

Effect of Single Overload Ratio and Stress Ratio on Fatigue Crack Growth

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Abstract—In this investigation variation of cyclic loading effect on fatigue crack growth is the studied. This study is performed on 2024 T351 and 7050-T74 aluminum alloys, used in aeronautical structures. The propagation model used in this study is NASGRO model. In constant amplitude loading (CA), effect of stress ratio has been investigated. Fatigue life and fatigue crack growth rate were affected by this factor. Results showed an increasing in fatigue crack growth rates (FCGRs) with increasing stress ratio. Variable amplitude loading (VAL) can take many forms i.e. with a single overload, overload band... etc. The shape of these loads affects strongly the fracture life and FCGRs. The application of a single overload (ORL) decrease the FCGR and increase the delay crack length caused by the formation of a larger plastic zone compared to the plastic zone due without VAL. The fatigue behavior of the both material under single overload has been compared.

Keywords—Fatigue crack growth, overload ratio, stress ratio, generalized willenborg model, retardation, Al-alloys.

I. INTRODUCTION

FATIGUE crack growth behavior of metals depend upon a number of variables namely the mechanical properties and microstructure, specimen, environment, applied cyclic loading, stresses and strains acting at the crack tip. Most of fatigue research has been concentrated on examining the phenomena under constant amplitude fatigue cycling for aluminum alloys [1]-[4]. During service, mechanical and aeronautical structures are subjected mostly to complex cyclic loading. It is well known that load fluctuations lead to fatigue crack propagation, the rate of which depends on the interaction of loads or stresses. The simplest case for the spectrum loading is when single and multiple peak overloads are applied to constant amplitude loading. Research on variable applied loading (VAL), determined that appreciable crack growth retardation can occur following tensile overloading [5]-[7]. A numbers of models have been developed to account for crack growth retardation due to tensile overloads [8]-[11] namely Willenborg, Wheeler model, Gallagher modified Willenborg model [12]. Crack growth retardation due to tensile overloads has been explained by several theories. The most commonly discussed theories are

fatigue crack closure [13]; residual stresses [8]-[9], crack tip blunting and sharpening [14] and cyclic strain hardening and softening [15]. Really, all mechanisms are not dissociable. Overload retardation has been widely investigated in a range of engineering materials [4], [13], [16], [17] and many research's were oriented to the study of several form of variable amplitude and associated parameter namely single or block overloading on fatigue behavior of aluminum alloys.

Fatigue crack retardation due to variable amplitude loading spectra was studied in 7075 T6511 aluminum alloy by Corbly and Packman [18]. It was shown that the degree of retardation depend strongly on the relative amplitudes of the peak stress intensity, the number of stress applications N_i at the peak stress intensity, the magnitude of the constant amplitude crack growth rate at the lower stress intensity range and the number of fatigue cycles N_i at the lower stress intensity level after the last peak stress is applied. The influence of overload ratio has been investigated primarily in aluminum alloys for the aerospace industry. In the investigation of Vardar [19], overload ratios between 1.3 and 2.4 were considered in a 7075-T6 alloy under plane strain conditions. A linear correlation was found between the number of retardation overload cycles and the overload ratio.

In fatigue crack growth investigation conducted by Bathias and Vancon [20] on 2024 and 2618 aluminum alloy, fatigue crack growth rate was retarded after application of one or several overload. In this study, it was demonstrated that the process of fatigue crack retardation by application of overloads results from the plastic deformation at the crack tip and the nature of the test specimen surface. Plastic zone diameter and the retardation relationships depend on toughness, on the metal cyclic strengthening and cyclic plastic deformation. The delayed retardation phenomena after single overload in three steels and two aluminum alloys were investigated by Matsuoka and Tanaka [21]. It was confirmed that the model proposed early by Matsuoka et al. [22] was in good agreement with the experimental data for these materials when the stress state at the overloading was satisfied with the small scale yielding condition. Effect of overload on fatigue crack growth studied by Robin and Pelloux [23] was performed on a 2124 T351 aluminum alloy. The results showed that crack retardation near the surface of the specimen was greater than in the plane strain region near the center and Wheeler's and Willenborg's models of were found to provide a fair approximation of the retardation phenomenon.

Recently, evaluation of retardation in fatigue life due to application of a single overload was conducted by Hairman

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[24]. Based on modifications of Wheeler's model with account of Elbert concept, overload ratio/Wheeler's exponent and FCGR calculations, a model for prediction of crack growth behavior following single overload is elaborated. The model tested for 2024-T3 aluminum alloy and 6061-T6 aluminum alloy give good agreement with experimental data. The study conducted by Kumar and Garg [25] on aluminum alloy 6061 T6, shown an increasing of life in applied periodic band of overload test compared to constant amplitude loading life. In recent work, the investigation of Bao and Zhang [26] on aluminum alloy 2324 T39 subjected to truncated load spectra, crack growth life was predicted using NASGRO model and generalized Willenborg model [12]. Good prediction has been given using this model for 2324 T39 for lower stress.

The aim of the present investigation is shown the effect of single overload ratio and stress ratio in constant amplitude loading on fatigue propagation of double through crack at hole of two Al-alloys (2024 T351 and 7050-T74) using Generalized Willenborg model [12].

II. FATIGUE CRACK GROWTH BEHAVIOR

A. Material & Specimen

Materials used in this study are 2024 T351 and 7050-T74 aluminum alloys obtained on rolled plates in L-T orientation. The basic mechanical properties for both materials are presented in Table I. Simulation of fatigue crack growth in mode I used finite plate with double through crack at hole with initial crack $a_0=0.5$ mm, is shown on Fig. 1. The stress intensity factor for the studied specimen implemented in AFGROW code depends on several parameters is written below:

$$\Delta K = \sigma \sqrt{\pi a} \beta \left(\frac{a}{r} \right) \quad (1)$$

where β is the geometry correction factor, proposed by Newman [27], is expressed below:

$$\beta \left(\frac{a}{r} \right) = 1 - 0.15 \lambda + 3.46 \lambda^2 - 4.47 \lambda^3 + 3.52 \lambda^4 \quad (2)$$

where: $\lambda = 1/(1 + (a/r))$

B. Fatigue Crack Growth & Retardation Models

In order to account of the different stages of the propagation NASGRO model is used in this study (see (3)). The different parameters of this equation are defined in the AFGROW manual [28]. The main parameters of NASGRO equation for the studied material are presented in Table II.

$$\frac{da}{dN} = C \left[\left(\frac{1-f}{1-R} \right) \Delta K \right]^n \frac{\left(1 - \frac{\Delta K_{th}}{\Delta K} \right)^p}{\left(1 - \frac{K_{max}}{K_{crit}} \right)^q} \quad (3)$$

TABLE I
MECHANICAL PROPERTIES OF AL- ALLOY (AFGROW DATABASE)

Materials	$\sigma_{0.2}$ (MPa)	KC MPa \sqrt{m}	KIC MPa \sqrt{m}	E (GPa)
2024T351	372.32	74.72	37.36	73.08
7050T74	448.16	72.52	36.26	71.70

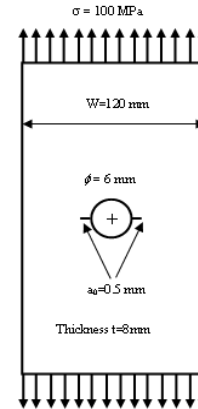


Fig. 1 Double through crack at hole in finite plate

The Generalized Willenborg model [12] is one of the most common load interaction models used in crack growth life prediction programs. The model use an "effective" stress intensity factor based on the size of the yield zone in front of the crack tip. The formulation of the Willenborg retardation model used in AFGROW is given below:

TABLE II
PARAMETERS OF CRACK GROWTH MODEL

Materials	σ_{max}/σ_0	C	n	p	q
2024 T351	0.3	1.71×10^{-10}	3.353	0.5	1
7050 T74	0.3	1.14×10^{-10}	3.368	0.5	1

$$\begin{cases} K_{max(eff)} = K_{max} - K_r \\ K_{min(eff)} = K_{min} - K_r \\ R_{eff} = K_{min(eff)} / K_{max(eff)} \end{cases} \quad (4)$$

K_r is residual stress intensity factor due to overload (5) and R_{eff} is effective stress ratio.

$$K_r = \phi \left(K_{max(ol)} \sqrt{1 - \frac{(x - x_{(ol)})}{R_{y(ol)}}} - K_{max} \right) \quad (5)$$

factor ϕ and is expressed by (6).

$$\phi = (1 - \Delta K_{th} / K_{max}) / (SOLR - 1) \quad (6)$$

and yield zone created by overload $R_{y(ol)}$ is expressed by:

$$R_y(ol) = \left(\frac{K_{\max}(ol)}{\sigma_{0.2}} \right)^2 \cdot \left(\frac{1}{\alpha \cdot \pi} \right) \quad (7)$$

III. RESULTS AND DISCUSSION

A. Constant Amplitude Loading (CA)

Plate specimen in L-T orientation for 7050 T74 Al-Alloy was subjected to a constant amplitude loading (CA) associated to the stress ratio effect and variable amplitude loading (VAL) associated to single overload. A K_{\max} failure criterion is adopted for the limit of crack growth. Fig. 2 shows effect of stress ratio on fatigue life. The fatigue crack growth rates for different stress ratio are shown on Fig. 3. The curves illustrate a general increase in da/dN with increasing R-ratio for a given ΔK . An important effect of R has been observed clearly for this material at high ΔK and at fatigue crack growth threshold stress intensity factor.

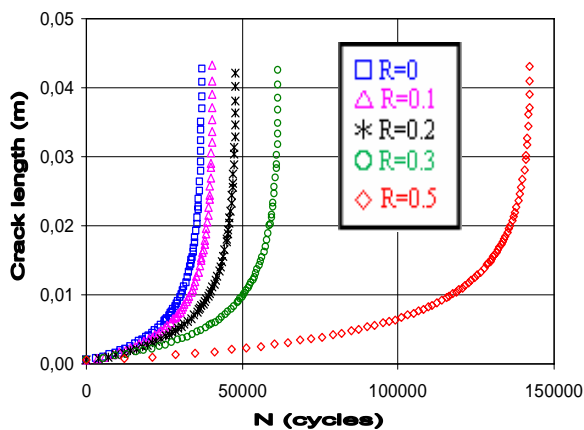


Fig. 2 Stress ratio effect on fatigue life

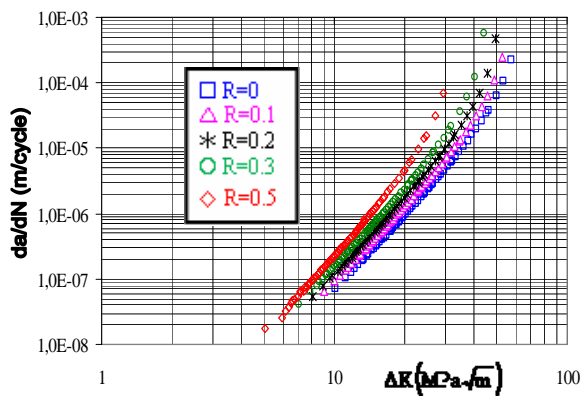


Fig. 3 Stress ratio effect on fatigue crack growth rate for 7050 T74 Al-Alloy

B. Variable Amplitude Loading (VAL)

Variable amplitude loading in this study is characterized by overload ratio "ORL = $\sigma_{\max\text{-overload}}/\sigma_{\max\text{-CA}}$ " allow to create an instantaneous yield zone resistant to crack growth. Fig. 4

show effect of single overload after 50000 cycle amplitude loading for two overload ratio (ORL=2.0, 2.5) on fatigue life. It was shown that an increasing in overload ratio increase the fatigue life of fracture. This is due to the retardation resulted from the application of overload. The retardation is characterized by retardation fatigue life N_d . A slight variation of fracture fatigue life is found between the constant amplitude and variable amplitude without delay effect. Extension of crack length in function of numbers of cycles of the batch overload load ratio is shown on Figs. 5 and 6. Numbers of cycle of retardation are indicated. Fracture fatigue life is 3.74 times for ORL=2.5 compared to fatigue life for ORL=2.0.

Result of the evolution of fatigue crack growth rates shows a decreasing of fatigue crack growth rate's (Fig. 7) for both overload ratio after applied of overload. Fig. 7 shows in detail the decrease in FCGRs which decreased from 4×10^{-8} to 1×10^{-8} m/cycle just for application of overload. In others research is shown acceleration after application of overload.

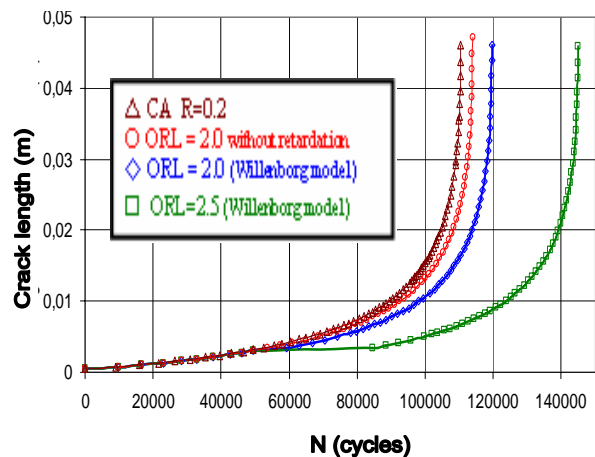


Fig. 4 Effect of overload ratio (ORL) on fatigue life delay for 7050 T74 Al-Alloy

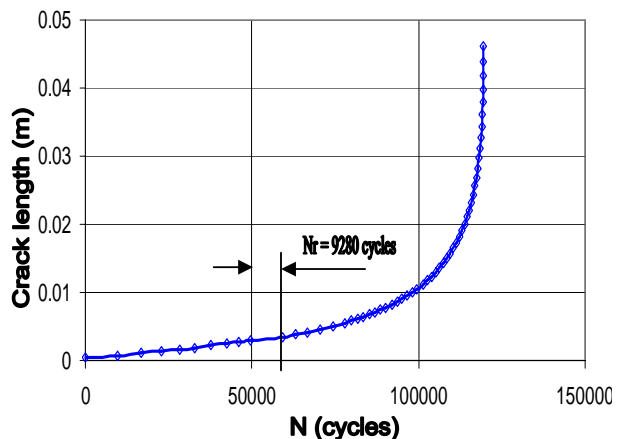


Fig. 5 Evaluation of retardation in single overload ORL= 2.0 for 7050 T74 Al-Alloy

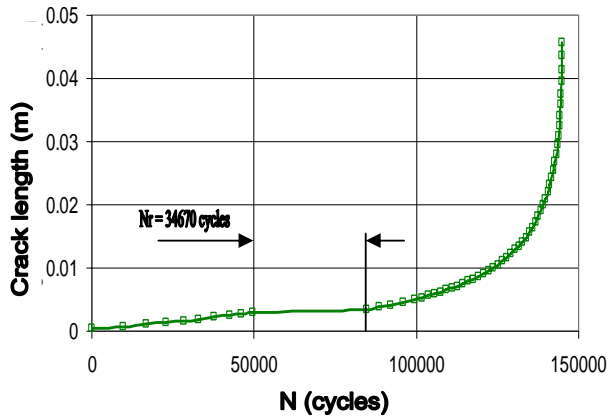


Fig. 6 Evaluation of retardation in single overload ORL= 2.5 for 7050 T74 Al-Alloy

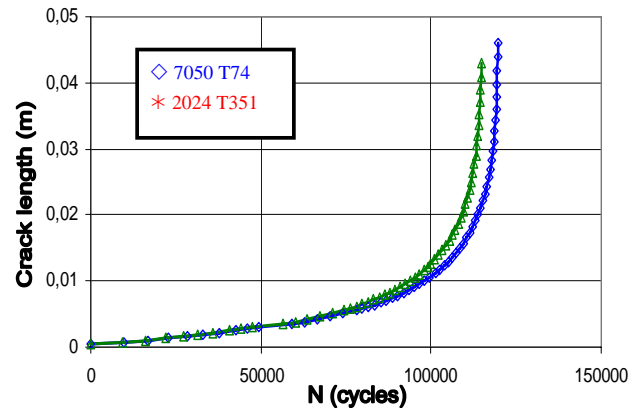


Fig. 8 Fatigue life delay for 7050 T74 and 2024 T351 Al-Alloy

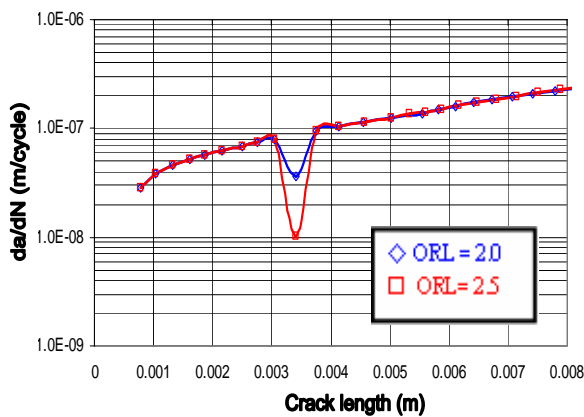


Fig. 7 Effect of overload ratio on FCGRs using generalized willenborg model

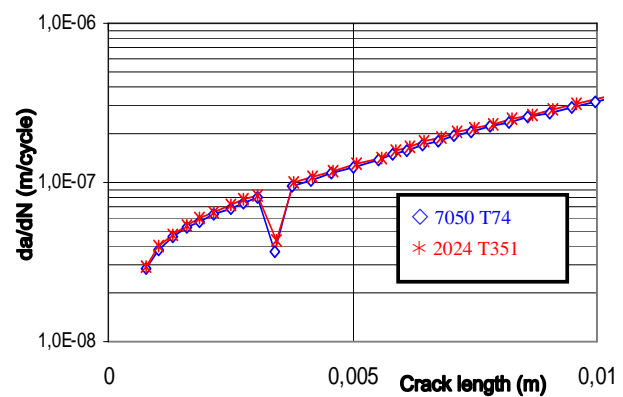


Fig. 9 Effect of overload on FCGR for 7050 T74 and 2024 T351 Al-Alloy

C. Comparison in FCGR under Same Variable Amplitude Loading between 2024 T351 and 7050 T74 Al-alloy

Both Al-Alloys are subjected to the same spectrum (variable amplitude loading with single overload) at ORL=2 and maximum constant amplitude loading $\sigma_{\max}=80$ MPa. In Fig. 8 we show the evolution of fatigue life for two specified materials. 7050 T74 Al-alloy presents good resistant comparatively to 2024 T351 Al-Alloy. A difference is shown in final fatigue life and retardation fatigue life. For the first material (7050 T74), the delayed in fatigue life is 9280 cycles but for the second (2024 T351) is 6530 cycles. In term of fatigue crack growth rate (FCGR), no high difference between studied materials is signaled after applied single overload (Fig. 9). The ratio of FCGRs for both alloys is approximately 0.85. This result shows that difference in the size of plastic zones is low.

NOMENCLATURE

a	Crack length
C	Parameter of Nasgro equation
n	Exposant of Paris_law
R	Stress ratio
R_{oy}	Yield zone created by overload
ΔK	Amplitude of stress intensity factor
K_r	Residual stress
K_{\max}	Maximum stress intensity factor
K_{\min}	Minimum stress intensity factor
N	Number of cycle (fatigue life)
da/dN	Fatigue crack growth rate
SORL	Shutoff Overload Ratio (ratio of the overload to nominal load required to effectively stop further growth under nominal loading.
x, x(ol)	crack length and crack length at overload
" α ":	stress state in a given crack growth direction

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REFERENCES

- [1] Jr J.C. Newman, J.J. Ruschau. "The stress-level effect on fatigue crack growth under constant amplitude loading". *Int. J. of Fatigue*, 29, pp 1608-1615, 2007.
- [2] J.R Mohanty, B.B Verma, P.K. Ray. "Prediction of fatigue crack growth and residual life using an exponential model: Part I (Constant amplitude loading)". *Int. J. of Fatigue*, 31, pp 418-424, 2009.
- [3] M. Benachour, A. Hadjoui, M. Benguediab, N. Benachour, (2010). "Effect of the amplitude loading on FCG". *Procedia Engineering*, 2, pp 121-127, 2010.
- [4] A.T. Kermanidis, Sp.G. Pantelakis. "Prediction of crack growth following a single overload in aluminium alloy with sheet and plate microstructure". *Engineering Fracture Mechanics*, 78, pp 2325-2337, 2011.
- [5] R. Kumar, S.B.L. Garg. "Effect of single and intermediate tensile overload cycles on effective stress range ratio in 6063-T6 Al-alloys". *Int. J. of Press. Vess. & Piping*, 36, pp 257-68, 1989.
- [6] D.M. Corbly, P.F. Packman. "On the influence of single and multiple peak overloads on fatigue crack propagation in 7075 T6511 aluminum". *Engineering Fracture Mechanics*, 5, pp. 479-497, 1973.
- [7] G.R. Chananani, B.J. Mays. "Observation of crack closure behaviour after single overload cycles in 7075-T6 single edge notched specimens". *Engineering Fracture Mechanics*, 9, pp 65-73, 1977.
- [8] O.E. Wheeler. "Spectrum Loading and Crack Growth", *Transaction of the ASME, Journal of Basic Engineering*, pp. 181-186, 1972.
- [9] J. Willenborg, R. M. Engle, H. A. Wood. "A crack growth retardation model using an effective stress concept" AFFDL-TM-FBRgl-7 (Air Force Dynamics Laboratory, Dayton, OH, USA), 1971.
- [10] K. Sadananda, AK. Vasudevan. "Analysis of overloads effects and related phenomena". *Int. J. of Fatigue*, 21, pp. S233-246, 1999.
- [11] F. Taheri, D. Trask, N. Pegg. "Experimental and analytical investigation of fatigue characteristics of 350WT steel under constant and variable amplitude loadings" *Journal of Marine Structure*, 16, pp. 69-91, 2003.
- [12] J.P. Gallagher. "A Generalized Development of Yield-Zone Models" AFFDL-TM-74-28, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, 1974.
- [13] C.M. Ward-Close, A.F. Blom, R.O. Ritchie. "Mechanisms associated with transient fatigue crack growth under variable-amplitude loading: an experimental and numerical study". *Engineering Fracture Mechanics*, 32, pp 613-38, 1989.
- [14] R.H. Christensen (1959). "Metal fatigue". New York: McGraw-Hill.
- [15] J.F Knott, A.C. Pickard. "Effects of overloads on fatigue-crack propagation: aluminium alloys". *Metal Science*, 11, pp 399-404, 1995.
- [16] Ch. Bichler, R. Pippan. "Effect of single overloads in ductile metals: a reconsideration", *Engineering Fracture Mechanics*, 74, pp 1344-1359, 2007.
- [17] L.P. Borrego, J.M. Ferreira, J.M. Pinho da Cruz, J.M. Costa. "Evaluation of overload effects on fatigue crack growth and closure". *Engineering Fracture Mechanics*, 70, pp 1379-1397, 2003.
- [18] D.M. Corbly, P.F. Packman. "On the influence of single and multiple peak overloads on fatigue crack propagation in 7075 T6511 Al". *Engineering Fracture Mechanics* 5, pp. 479-497, 1973.
- [19] O. Vardar. "Effect of single overload in FCP", *Engineering Fracture Mechanics*, 30, pp 329-335, 1988.
- [20] C. Bathias, M. Vancon. "Mechanisms of overload effect on fatigue crack propagation in aluminium". *Engineering Fracture Mechanics*, 10, pp 409-424, 1978.
- [21] S. Matsuoka, K. Tanaka. "Delayed retardation phenomenon of fatigue crack growth resulting from a single application of overload". *Engineering Fracture Mechanics*, 10, pp. 515-525, 1978.
- [22] S. Matsuoka, K. Tanaka, M. Kahawara. "The retardation phenomenon of fatigue crack growth in HT80 steel". *Engineering Fracture Mechanics*, 8(3), pp 507-523, 1976.
- [23] C. Robin, R.M. Pelloux. "Fatigue crack growth retardation in an aluminum alloy". *Materials Science and Engineering*, 44, pp 115-120, 1980.
- [24] G.A. Harmain. "A model for predicting the retardation effect following a single overload". *Theor. Appl. Fract. Mech.*, 53, pp 80-88, 2010.
- [25] R. Kumar, S.B.L. Garg. "Effect of Periodic Bands of Overloads on Crack Closure". *Int. J. Pres. Ves. & Piping* 38, pp 27-37, 1989.
- [26] Rui Bao, Xiang Zhang. "Fatigue Crack Growth Behaviour and Life Prediction for 2324-T39 and 7050-T7451 Aluminium Alloys under Truncated Load Spectra". *Int. J. of Fatigue*, 32(7), pp 1180-1189, 2009.
- [27] J.C. Newman. "Predicting failures of specimens with either surface cracks or corner crack at holes". TN D-8244, NASA Langley Research Center, 1976.
- [28] J.A. Harter. "AFGROW users guide and technical manual: AFGROW for Windows 2K/XP". Version 4.0011.14, Air Force Research Laboratory, 2006.