FATIGUE CRACK GROWTH PREDICTION UNDER FALSTAFF LOAD SEQUENCE BY K*-RMS APPROACH

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ABSTRACT

Fatigue crack growth behavior in a single edge notched tension specimen of an airframe grade D16 aluminum alloy under the standard FALSTAFF aircraft load sequence was predicted. Considering K* as the crack driving force parameter, the crack growth law was obtained from the constant amplitude fatigue crack growth rate (FCGR) test data. The FALSTAFF spectrum load sequence was approximated as equivalent constant amplitude (CA) load sequence with maximum and minimum stresses as root-mean square (RMS) maximum and minimum stresses of the spectrum, respectively. The crack growth behavior was then predicted under this apparent CA load sequence through cycle-by-cycle estimation. The analysis was performed for various reference stress levels. For comparison, conventional crack closure approach where the crack growth law in terms of effective stress intensity factor, ΔK_{eff} along with constant crack opening level, K_{op} concept for the spectrum was used to predict the growth behavior. In general, fatigue crack growth life predicted by the proposed K*-RMS approach was comparable to that predicted by conventional crack closure approach within the allowable scatter limits. The simplicity of the K * -RMS approach is quite encouraging. Comparison of predicted results with experiments and the applicability of this approach to other types of spectrum loads need to be investigated further.

Key words: *Fatigue crack growth, FALSTAFF, Root mean square, Aluminum alloy*

1. INTRODUCTION

Increasing demand for lighter and efficient aircraft structures is forcing design engineers to shift focus on damage tolerant as against safe-life design concepts. The structure is evaluated for the residual strength in presence of defects like cracks. The growth behavior of these cracks under service loads is investigated and the residual strength of the component as a function of time or crack size is estimated. Structural components are designed based on such information so that it is safe within the specified lifetime.

Fatigue crack growth behavior under spectrum loads could be estimated using well-developed fracture mechanics principles. The general procedure of cycleby- cycle method employed for fatigue crack growth life prediction can be found elsewhere [1]. Conventionally, Elber’s crack closure concept [2], a phenomenon occurring behind the crack tip, is widely employed is such calculations. Though it has been able to model and predict growth behavior under spectrum loads fairly well, the recent advances made in the understanding of crack closure has raised the debate on use and applicability of this concept [3-7].

Alternatively, analytical models for crack growth predictions based on plastic zone and deformation behavior ahead of the crack tip utilize crack driving force parameters as ΔK and K_{max} to account for crack extension and load-interaction effects [1],[8]. Recently, it has been shown [9],[10] that crack driving force parameter K* can account for effects of stress-ratio on constant amplitude FCGR in many materials. In this investigation, K* is used to predict FCGR behavior under a combat aircraft load sequence in an aluminum alloy. For the sake of comparison, FCG behavior was predicted by conventional crack closure approach as well. It will be shown that K* -RMS approach provides similar results as compared to conventional method.

2. FALSTAFF LOAD SEQUENCE

The original FALSTAFF load sequence [11] is shown in Figure 1. This spectrum was produced from actual flight records of the wing-root loads from four different types of fighter aircraft on a variety of missions. The data were normalized and simplified in various ways to give a uniquely defined sequence of relative loads. This one block represents 200 flights.

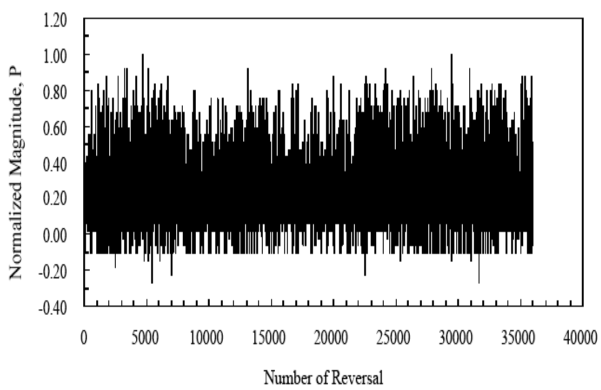

Figure 1- The standard FALSTAFF load sequence [11]

The total number of load reversals is 35,966. For the sake of analysis, the reference stress, sref was set to a particular value ranging from 130 MPa to 220 MPa) corresponding to 1.0 and all the other reversal points were correspondingly multiplied to obtain the stress pattern.

3. FCG PREDICTION PROCEDURE

The material used in this investigation was a D16 (equivalent of 2024-T3) aluminum alloy, which is mainly used in airframe construction. The chemical composition (wt%) of the material was as follows: Cu- 3.8-4.9, Mg- 1.2-1.8, Mn- 0.3-0.9, Si-0.5, Fe-0.5, Zn 0.3 and balance is aluminum. Further details of the material and specimen geometry considered are shown in Table 1 . The stress intensity factor, K for an SENT specimen was calculated as [12]

$$K = f\left(\frac{a}{W}\right)\sigma\sqrt{(\pi a)} \qquad (1)$$

Where,

$$f\left(\frac{a}{W}\right) = \frac{5}{\left[\left(20 - 13\left(\frac{a}{W}\right) - 7\left(\frac{a}{W}\right)^2\right)^{0.5}\right]} \qquad (2)$$

3.1 K*-RMS Approach

The crack driving force parameter K* is defined as [9]

$$K^* = [(\Delta K^+)^\alpha \ (K_{max})^{1-\alpha}] \qquad (3)$$

Where, ΔK^+ is the value of the positive part of applied SIF range and, K_{max} is the corresponding maximum value of the applied SIF. For aluminum alloys, a value of $\alpha = 0.5$ provides a fairly good correlation for R-ratio effects [9, 10]. The fatigue crack growth law in terms of K* is expressed as [1]

$$\frac{da}{dN} = C_1\left(K^*\right)^{C_2} \frac{\left[1 - \left(\frac{K^*_{th}}{K^*}\right)^2\right]}{\left[1 - \left(\frac{K^*}{C_3}\right)^2\right]} \qquad (4)$$

The spectrum load sequence was approximated as equivalent constant amplitude (CA) load sequence with maximum and minimum stresses as root-mean square (RMS) maximum and minimum stresses of the spectrum, respectively. The maximum and minimum RMS stresses were estimated as [13]

$$\sigma^{RMS}_{Max} = \left[\frac{1}{N}\sum_{i=1}^{N_r}\left(\sigma_{max}\right)^2\right]^{0.5} \qquad (5)$$

$$\sigma^{RMS}_{Min} = \left[\frac{1}{N}\sum_{i=1}^{N_r}\left(\sigma_{min}\right)^2\right]^{0.5} \qquad (6)$$

Table 1- Details of the material and specimen used for crack growth prediction

Details of the Material		Specimen geometry details, mm		
Type of Material	Al-Cu alloy (2024-T3)	SENT	Width	45
Yield Strength, σ_y	347 MPa		Thickness	1.5
Tensile Strength, σ_{UTS}	460 MPa		Initial Crack length	4

For the normalized spectrum, the calculated. RMSmax was 0.3513 and the RMSmin was 0.1497. The reference stress was set to values ranging from 130 MPa to 220 MPa. For each of this sref, the RMS stresses were calculated. The crack growth under this apparent CA load sequence was estimated from eqn. (4). The total number of reversals in the original load sequence was 35,966 and hence, application of 17,983 apparent CA load cycles was considered as an equivalent to completion of one block of spectrum load sequence. Thus, crack length was predicted at the end of every block of loading to obtain 'a' Vs 'N_b' data

3.2 Crack Closure Approach

For the sake of comparison, crack growth predictions were made from conventional crack closure based method. In this approach, the crack driving force is considered as $\Delta K_{eff} = (K_{max} - K_{op})$ and the crack growth law in terms of ΔK_{eff} is given by [14]

$$\frac{da}{dN} = C_4\left(\Delta K_{eff}\right)^{C_5} \frac{\left[1 - \left(\frac{\Delta K^{th}_{eff}}{\Delta K_{eff}}\right)^2\right]}{\left[1 - \left(\frac{\Delta K_{eff}}{C_6}\right)^2\right]} \qquad (7)$$

Though crack opening stress varies cycle-by-cycle in a spectrum load sequence, assumption of constant Kop has been found to provide reasonably good results [15]. The constant Kop level for the spectrum load sequence was obtained from the following equations [16].

$$\gamma = K_{op} / K_{max} = \sigma_{op} / \sigma_{max} = 1 - (1\text{-}R)\ U(R) \qquad (8)$$

$$U(R) = 0.55 + 0.33\ R + 0.12\ R^2 \qquad (9)$$

In the FALSTAFF load sequence considered, the minimum stress ratio, R = -0.2667/1.0 = -0.2667 and hence g=0.404. For a reference stress of 130 MPa, the calculated sop = 52.52 MPa. The amplitude of all the load cycles in the FALSTAFF load sequence, above this crack opening stress level was obtained by rain flow counting method. The crack extension for each of this cycle was obtained from eqn (7). Thus, crack length was predicted at the end of every block of loading to obtain ‘a’ Vs ‘N_b’ data. Similar calculations were made for other reference stresses as well.

4. RESULTS AND DISCUSSION

The constant amplitude fatigue crack growth rate data at various stress ratios in D16 aluminum alloy, determined by the authors [1] in an earlier investigation, is shown in Figure. 2. In order to determine the constants in eqn. (4) and in eqn. (7), this FCGR data was re-plotted as a function of K* and ΔK_{eff} in Figure. 3 and Figure. 4 respectively. The values of the constants determined by fitting the sigmoidal shape of the curve are as follows. C_1= 1.76 x 10-8, C_2 = 3.71,

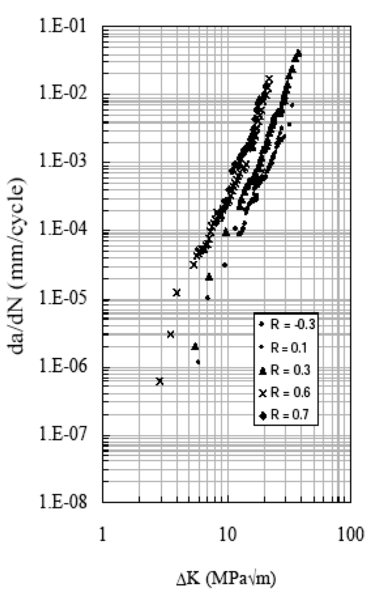

Figure 2 - Constant amplitude fatigue crack growth rate data for D16 aluminum alloy [1]

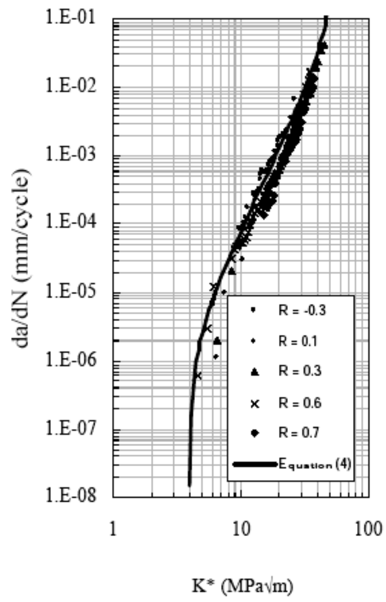

Figure 3 - FCGR data plotted as a function of K* for D16 aluminum alloy

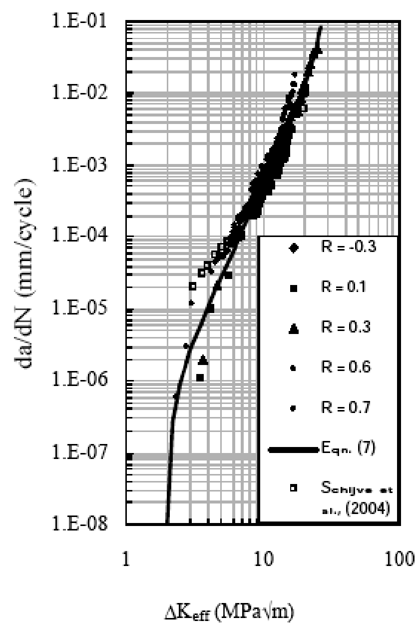

Figure 4 - FCGR data plotted as a function of ΔK_{eff} for D16 aluminum alloy

C_3 = 55.0, K^*_{th} = 4.0, C_4= 7.53 x 10-8, C_5 = 3.81, C_6 = 30.25 and $\Delta K_{eff\ th}$ = 2.0. Fatigue crack growth behavior under FALSTAFF load sequence predicted in SENT specimen of D16 aluminum alloy by K*-RMS method as explained above is shown in Figure. 5. Results obtained by conventional crack closure method are also shown in this Figure. The total fatigue crack growth life determined by both these methods for various reference stresses are shown in Table 2. It can be observed that

K*-RMS approach show comparable crack growth behavior as that of conventional method, considering the scatter in life prediction methods can vary from 0.5 to 3.0 times [18].

Table 2 - Predicted crack growth lives

Reference stress (MPa)	Crack growth life (No. of blocks)		Ratio (K*-RMS) / (Closure)
	K*-RMS method	Closure method	
130	84	98	0.85
145	43	62	0.69
156	30	45	0.66
175	17	27	0.62
190	12	19	0.63
220	6	8	0.75

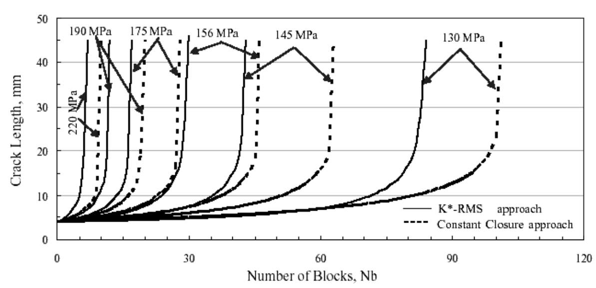

Figure 5 - Fatigue crack growth behavior predicted by two different methods in SENT specimen of D16 aluminum alloy under FALSTAFF load sequence

The crack growth life predicted by K*-RMS method is always conservative compared to that predicted by the closure method. The ratio of life predicted by K*-RMS method to conventional method varies from 0.62 to 0.85 (Table 2) for the reference stresses ranging from 130 MPa to 220 MPa. In spite of using a characteristic approach, the results obtained are quite acceptable. Further improvement in prediction accuracies may be obtained by using models based on K* parameter which account for load interaction effects.

The K* - RMS method is quite simple and appears to be reasonably accurate. However, it may be noted that the RMS approach for crack growth prediction under spectrum loading should be used with caution [13]. Also, these predictions need to be compared with experimental results. Further, applicability of this method for fatigue crack growth behavior prediction under other types of spectrum loads also need to investigated

5. CONCLUDING REMARKS

Fatigue crack growth behavior in an aluminum alloy under a combat aircraft load sequence was predicted by K*-RMS approach as well as conventional closure based method. The effect of varying reference stress on growth prediction was investigated. It was observed that the results obtained through the proposed K*-RMS approach is conservative and comparable to those predicted by the conventional crack closure approach. However, further predictions under other types of load sequences along with experimental evidence are required to investigate the suitability of this method

6. ACKNOWLEDGEMENTS

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