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PREDICTION OF FATIGUE CRACK GROWTH BEHAVIOR IN AN ALUMINIUM ALLOY UNDER SPECTRTUM LOADING

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Abstract When the aircraft is in the service, the components are subjected to spectrum loads. The analysis of crack growth rates under spectrum loading is very important to estimate the life of the component. To study the fatigue crack behavior under spectrum loads, it is necessary to know the behavior in constant amplitude loading at various stress ratios. Fatigue crack growth rate at constant amplitude for an aluminium alloy of BS-L73 were determined at various stress ratios. The tests were performed using single edge notch specimens SEN (T) in a 50kN servo-hydraulic INSTRAN testing machine. Crack length has been measured by both traveling microscope and replication technique. It is observed that the fatigue crack growth rates increases and the threshold stress intensity range decreases with increase in stress ratio. A hypothetical spectrum load sequence was generated and theoretical estimation of crack growth under this spectrum load sequence has been made by using constant amplitude fatigue crack growth data. Also, fatigue crack growth behavior under spectrum loading sequence was determined experimentally. A comparison of the theoretical and the experimental results of crack growth under spectrum loading shows that the estimation was highly conservative. This behavior was explained on the basis of effect of overload on fatigue crack growth rates.

Key words: Fracture Mechanics, Spectrum loading, Fatigue crack, Stress Intensity Factor.

NOMENCLATURE

a = crack length
da/dN = crack growth rate
K = stress intensity factor
K_{1c} = critical stress Intensity factor in mode I
K_{max} = maximum stress Intensity factor
ΔK = stress intensity factor range
ΔK_{cr} = critical stress intensity factor range
P_{max} = maximum load
P_{min} = minimum load
R = stress Ratio
T = thickness of the specimen
w = width of the specimen
ε_{max} =Maximum strain
ε_{min} = Minimum strain
$\Delta\varepsilon$ = Strain Range

INTRODUCTION

Spectrum Load

The term load spectrum is frequently used in fatigue studies. It means a curve giving the variation of load as a function of time. The number of crossing of a value or the number of reversals per unit time is taken as a measure. Most time varying loads in reality are not a perfect sinusoidal curve. In fact most are random fluctuating in times. In case of airplane the spectrum loads occurs mainly due to the cabin pressurization and maneuvering loads. As the plane takes to flight from the ground, the inside cabin pressure remains constant. However, the outside atmospheric pressure decrease with the altitude resulting in a general expansion of the vehicle, Gusts are suddenly encountered burst of wind with turbulence, which are highly random and chaotic in nature. Notice that the landing impact is the most severe dynamic loading, since the loads are sharply varying with time. They are bound to contain a wide range of frequencies. The standard discrete Fourier analysis analyzes the random functions numerically, especially with a modern computer. From the total frequency response, the dominant few frequencies can be selected for the fatigue testing and experimentation, using standard fatigue testing machines.

THE CONSTANT LOAD AMPLITUDE TEST

The field of fracture mechanics deals with the strength of structure in presence of flaws. It provides the appropriate failure correlating parameters. In linear elastic fracture mechanics the fracture is solely described through stress intensity factor K, the one parameter that characterizes the crack tip field uniquely. Where as in case of cyclic loading, the crack tip field is completely characterized by any of the following pairs of crack tip strain variables ($\varepsilon_{max}, \varepsilon_{min}$), ($\varepsilon_{max}, \Delta\varepsilon$) or any other combination. The essential point is that, there are only two crack tip strain variables to which material response to the fatigue loading can be correlated, one can write

$$\frac{da}{dN} = f\,(\varepsilon_{max}, \Delta\varepsilon)$$

Paris and Erodogon (2) demonstrated ΔK to be the better correlating parameter compared to K_{max}, highlighting the cyclic nature of the fatigue crack growth process. They proposed this type of relationship expressed as

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

Where 'c' and 'm' are experimentally determined constants. The schematic variation of fatigue crack growth rate da/dN with alternating stress intensity range ΔK is drawn in log-log plot as shown in figure (1). It has a sigmodial shape and depends on the given material. If we get da/dN ~ ΔK plot, as shown in figure (2), we can characterize the given material for fatigue characteristics. Later it is found that, this plot depends also on applied stress ratio i.e., ($R = \sigma_{min}/\sigma_{max}$). It is known that, there is no static mode of crack extension under cyclic loading below K_{1c} and fatigue crack growth, depends only on ΔK and not on the K_{max}. The ΔK_{cr} corresponding to K_{1c} at any stress ratio is given by

$$\Delta K_{cr} = K_{1c}\,(1 - R)$$

With an increase in the stress ratio, ΔK_{cr} decreases and therefore a family of da/dN~ ΔK curve depends on stress ratios obtained.

MATERIAL

The material used in this investigation is widely used in airframes. (BS-L73 aluminium-copper alloy)

Chemical Composition

Alloying Element	Copper	Magnesium	Silicon	Manganese	Aluminum
% By weight	4	0.75	0.8	0.8	Balance

Mechanical Properties Of Bs-L-73 Al-Cu Alloy

Ultimate tensile strength	Elongation	Proof strength 0.2%
400 MPa	8 %	310 MPa

Specimens of 90 * 45 * 2.5 mm were cut from a sheet, and a notch of 3 mm was made at the mid length using wire EDM. It is as shown in the fig 5.

CALCULATION OF STRESS INTENSITY RANGE

The stress intensity range experienced by the crack during the test was calculated from the equation

$$\Delta K = \Delta\sigma\,\sqrt{\pi a}\;f\,(a/w)$$

Where $\Delta\sigma$ is the applied alternating stress ($\sigma_{max} - \sigma_{min}$)

$\Delta\sigma$ is calculated by

$$\Delta\sigma = \frac{P_{max} - P_{min}}{w * t}$$

$$\text{And}\quad f\,(a/w) = \frac{5}{\left[20 - 13(a/w) - 7(a/w)^2\right]^{\frac{1}{2}}}$$

Where 'a' is crack length at that instant and 'w' is width of the specimen in mm

Constant Amplitude testing

All the test was conducted using a closed servo-hydraulic INSTRAN testing machine at a frequency of 4Hz. The SEN (T) specimen was tested at stress ratio of R=0.7, 0.5 and 0.3 under constant amplitude. Crack length was measured with the help of traveling microscope with 100X magnification. Care is taken to record crack extension not greater than 0.2mm. At the end of test a record of crack length and associated number of cycle is available. The 7th degree polynomial is fitted to this data to get smooth curve in da/dN ~ ΔK plots. The da/dN ~ ΔK correlation for various stress ratios is as shown in fig (2). The variation in curves in the Paris region is entirely due to the effect of stress ratio. It can be clearly observed that for given stress intensity factor range, the crack growth rate was higher in stress ratio of 0.7 than for the stress ratios 0.5 and 0.3. The reason for lower crack growth rate into the stress ratios of 0.5 and 0.3 than 0.7 is due to crack closure occurs at the lower stress ratios.

SPECTRUM LOADING

We know that crack growth rate (da/dN) are uniquely related to the stress intensity factor range ΔK and stress ratio R. Material crack growth behavior is generally obtained in the form of a family of crack growth rate, da/dN vs ΔK curve covering a range of stress ratios. The spectrum load history applied on the aircraft component can be converted to local area nominal stress history of the component by stress analysis technique. The local nominal stress history can be converted to the stress intensity factor history for any crack size. Analytical and experimental techniques are available to do this. It may be observed that the stress intensity factor is a linear function of nominal stress. Hence the stress intensity factor, when normalized with respect to applied nominal stress, will become purely a function of geometry of the local cracked area in the component and the crack size. This means,

K/σ or K/P = f (size &shape of crack, local area & geometry, loading configuration)

Hence K/σ or K/P can be considered to characterize the 'structural configuration property'.

Once the material crack growth behavior data in the form of da/dN ~ ΔK curves and structural configuration property data in the form of ΔK/Δσ ~ a, curve are available, it is easy to predict the crack growth and life of the structural component.

The procedure for calculating crack growth under the spectrum loading from an assumed initial crack length up to final fracture is as follows. The calculation starts with the selection of a unit time of the stress history called ‘a block of load’ and an assumed initial crack length. The stress history of ‘unit time’ interval is analyzed to deduce the relative frequency of occurrence of different stress ranges or amplitudes. This is obtained in the form of a table giving number of cycles n_1, n_2, …………..n_n of stress ranges $\Delta\sigma_1$, $\Delta\sigma_2$, $\Delta\sigma_3$,……………. $\Delta\sigma_n$ contained in the stress history in unit time. Then for the initial crack length selected, the ΔK / Δσ is obtained from the structural configuration property plot. Using this value of ΔK / Δσ the value of ΔK_1, ΔK_2, ΔK_3… ΔK_n are calculated. The growth rates $(da/dN)_1$………$(da/dN)_n$ corresponding to these values of ΔK_1, ΔK_2, ΔK_3, …… ΔK_n are then obtained from the number of cycles of different stress range $\Delta\sigma_1$, $\Delta\sigma_2$, $\Delta\sigma_3$,……$\Delta\sigma_n$ are known. The growth increments due to these ranges are easily calculated from the growth rates as $\Delta a_1 = (da/dN)_1\, n_1$, $\Delta a_2 = (da/dN)_2\, n_2$, etc. The total growth increment during the unit time is obtained by summation of different growth increments. Crack length, a_1, after the first unit time is obtained by adding the growth increments to the initial crack length a_o. This procedure is repeated to obtain the growth increment for the second unit of time (block). The new crack length a_2 is then obtained by adding this increment to a_1. The procedure is repeated. Finally we obtain a plot of crack length versus time or duration of service experience. Since this prediction technique is based on crack growth behavior under constant amplitude loading it becomes essential to identify individual load cycles from the random sequence of peaks and troughs defining the load of stress history. There are many methods available to find the load cycles. The most widely used is Rainflow cycle counting method.

CYCLE COUNTING IN FATIGUE ANALYSIS

Cycle counting is used to summarize irregular Load versus time histories by providing the number of times cycles of various sizes occur. The definition of a cycle varies with the method of cycle counting. There are various methods of cycle counting in fatigue. They are

- Level – crossing counting
- Peak counting
- Simple range counting
- Rainflow counting

In the above methods, Rainflow cycle counting method is widely used

EXPERIMENTAL INVESTIGATION

A hypothetical spectrum load sequence was generated which consists of 100 cycles and is made as one block of cycles, which is shown in the fig (3). A program was developed to count the cycles using Rainflow cycle counting method. The result from the program is used to estimate theoretically the crack growth for unit block of spectrum load sequence, by using constant amplitude fatigue crack growth data. The spectrum load sequence data, which was generated hypothetically is used experimentally to determine the fatigue crack growth behavior under servo hydraulic INSTRAN machine. The data of crack length versus Number of blocks of cycles is noted.

RESULT AND DISCUSSION

The comparison of theoretical and experimental results of the crack growth under spectrum loading is shown in figure (4) that the estimation was highly conservative. This is due to the effect of the overload on the fatigue crack growth rate. A single tensile overload cycle in a load sequence causes a retardation or delay in crack growth propagation. It was noticed that the retardation effect was confined to crack extension equal to the overload plastic zone length in line with the crack. The retardation effect is in the wake of the residual plastic deformation left by the overload which causes crack closure. The overload cycle affects the effective stress intensity range of the following load cycles. The retardation effect is also influenced by the load amplitude prior to the overload. Retardation increases, if the amplitude of the load cycle prior to overload cycle is increased. Retardation also increases with the number of overloads cycles. In general it has been observed that the tensile overload cycles produce retardation or delay in subsequent crack growth. The extent of retardation can be increased right up to complete crack arrest by

- Increasing the tensile overload level
- Increasing the number of overload cycles
- Applying the overload cycle at intervals

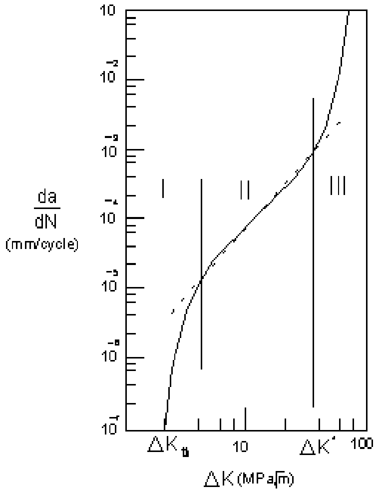

Fig. 1 Schematic curve of da/dN –ΔK curve

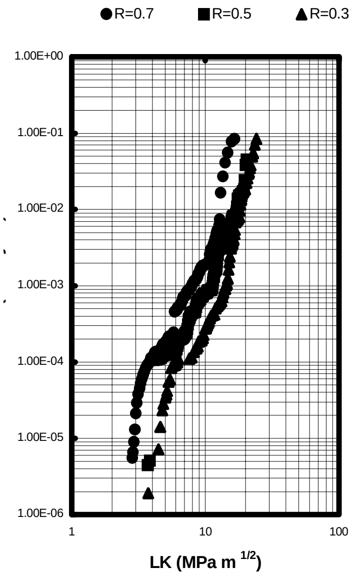

Fig. 2 Stress Ratio Effect on da/dN ~ LK Correlation

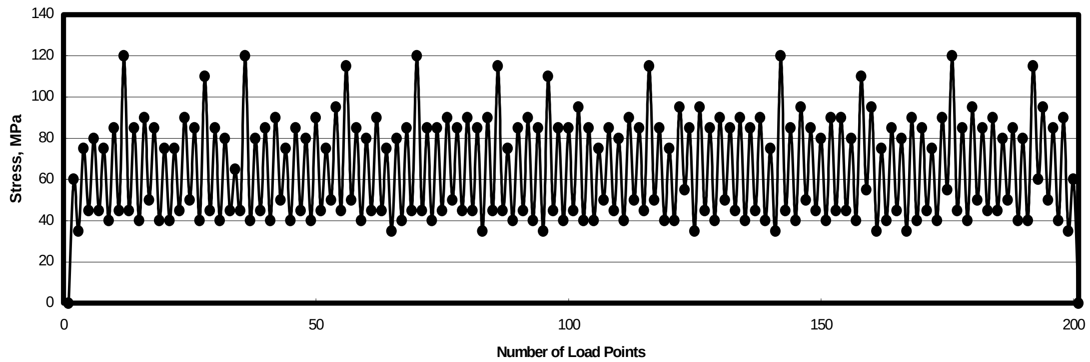

Fig.3 Spectrum Load Sequence

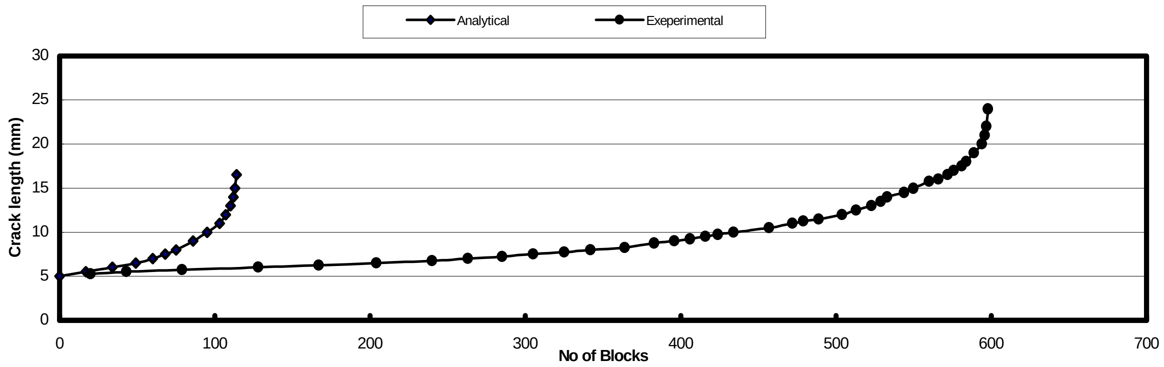

Fig. 4 Crack Length versus No. of blocks in spectrum loading

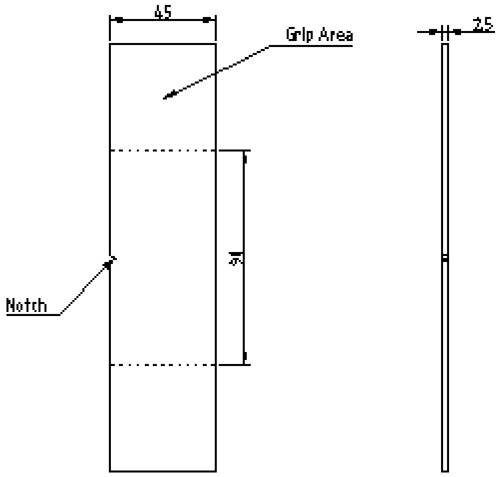

Fig. 5 Specimen used for testing

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