL) change. For example, under certain conditions, the crack growth acceleration occurs following the application of the single overload [9,12,14], while in other circumstances, the initial acceleration is not observed [4,13]. Moreover, in most conditions, delayed retardation occurs after the application of the single overload; while in some cases, immediate retardation takes place.

Studies on the single overloading have revealed that the overload ratio (OLR) is the most effective parameter in the controlling of crack growth. This subject has been thoroughly studied by a great number of researchers [2,4,14,19]. All the investigations on single overloading indicate that the number of retardation cycles goes up with the increases of the OLR [2,8,19].

If the overloads are applied periodically, their interaction can increase or decrease the retardation effect. In addition to the overload ratio, the time interval between overloads is an important factor in periodic overloading as well [18,20,23]. In periodic overloading, the occurrence ratio (OCR) is defined as the ratio of the number of overload cycles to the number of constant amplitude cycles between overloads. Fleck [5] and Borrego et al. [3] have shown that crack growth acceleration occurs under the overloads that have a high rate of occurrence. Porter [10] has shown that retardation increases as the OCR^{-1} rises. On the other hand, experiments of Yildirim, Vardar, Tür, and Borrego et al. [3,18,20,23] have demonstrated that retardation increases and then decreases with the increase of the OCR^{-1}. However, the maximum retardation occurs when tensile overloads are applied at $\frac{1}{2}N_{\mathrm{D}}^{*}$, where N_{D}^{*} is the number of cycles of retarded growth in the single-peak overload test. For Al-alloy 7075-T6, they [23] also mentioned that the crack growth rate for different occurrence ratios follows

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Nomenclature

CAL	Constant amplitude loading
FCGR	Fatigue crack growth rate
OCR	Occurrence ratio
OLR	Overload ratio
POL	Periodic overload
SOL	Single overload
VAL	Variable amplitude loading
a	Crack length
B	Specimen thickness
C, n	Constant and exponent in the Paris equation
da/dN	Fatigue crack growth rate
$(da/dN)_{CA}$	Fatigue crack growth rate at constant amplitude loading
$(da/dN)_{POL}$	Fatigue crack growth rate at periodic overloading
F_{max}	Maximum load
K_C	Plane strain fracture toughness
K_{max}	Maximum stress intensity factor
$K_{max,\,th}$	Threshold stress intensity factor level
K_{OL}	Stress intensity factor at overload
m	Walker exponent
N_{CA}	Fatigue life at constant amplitude loading
N_D^*	Number of cycles of retarded growth in the single-peak overload test
R	Ratio of minimum to maximum stress
s^{OL}	Overload shut-off ratio
W	Specimen width
ΔK	Stress intensity factor range
ΔK_b	Base line stress intensity factor range
$\Delta K_{effective}$	Effective stress intensity factor range

a constant-amplitude loading behavior with a parallel shift, which can be modeled as a pseudo-constant-amplitude crack growth.

Few researches in the field of periodic overload (POL) have shown that, at a constant occurrence ratio, the specimen fatigue life improves with the increase of the OLR. The experiments of Smith [15] on $M(T)$ specimens made of Ti 8Al–1V–1Mo, in which periodic overload is applied with $OCR^{-1} = 30$, have demonstrated that the specimen life increases as the OLR goes up. In addition, the experiments of Yildirim and Vardar [23] on $C(T)$ and $M(T)$ specimens made of AL 7075–T6 alloy have shown that the specimen life improves with the increase of the OLR and that the peak normalized life of the specimen at various occurrence ratios falls on a straight line when plotted on a log–log scale versus the overload ratio. Yuen and Taheri [24] have pointed out the duration between the overloads and the frequency of overloading as critical parameters in the maximization of crack growth retardation where the effects of the overload ratio on the maximization of fatigue life have been disregarded.

So far, the abovementioned results indicate that in periodic overloading, fatigue life increases with the increase of overload ratio. However, considering the increase of crack jump during the overload cycle, compared to the retarded growth at high levels of OLR, it seems that there is an optimum OLR which can maximize the interaction between the overloads and the lifetime. Considering the great influence of fatigue failure on industrial expenditures, the finding of such a point will be of great importance. Hence, the main goal of this research is to find this optimum overload ratio in various loading conditions. To this end, two different loading conditions were investigated in this paper.

2. Numerical procedure

Investigations of fatigue tests and fatigue crack growth rate (FCGR) are very expensive and time-consuming. Hence, in order to save on time and cost, a numerical study was carried out on a $C(T)$ specimen before performing the tests. In this study, an optimum OLR, which maximizes the interaction between the overloads, was obtained numerically, and then the tests were carried out around this optimum OLR.

AFGROW [1,7], one of the most widespread software programs in this field, was utilized to predict the crack growth rate. Among different kinds of crack growth equations that are available in this program, the Walker equation was used. The Walker equation [22] is essentially an enhancement of the Paris equation that included a means to account for the effect of Stress ratio (minimum stress/maximum stress) on crack growth rate.

$$\frac{da}{dN} = C\left[\Delta K(1-R)^{(m-1)}\right]^n; \quad \text{for } R > 0 \tag{2.1}$$

The range of possible crack growth rate values is controlled by ΔK threshold and the plane stress fracture toughness (K_C) – both at $R = 0$. AFGROW calculates ΔK threshold and ΔK_C for each R value using the crack growth rate for each term at $R = 0$. These crack growth rates determine the lower and upper bounds on crack growth rate values. Points below the lower limit ($<\Delta K$ threshold) will be assumed to result in no crack growth rate, and those above the upper limit will be assigned a crack growth rate value equal to the upper limit.

The constant-amplitude crack growth rate was determined experimentally by $da/dN = 3.002 \times 10^{-7}(\Delta K)^{3.244}$, where da/dN is in mm/cycle and ΔK is in MPa $\sqrt{\text{m}}$.

To take the interaction effect into account, the generalized Willenborg retardation model was employed [6]. This model is one of the most common retardation models used in the crack-growth life prediction programs. The Willenborg model is based on early fracture mechanics works performed at the Wright–Patterson AFB, OH, and it was named after a student who worked on the model. The generalized Willenborg model utilizes an 'effective' stress intensity factor based on the size of the yield zone in front of the crack tip. In this model, there are two empirical constants: $K_{max,\,th}$, which is the threshold stress intensity factor level associated with zero fatigue crack growth rate, and s^{OL}, which is the overload shut-off ratio required to cause crack arrest for the given material. The typical value of s^{OL} for aluminium is 3.0 [7]. Ideally, s^{OL} should be a material parameter insensitive to spectrum or stress level; however, this isn't always true. It should be noted that the combination of walker equation and Willenborg retardation model is adopted from the works of Ray [11].

The baseline constant-amplitude loading consists of cycles with a maximum load (F_{max}) of 700 N, and a stress ratio of 0.11. Table 1 shows the OLRs (defined as: $OLR = K_{OL}/K_{max}$) and the OCRs used in the numerical study, and Figs. 1(a) and (b) illustrate the influence of the OLR in terms of the crack length versus the number of cycles for $OCR^{-1} = 50$ and 500, respectively. As shown in Fig. 1(a), with the increase in overload ratio from $OLR = 1$ to $OLR = 1.5$, the fatigue life increases. This fact was also concluded in other studies [15,20]. However, a further increase in the overload ratio toward $OLR = 1.85$ results in a considerable decrease in the fatigue life compared to that at $OLR = 1.5$. Moreover, Fig. 1(b) shows that there is an increase in lifetime as the amount of the OLR gets up to 2.0, but that a further increase in the OLR (from 2.0 to 2.25) results in a noticeable decline in the lifetime.