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Fatigue Crack Growth Simulation of Aluminium Alloy under Cyclic Sequence Effects

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1. Introduction

During service time machine and component failures may occur, that cause the structure breakdown. This generally yields enormous economical costs and sometimes in worst-case scenarios evens the death of human beings. Frequently such damage events originate from misconstructions, manufacturing and material failures, inappropriate fatigue strength calculations, overloads or other problems during service time or maintenance. Beginning from already existing or newly originating flaws, often extended fatigue crack growth (FCG) occurs due to service loads. Finally, the functional capability of structures and components is lost with the already mentioned consequences. In case of existing damage events, it is of major importance to fundamentally analyse them in order to obtain valuable information on structural improvements. Therefore, the knowledge about the real global and local loadings, the relevant material parameters and the initiation and growth of cracks under various general loading situations is essential. By fracture mechanics the development of FCG processes than can be reconstructed. So it is possible to improve the strength optimised and fracture safe design of structures and components. This goal can ideally be achieved by a composition of numerical and experimental simulations.

FCG in structure components, which is subjected to variable amplitude (VA) loading, is a complex subject. Studying of FCG rate and fatigue life calculation under the spectrum loading is vital in life prediction of engineering structures at higher reliability. The ability to understand and predict fatigue life remains a key technical factor in maintaining aircraft fleets, which are required to safely operate up to their design lives, and sometimes beyond. The load spectra applied to this aircraft are complex and highly variable, and experience has shown that traditional fatigue prediction tools do not always perform well in calculating the lives of modern, highly optimised airframes.

The main aim of this chapter is to address how to characterise the load sequence effects in fatigue crack propagation under VA loading and to select appropriate model from the large number of FCG models with validation of it. Thus, a fatigue life under various load spectra, which was predicted, based on the Austen, modified Forman and NASGRO models. This article analyses FCG under random loading using experimental results taken from literature on the subject and from growth simulations carried out based on different FCG models. These models are validated with the literature-based FCG test data in 2024-T3 aluminium alloys under spectrum loadings. This work summarises recent FCG models that appear to

be capable of producing more accurate fatigue life predictions using those loadings. With the consideration of the load cycle interactions, Load cycle interactions can have a significant effect in FCG under VA loading. Finally, the results show a good agreement in the behaviour with small differences in fatigue life compare to the test data and the previous literatures.

2. Literature review

Fatigue performance of structures is greatly affected by the presence of stress raisers such as fastener holes, manufacturing errors, corrosion pits, and maintenance damage, which serve nucleation sites for fatigue cracking. During service, sub-critical cracks nucleate from these sites and grow until catastrophic failure (unstable crack growth) takes place when the crack length reaches critical dimension. From economic point of view a costly component cannot be retired from service simply on detecting a fatigue crack. Hence, reliable estimation of fatigue crack propagation and residual life prediction are essential so that the component can timely service or replaced. VA loading involves load interaction effects and significantly affects the FCG and consequently, the fatigue life leading to either retardation (an overload tensile in nature) or acceleration (an under load compressive in nature) or reduction in retardation (an overload followed by an under load).

Nowadays, the study of FCG rate and fatigue life calculation under the spectrum loading is very important for the reliable life prediction of engineering structures. A number of load interaction models have been developed to correlate FCG rates and predict crack growth under VA loading over the past three decades. It is difficult to model all the parameters influence FCG correctly due to the random nature of VA loading. It overloads are known to retard crack growth, while under loads accelerate crack growth relative to the background rate. These interactions, which are highly dependent upon the loading sequence, make the prediction of fatigue life under VA loading more complex than under constant amplitude (CA) loading. The prediction of life is a challenging job for the engineering community because of two reasons. Firstly, it involves a robust integration scheme; secondly, no single universal method is available as far as the different load interaction mechanisms are concerned.

Many models have been developed to predict the fatigue lives of components subjected to VA loadings [James & Peterson, 1997; Paris, et al., 1999; Sadananda & Vasndern, 1999; Taheri, et al., 2003]. These models can be generally divided into global analysis and cycle-by-cycle analysis (see Fig.1). In particular, the global analysis concept predicts the FCG, considering the average of the applied loading cycles, while the cycle-by-cycle analysis evaluates the crack growth for each load cycle and determines the crack growth life by accumulation. The cycle-by-cycle analysis can be performed with or without involving the interaction effects, i.e. the effect of a load cycle on the crack growth in later cycles. A well-known interaction effect is caused by an overload on crack growth in the subsequent load cycle. The models that take interaction effects into account can be divided into three main categories namely yield zone models, crack closure models and strip yield models [Murthy, et al., 2004].

The earliest of these are based on calculations of the yield zone size ahead of the crack tip, and they are still widely used in many applications and research. The Wheeler model [1972] and Willenborg et al. model [1971], for example, both fall into this category. The Willenborg model, on the other hand, does not incorporate any empirical parameters, but it uses the material yield stress to give a plastic zone size [Corbly & Packman, 1973; Rudd & Engle, 1981; Chang, et al., 1981]. The amount of retardation is determined as a function of the stress

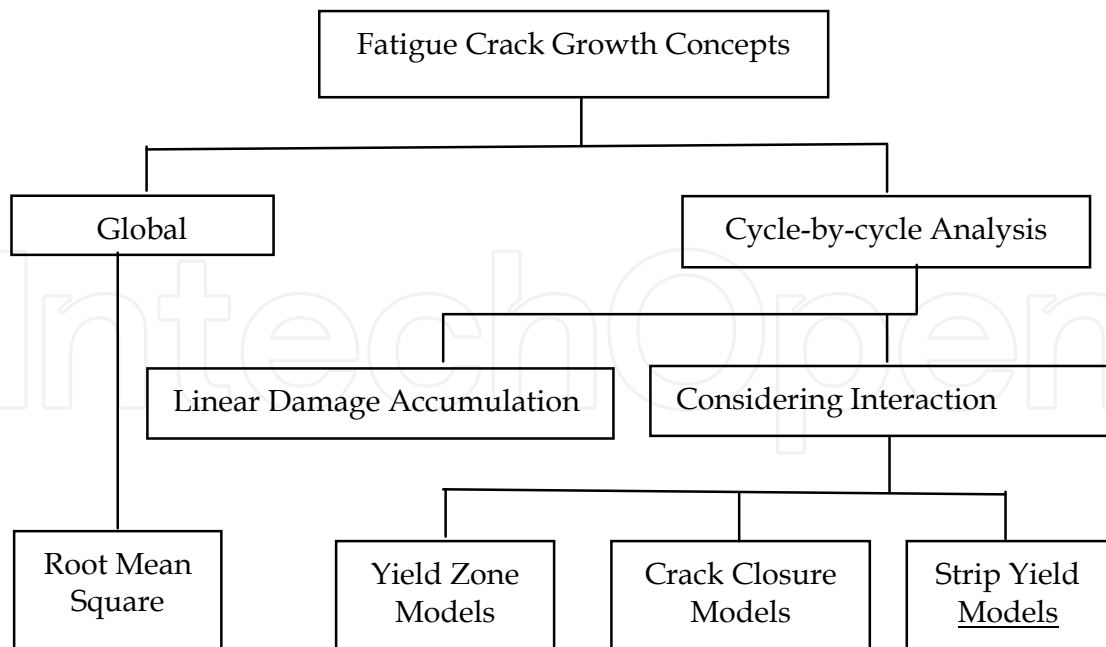


Fig. 1. Classification of the fatigue crack growth concepts

intensity factor necessary to cancel the effect of the overload plastic zone. The model computes an effective stress intensity factor that is being reduced by the compressive residual stress. However, the Willenborg model was found to be not reliable for predicting the overload retardation [Taheri, et al., 2003].

The second main category of retardation models, known as the crack closure models, is based on Elber's experimental observation [Elber, 1971], which used to model crack growth rates under VA loadings [Schijve, 1981; Newman, 1984; Ray & Patanker, 2001a; Ray & Patanker, 2001b]. As a result of the tensile plastic deformation left in the wake of a fatigue crack, a partial closure of the crack faces occurs during part of a fatigue load cycle. Since crack propagation can only occur during the time for which the crack is fully open, the formation of crack closure reduces the range of the applied stress that is effective for crack propagation. In addition, the magnitude of stress required for the crack to be fully open, i.e., the crack opening stress, depends on the previous load history. As a crack propagates through an overload plastic zone, the residual stresses in the zone increase the load required to open the crack and cause crack growth retardation. Thus, the use of the crack closure models required the crack opening stress to be determined throughout the load history. This is accomplished either by direct experimental measurements [Kim & Song, 1994; Dominguez, et al., 1999; Jono, et al., 1999] or by finite element computations [Lee, 2003; Sander & Richard, 2005; Ljustell & Nilsson, 2005]. However, the major drawback to using crack closure models is that measuring the crack opening stress under VA loading is very difficult and the magnitude and the precision might depend on the measuring techniques, while the finite element analysis for computing the crack opening stress is often complicated and relatively time consuming. More recent proposals include combinations of the Wheeler model with the Newman crack closure model [Huang, et al., 2005a] and model based on the strain energy density factor [Huang, et al., 2005b]. The most advance category is the strip yield models, which are based on the Dugdale model [Newman 1981]. The Dugdale model was used to estimate the size of the plastic zone at the tip of the crack. Dugdale assumes that yielding occurs in a narrow strip ahead of the crack tip.

Each of these models has its own capabilities and limitations as discussed in several literatures [Sadananda, et al., 1999; Kujawski, 2003; Murthy, et al., 2004]. Because of the complexity, large ambiguities and disagreements, and also lack of proper understanding of the mechanism of retardation, no fundamental and universally accepted model is available that would include all the mechanisms and could be applied to all materials.

With respect to the continuity information between this study and the available literature, the purpose of this work is two characterise the effects of load sequence on fatigue crack propagation under the spectrum loading. For that reason, a feasible study towards the crack propagation model under various spectra loading has been carried out based on the Austen, modified Forman and NASGRO models. These models are compared to FASTRN and AFGROW codes as well as test data under various VA and spectrum loading from previous literature. One of the aims of the analysis is to show the effect of using different FCG models with various load sequences. Every single FCG model developed so far attempts to correlate the crack growth information with different crack driving forces and several other parameters to predict the residual fatigue life. In the present work, the FCG rate has been correlated with crack length by correlations with the high percentage of a correction factor.

3. Fatigue crack growth models

The reason for building FCG models is to link theoretical ideas with the observed data. Modelling of FCG rate data has enhanced the ability to create damage tolerant design philosophies [Kassim, et al., 2008]. The influence of the mean stress is probably the most significant, and it usually results in closely spaced lines parallel to each other. Region I, which is shown in Fig. 2, represents the early development of a fatigue crack and the crack growth rate, for which da/dN is typically in the order 10^{-6} mm/cycle or smaller of the test data results from ASTM E647 [2002]. This region is extremely sensitive, and it is largely influenced by the microstructure features of the material such as grain size, the mean stress of the applied load. The most important feature of this region is the existence of a stress intensity factor range below which fatigue crack should not propagate. This value is defined as the FCG threshold and is represented by the symbol K_{th} . The limitation of the Paris law is that it is only capable of describing data in region II. If the data exhibits a threshold (region I) or an accelerated growth (region III) Paris law cannot adequately describe these regions. Region III represents the FCG at the very high rate, $da/dN > 10^{-3}$ mm/cycle due to rapid and unstable crack growth just prior to final failure. The da/dN versus ΔK curve becomes steep and asymptotically approaches the fracture toughness K_c for the material.

The common approach for FCG analysis is to describe the data using a differential equation, which is referred to as a FCG law or model. Modelling of FCG data has enhanced the ability to create damage tolerant design philosophies. Paris and Erdogan [1963] proposed the most important and popular work. In fact, they were the first to correlate FCG with the fracture mechanic's parameters (K_{min} and K_{max}), and describe the loading conditions in the region of the crack front. In addition, they also observed a linear relationship between the FCG rate (da/dN) and ΔK , when plotted on a log-log scale. Consequently, Paris and Erdogan [1963] proposed the power law relationship, as follows:

$$\frac{da}{dN} = C\Delta K^n \quad (1)$$

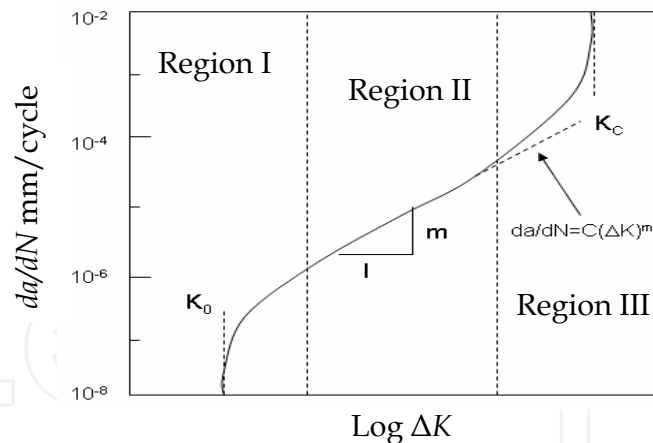


Fig. 2. Typical da/dN versus dK curve

where C and n are the material parameters that are determined experimentally. The Paris-Erdogan equation does not consider: (a) the effect of the stress ratio, (b) the existence of fatigue threshold, and (c) the accelerated FCG rate when the maximum stress intensity factor (K_{max}) approaches the material fracture toughness (K_c). Moreover, it does not adequately describe the region, I or III FCG rates, and it tends to overestimate region I, but underestimates region III FCG rates. Although the Paris-Erdogan equation is a simplification of a very complex phenomenon, it is still very popular on the account of significant engineering interest.

It is practically impossible to discuss every available model because of their large number in the literature. Therefore, the remainder of this section discusses about the models which are rather promising and/or commonly used. The fact that all used different FCG models reconfirms the fact that there is no standard methodology used to perform the FCG life predictions for structures under random loading.

The main goal of the crack propagation models is to relate the material damage to the cyclic loads applied. However, due to the number and complexity of the mechanisms involved in this problem, there are probably as many equations as there are researchers in the field. Though many models have been developed, none of them enjoys universal acceptance. In more specific, each model can only account for one or several phenomenological factors. Moreover, the applicability of each model varies from case to case, there is no general agreement among the researchers to select any FCG model in relation to the concept of fatigue crack behaviour [Kujawski, 2001; Hamam, et al., 2007; Richard, et al., 2008; Mohanty, et al., 2009]. Hence, three different models, namely, the Austen, modified Forman and NASGRO models, were selected in this study. Each model has its own capabilities and limitations as discussed in several literatures [Sadanada & Vasndevan, 1999; Murthy, et al., 2004; Mohanty, et al., 2009], which they belong to three categories. These models take into account the main properties, such as the crack closure, plane stress and plain strain, threshold, mean stress and region III. A comparison of the three models is shown in Table 1.

3.1 The austen model

The Austen growth model [nCode, 2003] is known as the implicitly model threshold and it is expressed in the following equation:

$$da / dN = C.(\Delta K_{eff})^n \quad (2)$$

Property	Models		
	Austen	Modified Forman	NASGRO
Crack closure	✓		✓
Plain strain	✓		✓
Plain stress	✓		✓
Threshold		✓	✓
Mean stress effect (R-ratio)		✓	✓
Region III		✓	✓

Table 1. A comparison between the three FCG models

Where, $\Delta K_{eff} = \Delta K_{max,eff} - \Delta K_{min,eff}$, $K_{max,eff} = K_{max} + K_{SF}$, $K_{min,eff} = \max(K_{min}, K_{CL})$, and K_{SF} is defined as the modification for static fracture and K_{CL} is known as the stress intensity at the crack closure. Furthermore, Austen modelled the onset of fast fracture using the following expression:

$$K_{SF} = \frac{K_{max}}{K_{IC} - K_{max}} \quad (3)$$

Austen also took into account the threshold and short cracks by applying a crack closure stress K_{CL} which is expressed as follows:

$$K_{CL} = K_{max} - K_{max} \sqrt{\frac{a + I_o}{a} + \frac{\Delta K_{th}}{1 - R}} \quad (4)$$

I_o is the smallest crack size that will propagate and is given by:

$$I_o = \frac{1}{\pi \left(\frac{K_{th}}{\Delta \sigma_o} \right)^2} \quad (5)$$

where, $\Delta \sigma_o$ is the un-notched fatigue strength and ΔK_{th} is the threshold stress intensity.

The threshold stress intensity is expressed as a bilinear function of the mean stress and the Austen model does not possess any explicit mean stress correction. Austen argued the irrelevance of this and attributed it to a manifestation of crack closure and retardation.

3.2 The modified forman model

Although Walker improved the Paris model by taking account of the stress ratio, neither of the models could account for the instability of the crack growth when the stress intensity factor approaches its critical value [Forman, 1972]. However, Forman improved the Walker model by suggesting a new model which is capable of describing Region III of the fatigue rate curve and includes the stress ratio effect. The Forman model is therefore given by the following mathematical relationship:

$$\frac{da}{dN} = \frac{C_F (\Delta K)^{m_y}}{(1-R)K_C - \Delta K} = \frac{C_F (\Delta K)^{m_y}}{(1-R)(K_C - K_{max})} \quad (6)$$

where, K_c is the fracture toughness for the material and thickness of interest. Eq. (6) indicates that as K_{max} approaches K_c & da/dN tends to infinity. Therefore, the Forman equation is capable of representing stable intermediate growth (region II) and the accelerated growth rates (region III). The Forman equation is capable of representing data for various stress ratios by computing the following quantity for each data point, i.e.:

$$Q = \frac{da}{dN} [(1-R)K_c - \Delta K] \tag{7}$$

If the various ΔK and R combinations fall together on a straight line on a log-log plot of Q versus ΔK , the Forman equation is applicable and may therefore be used. Comparing Eqs. (6 and 7), the Forman equation can be represented as:

$$Q = C_F (\Delta K)^{m_y} \tag{8}$$

A more simplified model, which does not include crack closure effects, is given by the following Forman equation:

$$\frac{da}{dN} = \frac{C(\Delta K)^n}{\left(1 - \frac{\Delta K}{(1-R)K_c}\right)^q} \tag{9}$$

for $0 \leq R < 1$

Forman proposed its modified model [Carlson & Kardomateas, 1996; Kassim, et al., 2006] as:

$$\frac{da}{dN} = \frac{C(1-R)^m \Delta K^n (\Delta K - \Delta K_{th})^p}{((1-R)K_c - \Delta K)^q} \tag{10}$$

Certain values of the exponents m , p , and q of Eq. (10) give other forms of the crack growth equation, as indicated in Table 2.

Exponent value	FCG Model
$m = p = q = 0$	Paris
$m = p = 0, q = 1$	Forman
$p = q = 0, m = (mw-1)n$	Walker

Table 2. Exponent values for crack growth laws

The Forman equation is capable of representing data of various stress ratios for regions II and III. Further modifications of the Forman's expression to represent regions I, II and III have been accomplished by including the threshold stress intensity parameter, ΔK . Thus, Hartman and Schijve [1970] proposed the following equation which is the continuation of Forman's work:

$$\frac{da}{dN} = \frac{C_{HS} (\Delta K - \Delta K_{th})^{m_{HS}}}{(1-R)K_c - \Delta K} \tag{11}$$

Another version of the Forman equation is given as follows:

$$\frac{da}{dN} = \frac{C_{MOD}(\Delta K)^{m_{MOD}}(\Delta K - \Delta K_{th})^{0.5}}{(1-R)K_C - \Delta K} \quad (12)$$

Both Eqs. (11 and 12) produce a sigmoid shaped curve; in this case, an asymptote does not only occur as K_{max} approaches, K_c , but it also occurs when ΔK approaches ΔK_{th} . One disadvantage of using these equations is that the value of ΔK_{th} is sensitive to R and a specific value of this parameter in the equation is generally needed for any given R value [Dowling, 1993]. In addition, the correct value of K_c for the given thickness should be used. Technically, the FCG rate da/dN can be described, for instance, by the modified Forman-Mettu equation [Richard, et al., 2008]:

$$\frac{da}{dN} = C \left[\left(\frac{1-f}{1-R} \right) \Delta K_{eq} \right]^n \frac{\left(1 - \frac{\Delta K_{th}}{\Delta K_{eq}} \right)^p}{\left(1 - \frac{K_{max}}{K_C} \right)^q} \quad (13)$$

In this equation, C , n , p and q are the material parameters, whereas $R = R_{min} / R_{max}$ or $R = K_{min} / K_{max}$ is the R -ratio of the load and f denotes the crack opening function [Forman & Mettu, 1992; Sandar & Richard, 2006]. Despite the fact that the influence of single loading change events likes over or blocks loads which are well-known [Sandar & Richard, 2006], extensive research for the arbitrary VA loadings is still necessary not only for the amplitude, but also the direction of the load (Mixed-Mode-loading) changes.

3.3 The NASGRO model

The Willenborg model is based on the yield zone concept. Meanwhile, retardation is accounted for the tensile overloads by a reduction in SIF and truncating the minimum effective SIF at zero. In this method, both the effective SIF and apparent SIF are the same and this method is effective in computing the crack growth only when the crack growth equation contains the stress ratio R . However, this method is not applicable for overloads as it does not predict acceleration which is caused by compressive overloads or underloads as well as the combination of both.

Another related development has lead NASGRO to extend the generalized Willenborg model [Forman, 1972; Maymon, 2005; Kassim, et al., 2008] by taking into account the reduction of retardation due to underloads. The NASGRO equation represents the most comprehensive growth law formulation comprising the mean stress effect, threshold, the honest of fast fracture and crack closure [nCode, 2003]. The NASGRO formula is expressed as:

$$\frac{da}{dN} = \frac{C(\Delta K_{eff})^m}{(1-R_{eff})K_C - \Delta K_{eff}} \quad (14)$$

where

$$\Delta K_{eff} = (K_{max})_{eff} - (\Delta K_{min})_{eff} \quad (15)$$

$$K_{\max,eff} = K_{\max} - K_{red} \tag{16}$$

$$K_{\min,eff} = \max\{(K_{\min} - K_{red}), 0\}, \text{ for } K_{\min} > 0 \tag{17}$$

$$= K_{\min} \text{ for } K_{\min} \leq 0$$

$$K_{red} = \phi \left[(K_{OL})_{\max} \left[1 - \left(\frac{a_n - a_{OL}}{\gamma P_{ol}} \right) \right]^{1/2} - K_{\max} \right] \tag{18}$$

$$\phi = 2.523\phi_o / (1.0 + 3.5(2.5 - R_U)0.6), \quad R_U < 0.25$$

$$= 1.0 \quad R_U \geq 0.25$$

$$R_U = \sigma_{UL} / \sigma_{\max,OL}, \quad \phi_o = 0.2 \quad \text{to} \quad 0.8$$

$$K_{\min,eff} = \max\{(K_{\min} - K_{red}), 0\},$$

$$K_{\max} = \frac{\Delta K}{(1 - R)}$$

and ΔK is the stress intensity factor (depends on the stress, crack length, geometry factor), ΔK_{th} is the threshold stress intensity range, K_c is the critical stress intensity factor, C, n, p and q are the empirically derived coefficients from the measured data. The other parameters, such as the crack tip opening function f , are determined using the following formulation:

$$f = \begin{cases} \max\{(R), (A_0 + A_1.R + A_2.R^2 + A_3.R^3)\} & \text{if } (R \geq 0) \\ A_0 + A_1.R & \text{if } (-2 \leq R < 0) \\ A_0 - 2.A_1 & \text{if } (R < -2) \end{cases} \tag{19}$$

where

$$A_0 = (0.825 - 0.34\alpha + 0.05\alpha^2) [\cos(\pi SR / 2)]^{1/\alpha}$$

$$A_1 = (0.415 - 0.071\alpha) SR \tag{20}$$

$$A_2 = 1 - A_0 - A_1 - A_3$$

$$A_3 = 2.A_0 + A_1 - 1$$

α is the plain stress/strain constraint factor and SR is the ratio of the maximum applied stress to the flow stress. These values are all empirically derived. Meanwhile, the threshold stress intensity is obtained from the following equation:

$$\Delta K_{th} = \frac{\Delta K_o \left(\sqrt{\frac{a}{a + a_o}} \right)}{\left[\frac{(1-R)}{(1-A_o)(1-R)} \right]^{1+C_{th}R}} \quad (21)$$

where, ΔK_o is the threshold stress intensity range at $R = 0$ obtained from the test results, a is the crack length, a_o is the intrinsic crack length given as the constant, and C_{th} is the threshold coefficient obtained from the test results.

3.4 The FASTRAN model

The crack-growth relation used in FASTRAN was:

$$\frac{da}{dN} = \frac{C_i (\Delta K_{eff})^{n_i}}{\left[1 - \left(\frac{K_{max}}{K_{le}} \right)^q \right]} \quad (22)$$

where C_i and n_i are the coefficient and power for each linear segment, K_{max} is the maximum stress-intensity factor, K_{le} is the elastic fracture toughness (which is, generally, a function of crack length, specimen width, and specimen type), and q was set to 2. The table-lookup form is used because many materials, especially aluminum alloys, show sharp changes in the crack-growth-rate curves at unique values of rates. These sharp changes have been associated with monotonic and cyclic-plastic-zone sizes, grain sizes, and environments [Yoder, et al., 1982]. The Functional relations for geometry factors ($F(a, w)$) are given in the FASTRAN manual [Newman, 1992] as:

$$F(a, w) = \sqrt{\sec\left(\left\{\frac{\pi}{2}\right\}\left\{\frac{a}{w}\right\}\right)} \quad (23)$$

3.5 The AFGROW model

AFGROW model is the Walker equation with Willenborg retardation model [Ray & Patankar, 2001b], which is a cycle-by-cycle structural crack growth fracture mechanics computer program developed at the Air Vehicles Directorate of the United States Air Force Research Laboratory (AFRL), and is widely used to predict the fatigue life of components [Harter, 2003].

4. Simulation and experiments

For many years, fatigue analysis has been thought of as following the logic as illustrated in Fig. 3. In this overview, the three main input parameters, namely geometry, material and loading, are regarded to have similar functions. These parameters seem to be the main input to any software for modelling and simulation. The details of these inputs are as follows:

In this application centre-cracked specimen geometry described in ASTM E647 [2002] is used with a width of 229 mm, thickness of 4.1 mm and 610 mm in length, while the initial crack size is 12.7 mm, for which $E = 71750$ MPa. Aluminium alloys are widely used in the design of many engineering application, due to their good mechanical properties and low densities. The chemical composition and mechanical and fatigue properties of this material

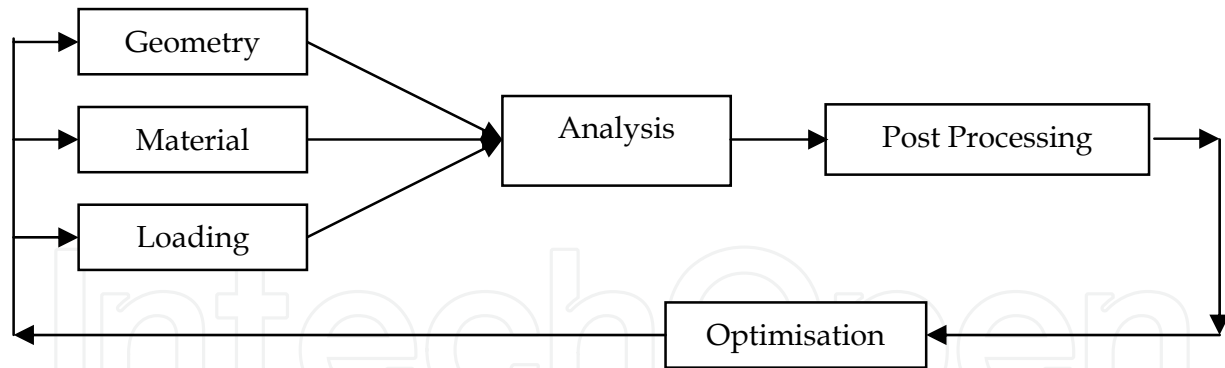


Fig. 3. A conventional schematic flow of the fatigue analysis process (the general durability process)

are shown in Table 3 and Table 4, respectively [ASM Handbook, 1985; 1990; ASM Metal Reference, 1993].

Components and structures that are subjected to quite diverse load histories, their histories may be rather simple and repetitive and at the other extreme, they may be completely random. The cycle-by-cycle analysis can be performed with or without involving the interaction effects, i.e. the effect of a load cycle on crack growth in later cycles.

Component	Wt%	Component	Wt%
Al	90.7-94.7	Cr	Max. 0.1
Cu	3.8-4.9	Fe	Max. 0.5
Mg	1.2-1.8	Mn	0.3-0.9
Si	Max. 0.5	Ti	Max. 0.15
Zn	Max. 0.25	Other, each	Max. 0.05
Other, total	Max. 0.15		

Table 3. Chemical composition of aluminium alloy 2024 T3

Titles	Symbols	Values
Yield Stress (MPa)	σ_y	345
Ultimate Tensile Strength (MPa)	σ_u	483
Plane Strain Fracture Toughness (MPa. \sqrt{m})	K_{IC}	36.262
Plane Stress Fracture Toughness (MPa \sqrt{m})	K_{ID}	72.524
Part Through Fracture Toughness (MPa \sqrt{m})	K_{IE}	50.547
Forman Exponent	m_y	3.284
Forman Co-efficient (m/MPa(m ^{1/2}) ⁽ⁿ⁻¹⁾)	C	1.5451×10^{-10}
NASGRO Exponent	p	0.5
NASGRO Exponent	q	1
Modulus of Elasticity (GPa)	E	71.75
Fatigue Strength coefficient (MPa)	f	130
Elongation at Break (%)		18

Table 4. Mechanical and fatigue properties of aluminium alloy 2024 T3

The programmable and VA load histories given by Ray and Patanker [2001b] and Huang et al.[2005b] are used in this analysis with different load sequences from high to low or low to high shown in Fig. 4 (load cases 1 to 5). These types of loading represent the load sequencing and spectrum loading in most of the application. To account load ranges and mean of the used load history, the rainflow counting method was then used. In this overview, as mentioned before, the three main input parameters are geometry, material and loading. The process proceeds by selection of the FCG model to show the behaviour of the geometry. The results of the previous process predict the fatigue life and FCG rate. At each cycle, to get a new result it is possible to change any of the factors (FCG model, geometry, material, loading and stress ratio), which mean the ability to make a new prediction. The detail flow of such process is shown in Fig. 5.

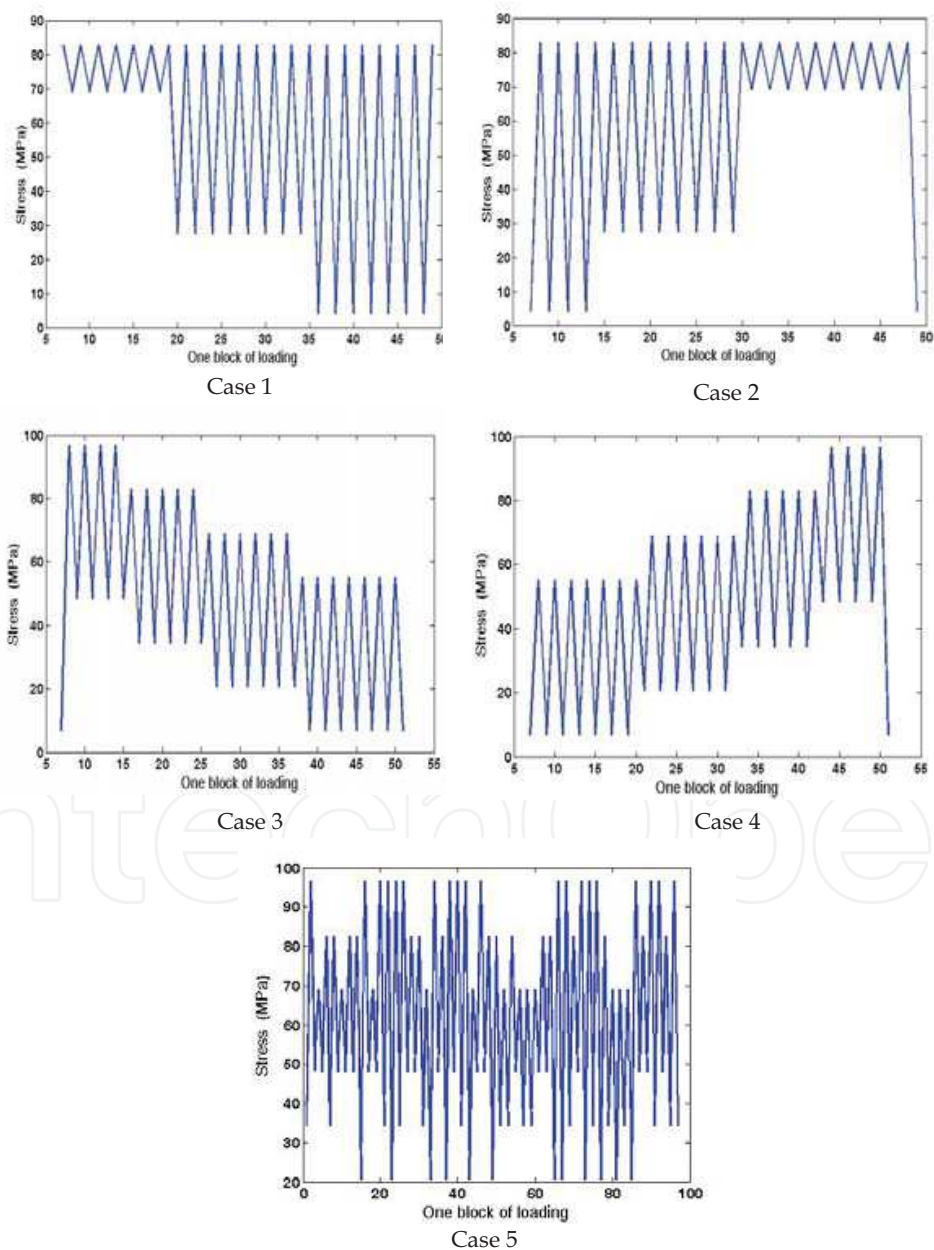


Fig. 4. Display of load histories with different sequences

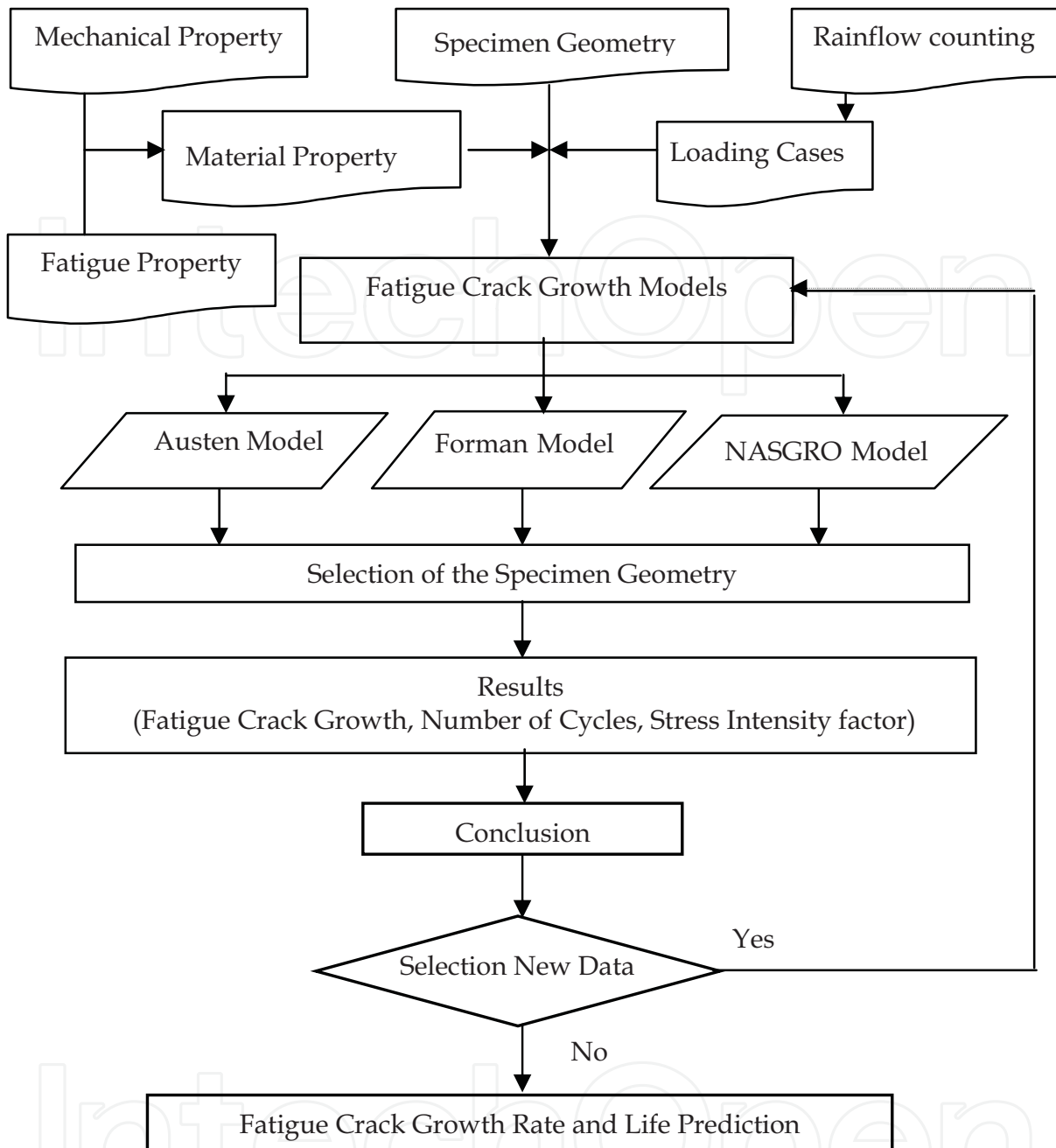


Fig. 5. Flow chart of the simulation process

5. Results and discussion

Many engineering structures are subjected to random loading in service and the fatigue life will be affected by load sequence. However, for design purposes it is particularly difficult to generate an algorithm to quantify these sequence effects on fatigue crack propagation, due to the number and to the complexity of the mechanisms involved in this problem [Kujawski, 2001]. The presence of interaction effects is always altering the crack growth rate under the application of VA loading. For correctly predicting the crack growth under VA loading, it is necessary to involve the interaction effects while developing the prediction models as a part of cycle-by-cycle analysis using different models. Hence, one of the purposes of this research

is to address how two characters the effect of VA loading in fatigue crack propagation. Despite the extensive work on crack growth, there is still a need for a satisfactory and generally applicable method to predict the fatigue crack propagation to consider various effects. In the current investigation, systematic crack growth predictions were conducted on an aluminium alloy. Several existing models were evaluated critically based on the experimental results [Richard, et al., 2008]. Thus, the fatigue crack propagation models under VA loading are presented in this section based on the Austen, modified Forman and NASGRO models. For demonstrating the validation of these models predictions are compared with test data, FASTRN and AFGROW codes given in Ray and Patanker [2001b]. Figs. 6 and 7 exhibit the results of the comparisons under two types of block loading, one with decreasing the minimum stresses (load case 1) and the other with increasing them (load case 2). The changes of a stress ratio related to changing of minimum stress with a constant maximum stress. The data predicted using the Austen, modified Forman and NASGRO models are compared with those models performed by previous literatures [Ray & Patanker, 2001b; Huang, et al., 2005a; Huang, et al., 2005b].

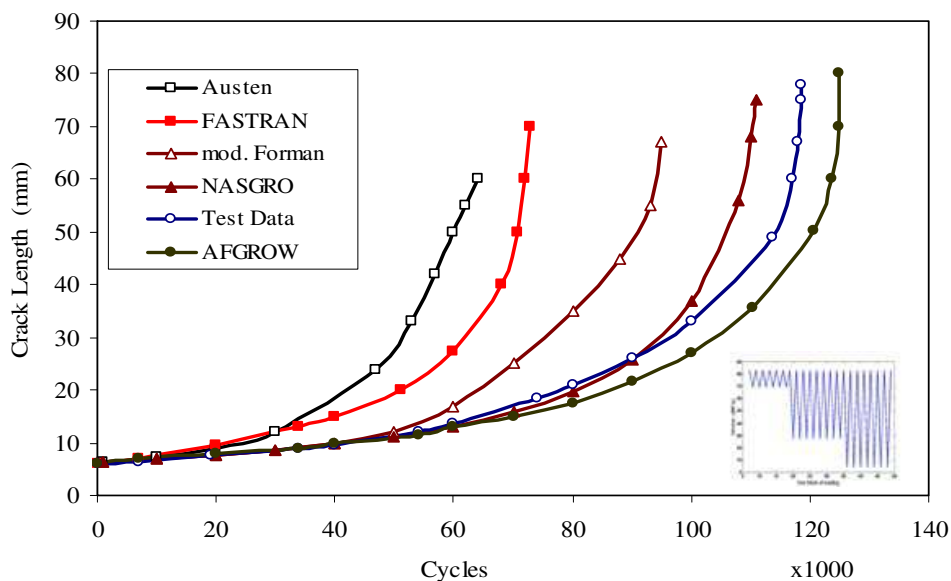


Fig. 6. Comparison of fatigue crack growth with different FCG models under load case 1

The maximum differences in life predicting for the load cases for all models are 40% as a maximum compared to the test data. The lowest life has been found using the Austen prediction model, while NASGRO gave the maximum and the others are in between both the Austen and the NASGRO models. Moreover, the fatigue life predicted under the load case 2 is higher than the case 1. The results show clearly the effect of changeable stress ratio and the first block is more effective than others, in other words, the sequence of the loads. The results indicate that, when the first value of R is high, it is clearly reduce the life, although this value will be decreased later. In the load cases when the stress ratio is low in the first block of the load, it has less effect, although its value will be increased later.

The effects of load sequence can be shown clearly in Fig. 8, which represent the comparison between these load cases based on test data and NASGRO model. The maximum difference in the test data is 8%, while in NASGRO model is 25%. These differences mainly due to the effects of load ratios for each load case.

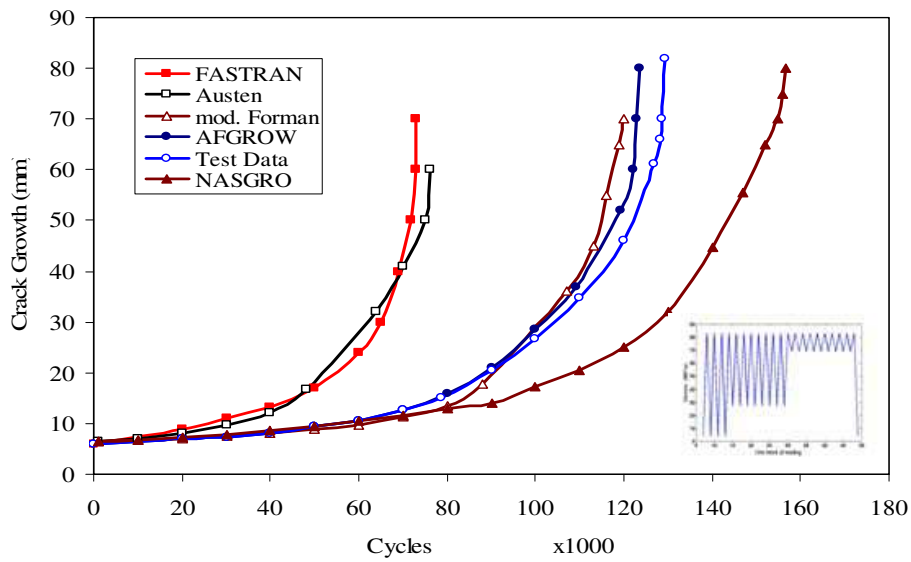


Fig. 7. Comparison of fatigue crack growth with different FCG models under load case 2

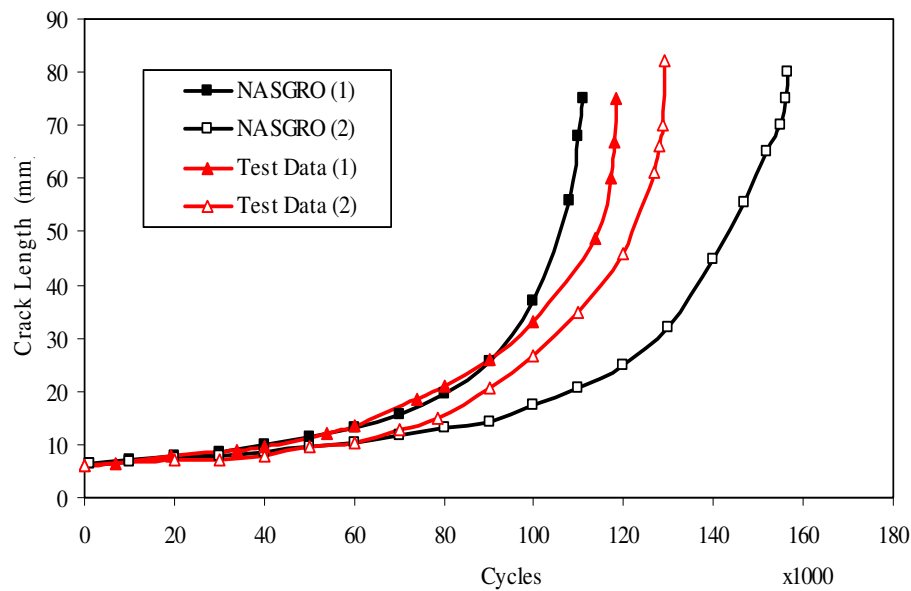


Fig. 8. Comparison of fatigue crack growth of test data and NASGRO model under load cases 1 and 2

From previous results mentioned in Figs. 6 and 7, it is possible to draw the FCG rate curve relating to crack length as shown in Fig. 9. The power equation gave a correction factor of 97.8% for load case 1 and 99.5% for load case 2. The two equations indicate that the rate of crack versus crack length approximately same with small difference in linear relationship. Tests on SM520B steel using CCT test specimens under four different variable amplitude block loading spectra were reported by Yamadaa et al. [2000] and presented in Fig. 10, while Pell et al. [2004] reported on Aluminum alloy by the same indication. Fig. 10 again reveals a near linear relationship between da/dN and the crack length, which introduce the same conclusion presented by this research (Fig. 9).

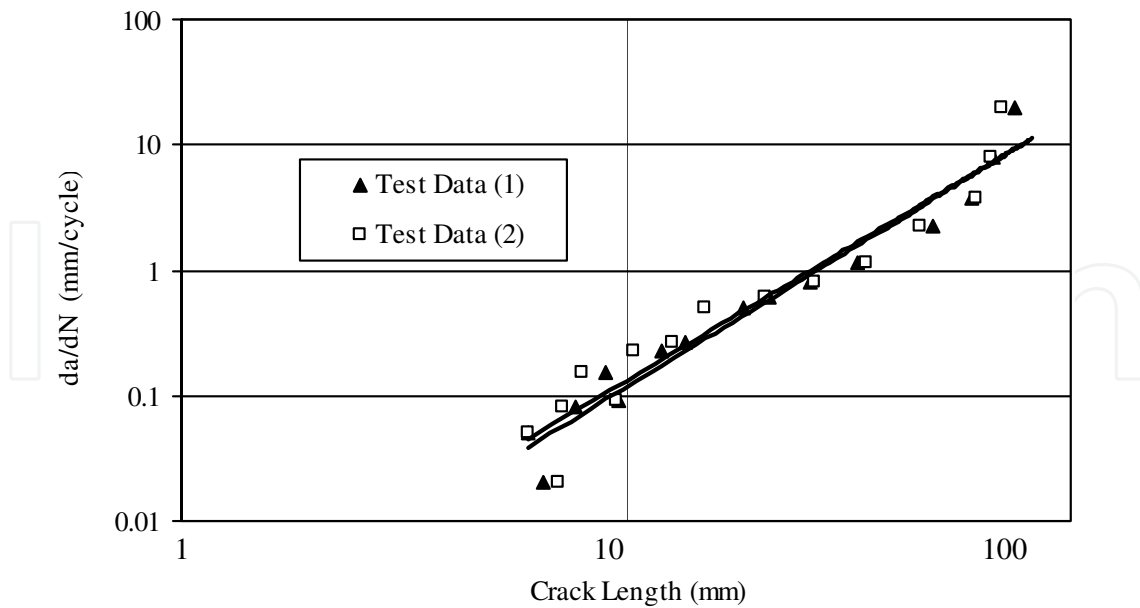


Fig. 9. Fatigue crack growth rate versus crack length of test data under load cases 1 and 2

For the load cases 3 and 4, the stress ratios are changeable either in a decreasing way (case 3) or increasing (case 4) due to the changes in both stresses (maximum and minimum), which differ from the cases 1 and 2. The results in Figs. 11 and 12 show good agreement to the predicted life for all models with a difference range from 17% to 30% related to experimental results for the two load cases (3 and 4), except the results of the Austen model, which are less by more than 50% for the load case 3 compared to load case 4.

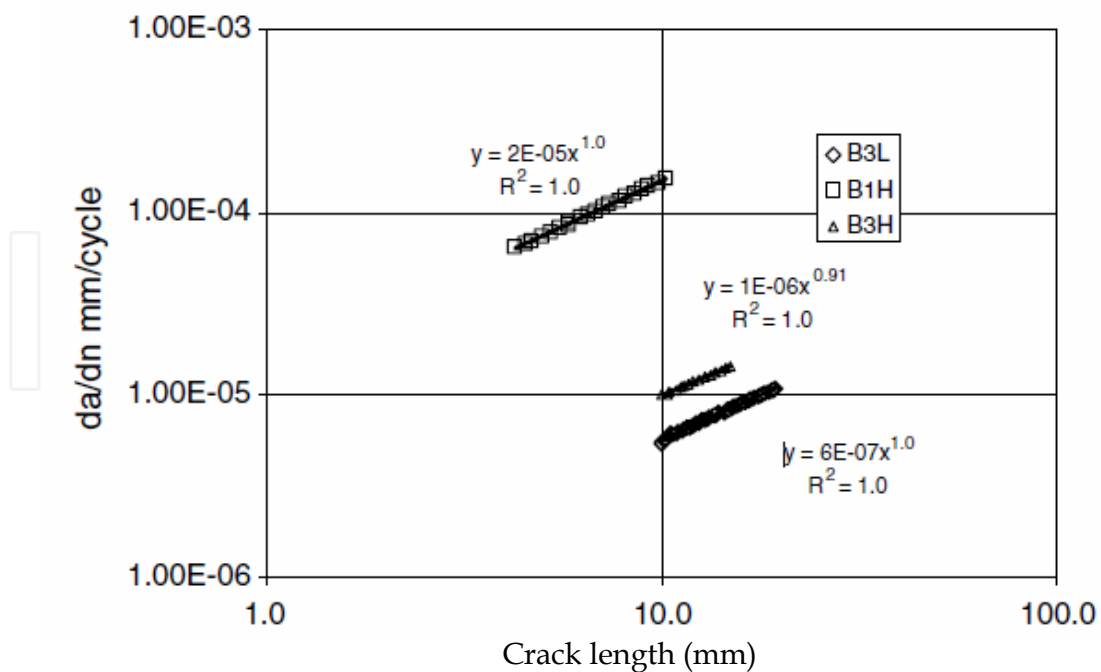


Fig. 10. Fatigue crack growth versus crack length for SM520B steel using CCT specimens adapted from Yamadaa et al., [2000]

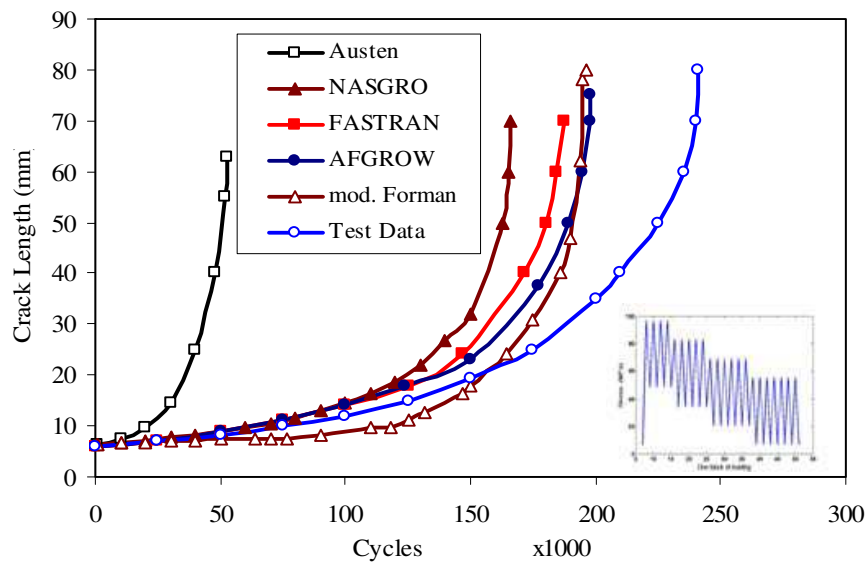


Fig. 11. Comparison of fatigue crack growth with different FCG models under load case 3

The comparison of test data and results predicted based on the NASGRO model for the two load cases (load cases 3 and 4) are shown in Fig. 13. The life predicted based on NASGRO model is 168×10^3 cycles, while for load case 4 is 160×10^3 cycles. The difference between the lives based on test data is 9%. These differences are due to the different load ratios and load sequence effects for the load cases.

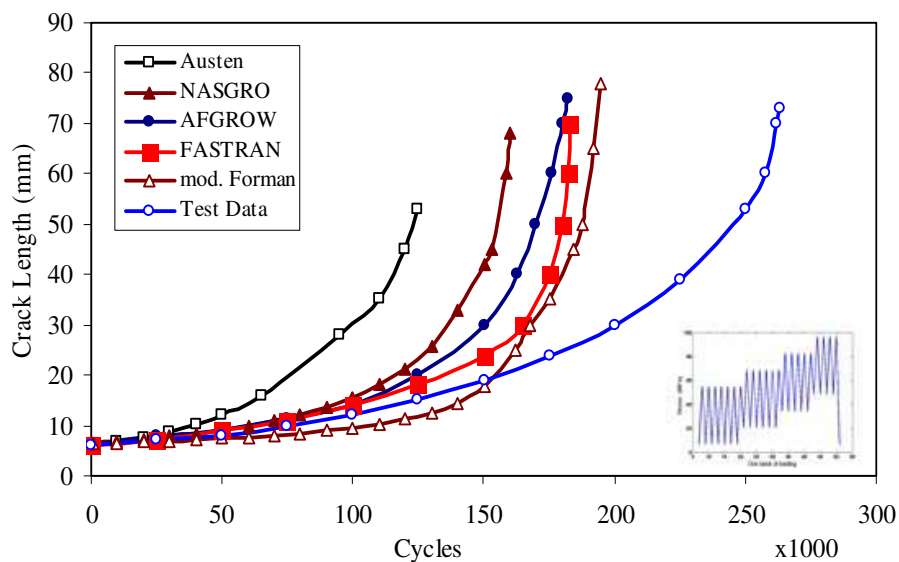


Fig. 12. Comparison of fatigue crack growth with different FCG models under load case 4

The FCG rate versus the crack length for the two load cases 3 and 4 shown in Fig. 14. The two power equations are approximately same ($da/dN = 0.0019 (a)^{1.6328}$) and the correction factor for these cases is 97.8%. This relation is a linear, which is in a good agreement with results published in literature [Molent, et al., 2006]. The crack growth results obtained by Roach [2002] as part of the FAA Aging Aircraft program are analysed in Fig. 15. We again

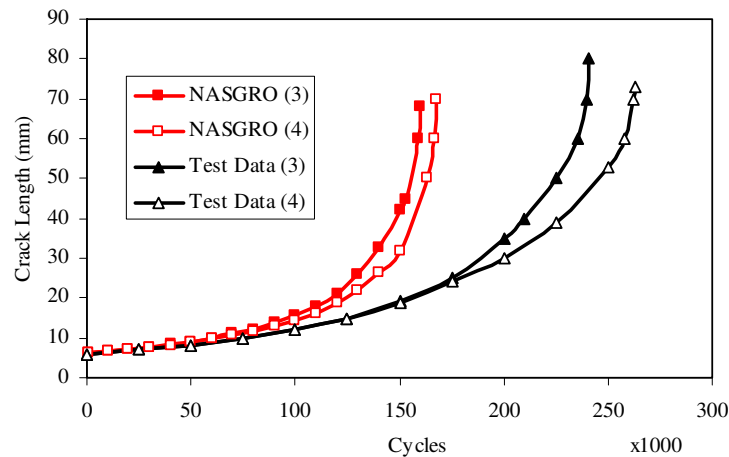


Fig. 13. Comparison of fatigue crack growth of test data and NASGRO model under load cases 3 and 4

see that there is a near linear relationship between the apparent growth rate and the crack length [Baker, 2002]. Although, the differences in the types of specimens and load magnitudes, it showed the same behaviour.

For the random loading case, i.e. case 5, the results show a good agreement of AFGROW model with experiment values and 10% difference with the modified Forman and NASGRO models, while for the FASTRAN and the Austen models are 30% and 50%, respectively. These results are clearly shown in Fig. 16. The correlation between the FCG rate and crack length for this load case is $(da/dN = 0.0387 (a)^{1.0051})$ and the correction factor is 98%, which shown in Fig. 17 in a linear relationship. The linear relationship between crack growth rate and crack length is in a good agreement in behaviour with the further test results illustrated and presented by Brot and Matias [2002]

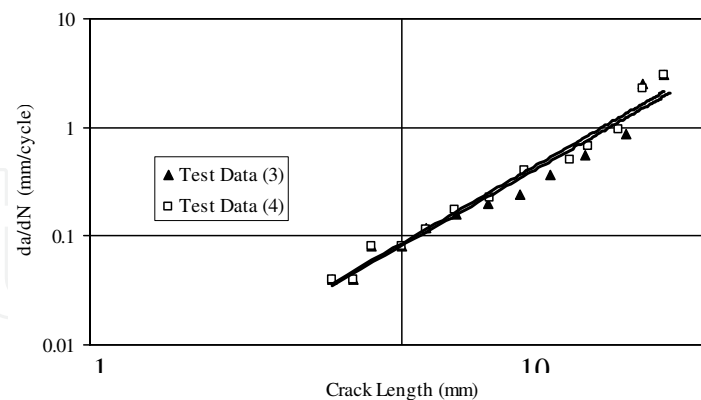


Fig. 14. Comparison of fatigue crack growth rate versus crack length of test data under load case 3 and 4

The above results indicates that, using VA loading in practice, the fatigue life is often affected by load or cycle sequences, although, the values of the load are same for each block. Neglecting the cyclic interaction effects in fatigue calculations lead to inaccurate life predictions [Kassim, et al., 2008]. These load cases, the load ranging from 4.14 to 82.8 MPa for the first two cases, while for the second two cases ranged from 6.9 to 96.6 MPa.

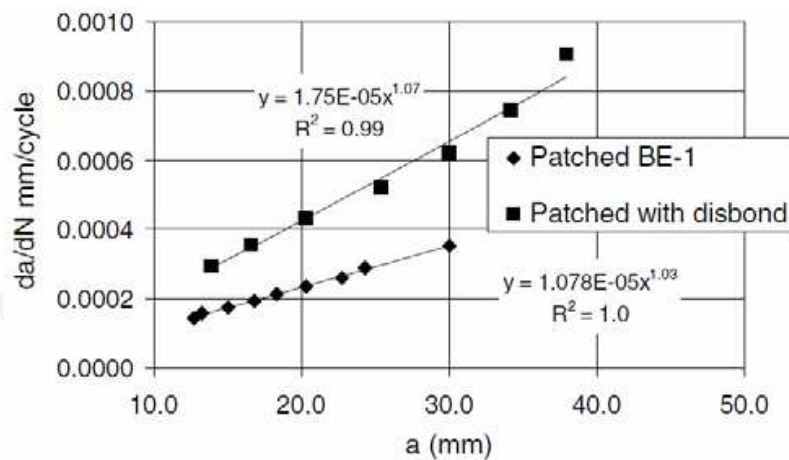


Fig. 15. Fatigue crack growth versus crack length in Al 2024-T3 adapted from Roach et al. [2002]

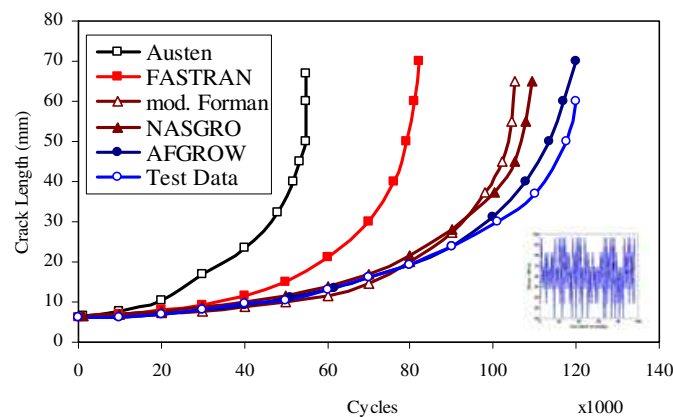


Fig. 16. Comparison of fatigue crack growth with different FCG models under load case 5

With reference to load cases 1 and 2, the changing in R ratio due to changing in the minimum stresses only, while for the load cases 3 and 4 the changes due to variability of both maximum and minimum stresses. For these cases (1, 2, 3 and 4) the results indicate that the value of stress ratio in the first block of the load had much effect on the crack growth. From the overall findings, therefore, the effect of load sequences on the fatigue life prediction is necessary to involve the interaction effects and neglecting the sequences effect lead to inaccurate results.

6. Conclusions

The application of multiple over and under loads can interact with each other, and as a result they could either accelerate or decelerate the overall crack growth retardation depending on the frequency of the overload. Three different models namely, the Austen, modified Forman and NASGRO have been used to predict the fatigue life on centre-cracked 2024-T3 aluminium alloy specimens under several program loadings. The load spectra and the schematic comparisons of predicted values with test data and those of FASTRN and AFGROW codes are compared. All the findings obtained from the comparisons with the five different program loadings agree with some discrepancies relating to the test data. It is

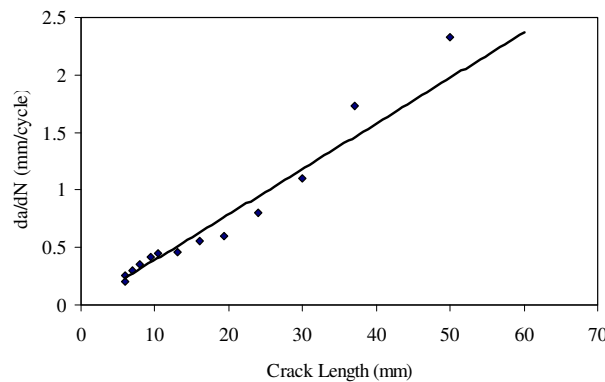


Fig. 17. Fatigue crack growth rate versus crack length of test data under load case 5

obvious that neglecting the effect of load sequence in fatigue calculations under VA loading can lead to inaccurate life predictions.

This work reveals that under the spectrum loading; there is a near linear relationship between the fatigue crack growth rate and the crack length when plotted on a log-log scale. These findings offer the potential to assess the effect on durability of an increase in the loading level due to different load ratios.

Finally, the present models have been proving applicable to crack propagation under VA loading with different approaches and the NASGRO model is the most proper model for VA loading fatigue life prediction.

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