“Analysis of fatigue crack growth retardation due to overloading by using AFGROW”

Project Review and Planning Report

Submitted in partial fulfillment of the requirements

For the award of

Master of Technology

In

Machine Design and Analysis

By

Rajesh Babu. Gunde

Roll No: 20503011

Department of Mechanical Engineering

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Under The Esteemed Guidance of

Prof. P.K. RAY

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National Institute of Technology

Rourkela

CERTIFICATE

This is to certify that the thesis entitled, **"Analysis of fatigue crack growth retardation due to overloading by using AFGROW"** submitted by **Mr. Rajesh Babu.Gunde** in partial fulfillment of the requirements for the award of MASTER of Technology Degree in **Mechanical Engineering** with specialization in **"Machine Design and Analysis"** at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him/her under my/our supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma.

Date:

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I also thankful to my batch mates who gave me the full support throughout my project work and I also extending my thanks to my friend **M.Kamal Kumar** (dept.ECE) for his valuable suggestions to my thesis work.

Rajesh Babu.Gunde

CONTENTS

Abstract

The effect of mode I and mode II overload on subsequent mode I crack propagation is studied on single edge notch specimen of Aluminum alloy. The application of overload spike during constant amplitude high cycle fatigue introduces a large plastic zone which enhances the magnitude and size of compressive residual stress field in the vicinity of the crack tip. This enhanced compressive residual stress field reduces the available crack tip driving force, thus causing a reduction in fatigue crack growth rate. It has been observed that the number of cycles to failure increases with increase in the overload application angle.

The material used in the present investigation was aluminum alloy (Zn-4.6, Mg-1.4, Mn-0.5, Cr-0.1, Zr-0.1, Ti-0.03) having yield strength of 250 MPa. Single edge notched specimens of dimensions 52 mm*170 mm*6.5 mm were prepared in the LT-direction. The notches were of flat type cut with jewellary saw up to a length of 15mm. Before the fatigue test, the notched specimens were precracked up to a length of 16mm. The fatigue tests were carried out in tension-tension constant stress amplitude mode using sinusoidal loading conditions in an Instron-4553 electromagnetic resonance (EMR) machine. The tests were performed at a stress ratio R=0.1 and loading range of ΔP=7000 Newton's. For the values obtained from the experiments we get the graphs. To calculate the plastic zone size for the applied overload we have to write the maximum fitting curve for the values obtained from the experimental data. The experimental work is carried out for the specimen on INSTRON machine and the experimental results can be noted down.

In the present work the fatigue crack growth retardation is obtained by AFGROW software using different boundary conditions and plastic zone sizes are obtained for mode I overloads. Plastic zone sizes are also calculated from experimental results and comparison of the experimental results with the simulation results are carried out.

Nomenclature

C	Paris exponent
m	wheelers parameter
R_y	cyclic plastic zone size
α	shaping component
K_{max}	maximum stress intensity factor
σ_y	yield stress of the material (250 MPa)
K_I	stress intensity factor for mode I
f (g)	Geometry correction factor
b	Thickness of the specimen
w	Width of the specimen
N	number of cycles
a	crack length
Z_{ST}	overload plastic zone size
Z_D	cyclic plastic zone size
K^{OL}	stress intensity factor at overloading point

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Chapter 1

INTRODUCTION

Introduction:

1.1 Basic analysis of crack growth rate:

The study of fatigue crack propagation in metals has been of foremost importance in regards to how well engineering structures withstand the complex loading conditions that they often encounter. Many studies have been carried out to investigate fatigue crack propagation due to a single- or mixed-mode only. But in practice, the loading could be variable and the flaw growth direction changeable. So it is necessary to consider the effects of different modes acting sequentially on the characteristics of a propagating crack. For many fatigue-critical parts of structures, vehicles and machines, fatigue crack propagation under service conditions generally involves random or variable amplitude, rather than constant amplitude loading conditions. Significant accelerations and/or retardations in crack growth rate can occur as a result of these load variations. Thus, an accurate prediction of fatigue life requires an adequate evaluation of these load interaction effects. Crack growth in structures is a function of the amplitude, stress ratio, frequency and the random nature of the load. The assessment of the behavior of structure subject to variable amplitude loading (VAL) is more complex than when subjected to constant amplitude loading. The majority of fatigue crack growth studies is concentrated on single-mode loading and is usually performed under mode-I loading condition. Unfortunately, single- mode loading seldom occurs in practice, and in many cases cracks are not normal to the maximum principal stress direction. Under mixed-mode loading conditions a crack will not grow in a self-similar manner, but instead deviates from its original direction. Furthermore, at micro scale level, depending on the micro structural features (e.g. grain size, inclusion size and shape, and reinforced composite microstructures) such deviations in the crack direction may take place even under pure mode-I loading condition. A major influencing parameter to be considered is the influence of load history, which is usually variable. Overloads (exceedance of yield) during a load cycle are of particular significance, as the magnitude and sense of the overload can have either a positive or negative effect on the fatigue crack propagation. Large tensile overloads (such as a ship encountering a storm), may create residual compressive stresses just beyond the crack tip and retard the crack growth rate for a number of cycles after the occurrence of the overload (OL). The amount of retardation depends upon a number of material and loading factors, which will be examined in more detail. The area of fracture mechanics analysis of cracks is fairly well established as long as restrictions are made to small scale plasticity, constant amplitude, fairly large crack size and uniaxial loading. The fracture mechanics approach is based on the assumption that the crack tip conditions are uniquely defined by a single loading parameter, e.g. the stress intensity factor. One equation of the type shown in, is Paris law, which can be written as

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

where C and m are material parameters.

If the crack growth is studied experimentally, a plot of d*a*/dN vs.ΔK will have a shape as shown in F IG. 1. From this plot, it can be concluded that Paris law should mainly be used to model crack growth in region II. There are several other models that are aimed at model all (or some parts of) theda/dN - ΔK relationship. The fatigue life can be directly estimated by integrating Paris law. However, this procedure presumes that region II includes the dominating part of the fatigue life.

Two interesting features of the curve in **FIG. 1** are the existence of a crack growth threshold K_{th} and the existence of a critical value K_c . If the stress intensity ranges do not exceed K_{th}, there will be no propagation of existing cracks. At the other extreme, K_{max} will approach the fracture toughness and the material will fail.

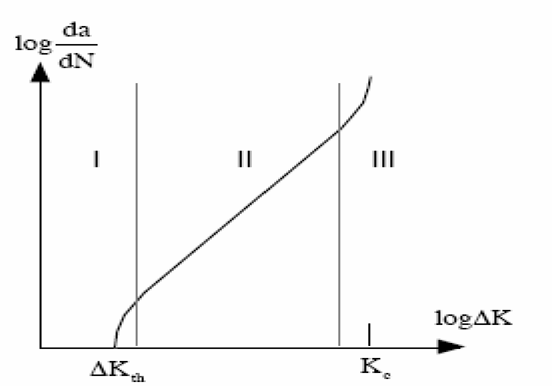

Fig: 1.1 Fatigue crack growth behavior in metals as described by the crack growth rate (da/dN) vs. the width of the stress intensity factor during one loading cycle (ΔK).

The Paris law is simple to use and requires the determination of two curve fitting parameters that are obtainable as long as fatigue crack growth data are available, and the data follows a linear relationship. Its limitation is however that it is only capable of describing data in region II of the crack growth rate curve, and does not consider the effect of stress ratio. Moreover, the model does not consider crack growth in the first region of the crack growth curve (i.e., the threshold region), nor the accelerated growth in the third region of the curve.

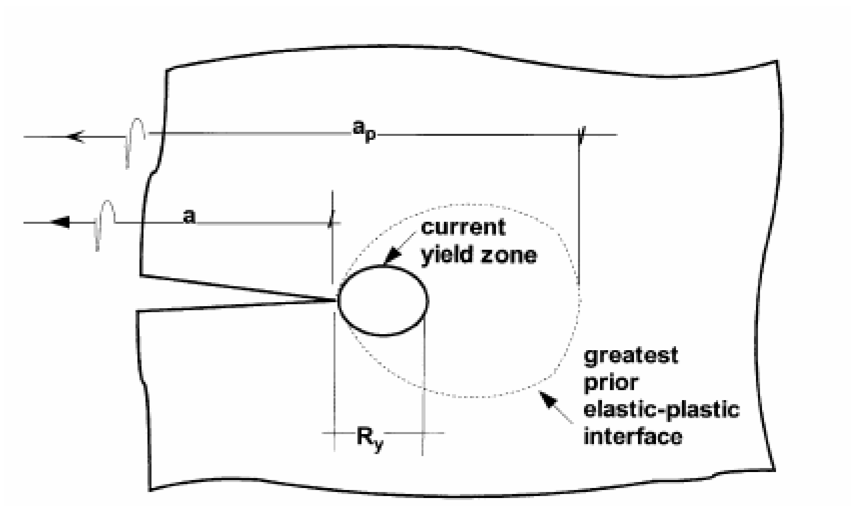

Fig 1.2: Crack tip yield zones

When the crack has propagated through the overload zone, the current yield zone is equal to the greatest of the elastic-plastic interface and $ø_R$=1 This corresponds to no retardation and thus the fatigue crack growth rate reduces to that of constant amplitude loading, da/dN=f(ΔK,R). The plastic zone size is calculated by using an appropriate equation. Wheeler suggested using the following relationship, which is applicable to plane strain condition.

$$R_y = \frac{1}{\alpha \Pi} \left(\frac{K_{max}}{\sigma_y} \right)^2$$

The shaping exponent, a; is determined by empirically fitting the variable amplitude loading test data and it generally depends on the material and the nature of the load spectrum that is being considered. Therefore, for a different loading scenario or load spectrum type, the shaping exponent must be re-calibrated; otherwise, serious errors will result.

1.2 Residual stresses:

The loading of a structure is divisible into primary and secondary stresses. Stresses due to the externally applied loads that can cause collapse of the structure fall into the primary group. The stresses in the secondary group, including residual stresses, are not capable of collapsing the structure, but they can increase or decrease fatigue life of a component.

In a cracked component, the externally applied load P causes yielding in the material in front of the crack tip, thus creating a monotonic plastic zone. Due to the proportional plastic flow, the components of the plastic strain tensor remain in constant proportion to one another throughout the plastic zone. During unloading, a reverse plastic flow is instigated leading to the formation of a reversed flow zone, which in fact is embedded within the monotonic plastic zone as shown in figure

The general opinion on residual stresses is that they reduce the crack growth rate as a direct effect apart from crack closure. The investigation by Blazewicz [8] showed that the residual stress is active in the wake of the crack because it promotes crack surface contact behind the crack tip, which in turn leads to crack closure and eventually crack growth retardation. His conclusions imply that the residual stress ahead of the crack tip is relatively insignificant and cracks only grow when they are open.

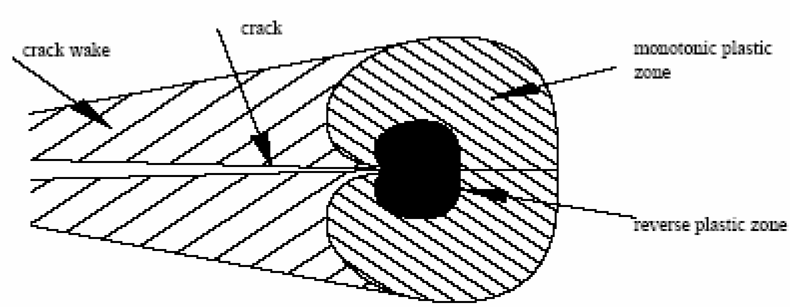

Fig: 1.3 Monotonic and reverse plastic zones

This thesis work includes numerical analysis to simulate the crack growth retardation due to single overload induced residual stress field at the crack tip by using AFGROW software and compare those results with the experimental results. The first part of the numerical analysis provides a significant insight to understand the mechanism of overload induced residual stress field in spite of its limitation. In this work, the crack tip displacement is recorded as the crack growth length by using the AFGROW software. In second part of the numerical work, modeling crack region and calculating the fracture parameters like plastic zone size are focused on. The plastic zone size calculations are carried out by using stress analysis procedure by using MATLAB and compare those results with the experimental results obtained.

Chapter 2

LITERATURE SURVEY

Literature survey:

2.1 Introduction to fatigue crack growth:

Cracks compromise the integrity of engineering materials and structures. Under applied stress, a crack exceeding a critical size will suddenly advance breaking the cracked member into two or more pieces. This failure mode is called fracture. Even sub-critical cracks may propagate to a critical size if crack growth occurs during cyclic (or fatigue) loading. Crack growth resulting from cyclic loading is called fatigue crack growth (FCG). Because all engineering materials contain micro structural defects that may produce fatigue cracks, a damage tolerant design philosophy was developed to prevent fatigue failure in crack sensitive structures. Damage tolerant design acknowledges the presence of cracks in engineering materials and is used when cracks are expected. Both sudden fracture, and fracture after FCG, must be considered as failure modes. Because initial critical defects are rare in well-designed engineering structures [1], FCG is of primary concern here. The stress intensity factor, K, was initially used to quantify crack-tip damage for fracture scenarios. Fracture was shown to occur when the crack-tip stress intensity factor reached a critical value, Kc, independent of crack size or net applied stress [2]. This observation led to the concept of crack similitude, *i.e.* cracks of different length will fracture at the same K_c.

2.2 Plane stress and plane strain conditions:

The nature of plastic deformation near the crack tip is strongly influenced by the Two-dimensional idealization assumed. The permanent elongation of material in the direction normal to the crack requires the transfer of material from somewhere in the cracked body due to incompressibility requirements during plastic deformation. Under plane-stress, a potential mechanism of material transfer is obvious. Since out-of-plane deformation is not constrained, material can be transferred from the thickness direction to the axial direction. However, the mechanism of material transfer postulated for plane stress is not admissible for plane-strain.

2.3 Constant amplitude loading:

Fracture mechanics analysis and crack similitude was modified for fatigue cracks by Paris [3]. Fatigue crack growth rates (increment of crack growth per load cycle, d*a*/dN) were related to ΔK, the cyclic range of crack-tip stress intensity, for constant amplitude loading. A schematic of typical constant amplitude load cycles are shown in Figure 1.1, where the stress intensity factor, K, is plotted as a function of time. As indicated by the solid curve, the stress intensity factor oscillates between minimum and maximum values, K_{min} and K_{max}, respectively. Arrows indicate change in K with increasing time. ΔK is shown schematically on the right side of the figure and is defined as K_{max} - K_{min}. Another useful parameter to describe constant amplitude loading is the load ratio, R, defined in the figure (lower right corner) as the ratio of K_{min} and K_{max}. Paris implied that similitude exists for fatigue cracks subject to the same ΔK. In other words, fatigue cracks of different length but subject to the same ΔK will grow at the same FCG rate, d*a*/dN. Therefore, FCG data obtained from laboratory specimens (of convenient size) can be used to predict the FCG response for any crack configuration.

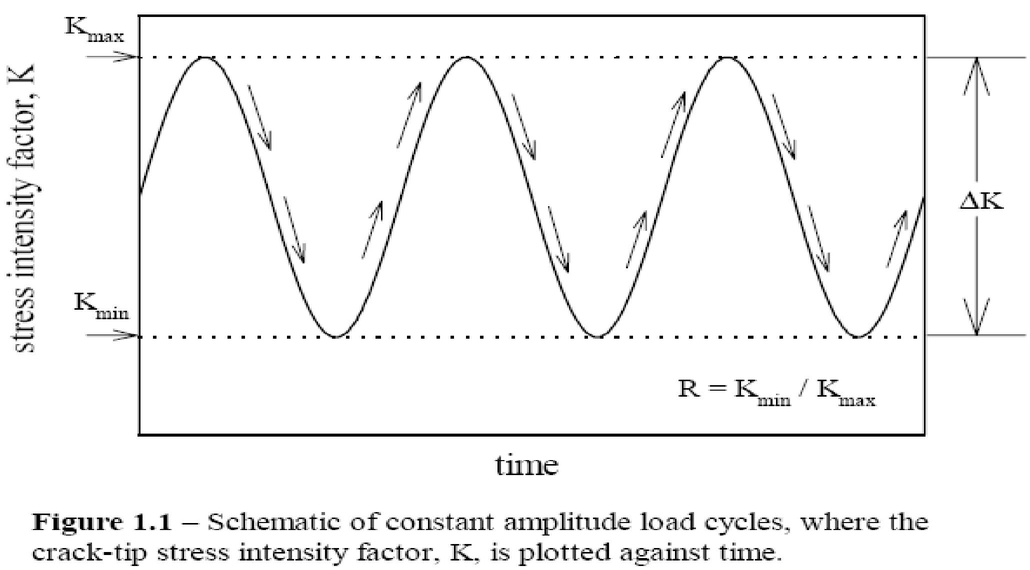

Fig 2.1: schematic of constant amplitude load cycles, where the crack-tip stress intensity factor, K, is plotted against time.

The total period of fatigue life may be considered to consist of three phases: (1) initial fatigue damage that produces crack initiation, (2) propagation of a crack or cracks that results in partial separation of a cross section of a member, until the remaining uncracked cross section unable to support the applied load, and (3) final fracture of the member. The typical log-log plot of *da/dN* versus ΔK is shown schematically in Figure 1-1. The sigmoidal shape can be divided into three major regions. Region I is the near threshold region and exhibits a threshold value, ΔKth, below which there is no observable crack growth. Below ΔKth, fatigue cracks are characterized as non propagating cracks. Micro structure, mean stress, frequency, and environment primarily control region I crack growth. Region II shows essentially a linear relationship between *log da/dN* and $log\Delta K$, which corresponds to Paris equation [4]

$$da/dN = C\left(\Delta K\right)^m \qquad (1)$$

Here m and C are material constants. Region II (Paris Region) fatigue crack growth corresponds to stable macroscopic crack growth that is typically controlled by environment. Microstructure and mean stress have less influence on fatigue crack growth behavior in region II than region I. In the region III the fatigue Crack growth rates are very high as they approach instability, and little fatigue crack Growth life is involved. This region is controlled primarily by fracture toughness Kc, Which in turn depends on the microstructure and environment.

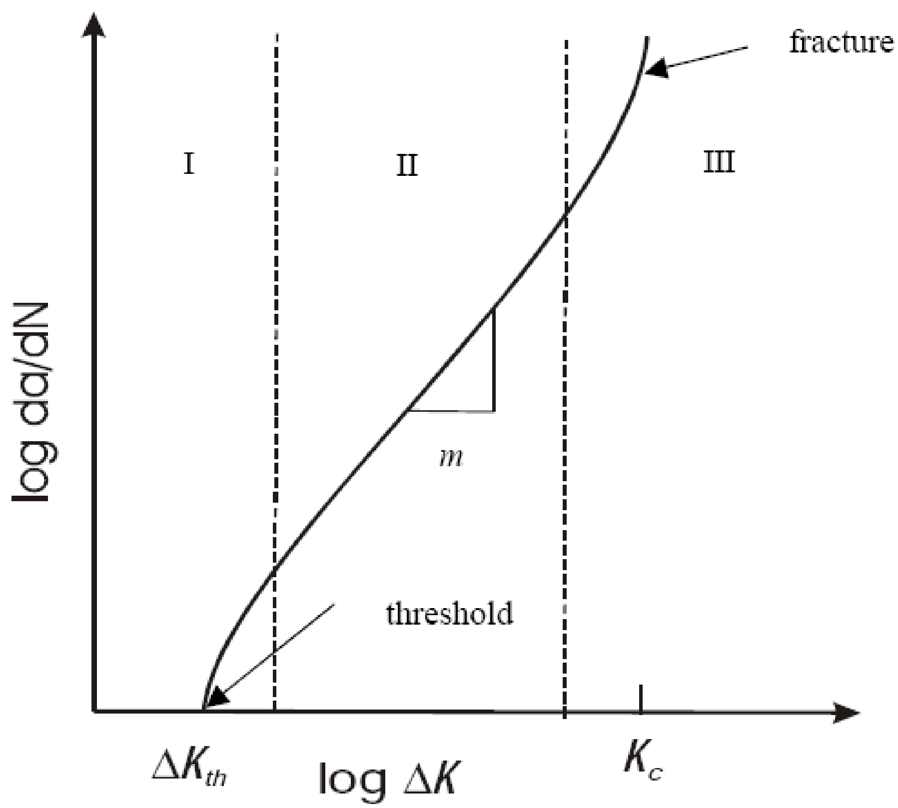

Figure 1-1 Typical Fatigue Crack Growth Behavior in Metals

Fig 2.2: typical fatigue crack growth behavior in metals

2.4 Variable Amplitude Loading:

It may be argued that crack closure analyses are primarily of interest when considering variable amplitude loading. However, the majority of research has considered only constant amplitude loading. Some effort has been directed toward simple load histories such as low-high, or high-low, or a single overload. This project has been used to explain crack growth acceleration and retardation. Due to the computationally intensive nature of closure modeling with finite element analysis, complex load histories are generally not suitable for study, since a large amount of crack growth and a subsequently large number of load cycles are required.

As described above, there is a history effect involved in the propagation of cracks. The mechanism behind this is similar to the mechanism of plasticity induced crack closure, as described earlier. In an overload application the overload will cause plastic flow in an area ahead of the crack tip. Because of redistribution of stresses in unloading, there will be a compressed zone just ahead of the crack tip. If the overload is high enough, there can even be a compressive yield zone ahead of the crack, FIG. 4. This will lead to retardation in the crack growth rate, since the compressive zone will both reduce the effective stress intensity factor (due to crack closure) and also reduce the tensile stress ahead of the crack tip in the following load cycles.

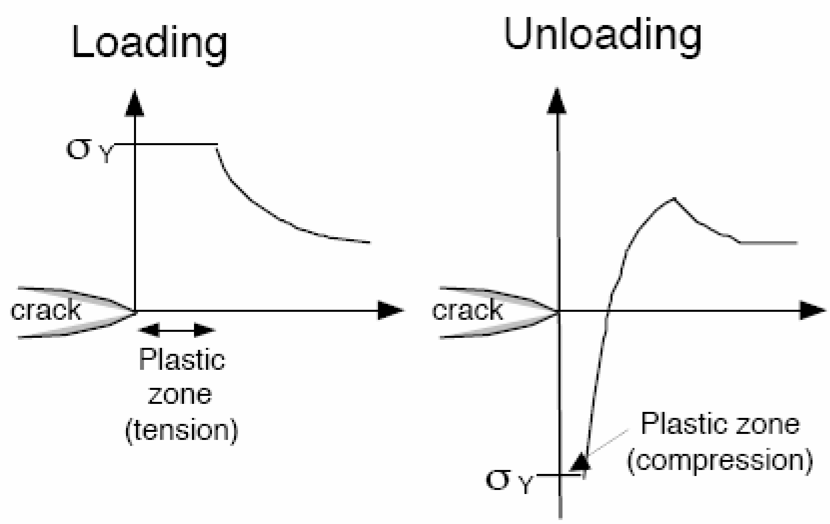

Fig 2.3: The influence of a compressive overload.

One model for analyzing this behavior is the Wheeler model, which compares a "current" plastic zone (which is the plastic zone ahead of the crack tip due to the current load cycle), to the tensile plastic zone due to the overload. retardation effects are assumed to take place only when the "current" plastic zone is within the overloading plastic zone.

The study of fatigue crack propagation in metals has been of foremost importance in regards to how well engineering structures withstand the complex loading conditions that they often encounter. Many studies have been carried out to investigate fatigue crack propagation due to a single- or mixed-mode only. But in practice, the loading could be variable and the flaw growth direction changeable, so it is necessary to consider the effects of different modes acting sequentially on the characteristics of a propagating crack.

For many fatigue-critical parts of structures, vehicles and machines, fatigue crack propagation under service conditions generally involves random or variable amplitude, rather than constant amplitude loading conditions. Significant accelerations and/or retardations in crack growth rate can occur as a result of these load variations. Thus, an accurate prediction of fatigue life requires an adequate evaluation of these load interaction effects.

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The majorities of fatigue crack growth studies are concentrated on single-mode loading and usually are performed under mode-I loading condition. Unfortunately, single-mode loading seldom occurs in practice, and in many cases cracks are not normal to the maximum principal stress direction. Under mixed-mode loading conditions a crack will not grow in a self-similar manner, but instead deviates from its original direction. Furthermore, at microscale level, depending on the micro structural features (e.g. grain size, inclusion size and shape, and reinforced composite microstructures) such deviations in the crack direction may take place even under pure mode-I loading condition.

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2.5 Use of constant amplitude fatigue models for modeling variable amplitude fatigue crack growth:

The simplest approach to fatigue crack growth for variable amplitude loading is to neglect all sequence effects and determine the crack growth on a cycle-by-cycle basis in conjunction with a constant amplitude fatigue crack growth law. The advantages of this approach are that it is relatively simple, inexpensive and not very time consuming. If it has been previously determined that the load sequencing effects may cancel each other or are entirely unpredictable, this may be the best method to use because nothing would be gained by conducting a more detailed analysis. Though our investigation included the assessment of most of the available constant and variable fatigue crack growth models, for the sake of brevity, we provide a summary of those models that were used for the comparison of our experimental data.

In reference to constant amplitude models, most models relay on parameters that are usually based on the availability of extensive amounts of fatigue data. Perhaps the most well-known and widely used method for predicting CAL is a power law described by Paris and Erdogan [2], commonly known as the Paris law, described by

$$\frac{da}{dN} = Cp\left(\Delta K\right)^{mp}$$

2.6 Linear elastic crack tip stress field:

Vasilios zitounis [5] suggested that the damage tolerance approach uses linear elastic fracture mechanics to analyze crack or flaws. Irwin has presented solution for crack-tip stress distributions, using the analytical method of Westrgaard. The solutions were associated with the three modes of fracture. Each mode involves different Crack surface displacements.

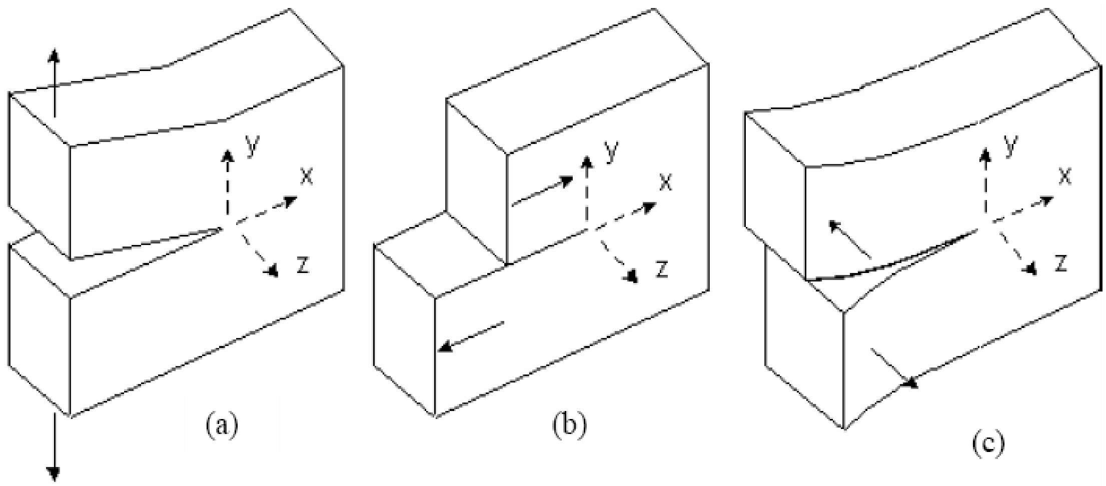


Fig 2.4: different modes of loading at the crack tip

Mode I is the tensile opening mode in which the crack faces separate in a direction normal to the plane of the crack. Mode II is the in-plane sliding mode in which the crack faces are mutually sheared in a direction normal to the crack front. Mode III is the tearing or the anti-plane shear mode in which the crack faces are sheared parallel to the crack front. The present study is only concerned with Mode I fracture. Therefore, only Mode I stress crack-length relations will be presented. For the notation of figure 3, the crack tip stresses are found to be:

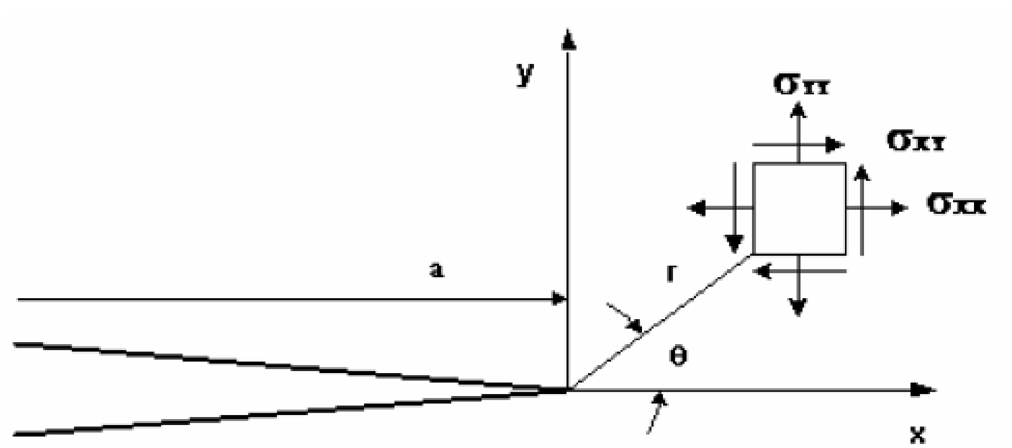


Fig 2.5: Coordinate system and stresses at the near crack-tip region

The stress intensity factor is a measure of the intensity of the near-tip fields under linear elastic conditions. The factor provides a unique measure of the intensity of stress within an annular zone ahead of the crack tip.

Theoretically, this means that at the crack tip the material is subjected to infinite stresses. This is not possible and what happens is that the material is plastically deformed near the crack tip and as a result stresses are lowered to a first approximation to the level of yield strength of the material (figure 5).

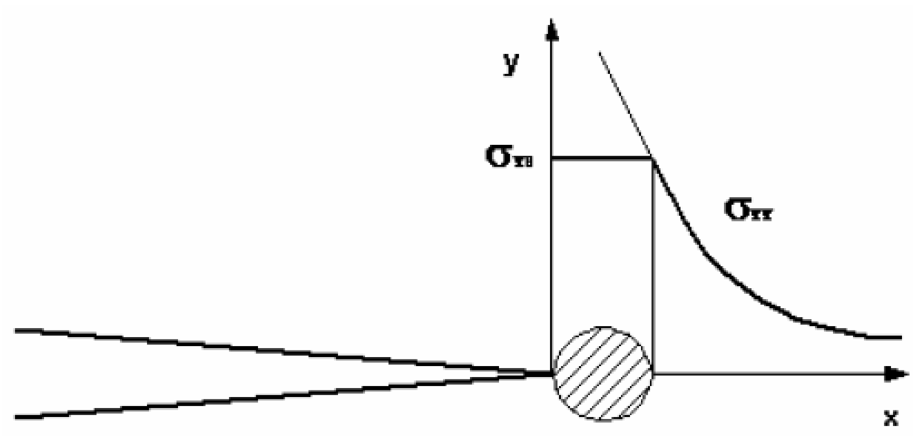


Fig 2.6: Crack tip plastic zone under small-scale yielding condition

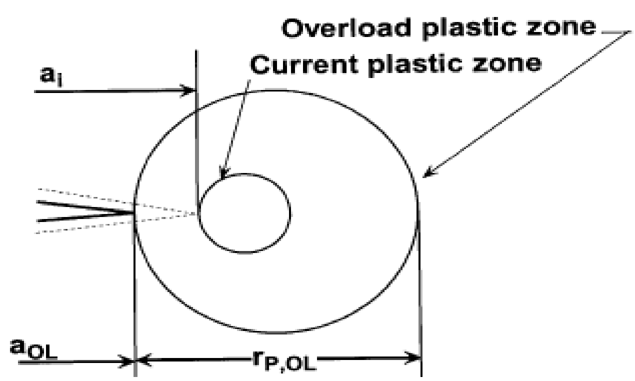


Fig. 1. Schematic of terms defining Wheeler's retardation model

Fig 2.7: plastic zone formation due to overloading

2.7 Cyclic loading:

The application of stress σ on a cracked solid creates a stress field near the crack tip, which can be characterized by the stress intensity factor K_I under small scale yielding conditions. Under this condition, the material yields ahead of the crack tip and develops a monotonic plastic zone of dimension given by the equation

$$r_p = (\pi / 8)(K_I / \sigma_{YS})^2$$
.

When the direction of loading reverses, the local stress is reduced to a level corresponding to a stress intensity factor K_{II}. The re-distribution of the stresses in the near crack tip region because of the reduction form K_I to K_{II} will lead to reverse plastic flow and the formation of plastic zone in front of the crack tip embedded within the monotonic plastic zone.

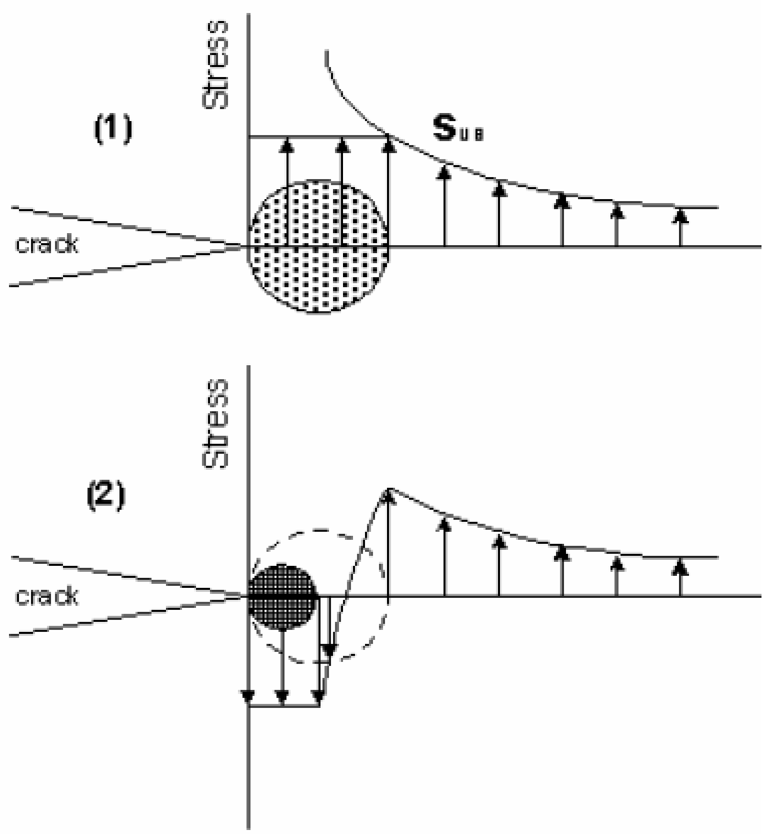


Fig 2.8: Monotonic and reversed plastic zone development at the crack tip during cycling Unloading.

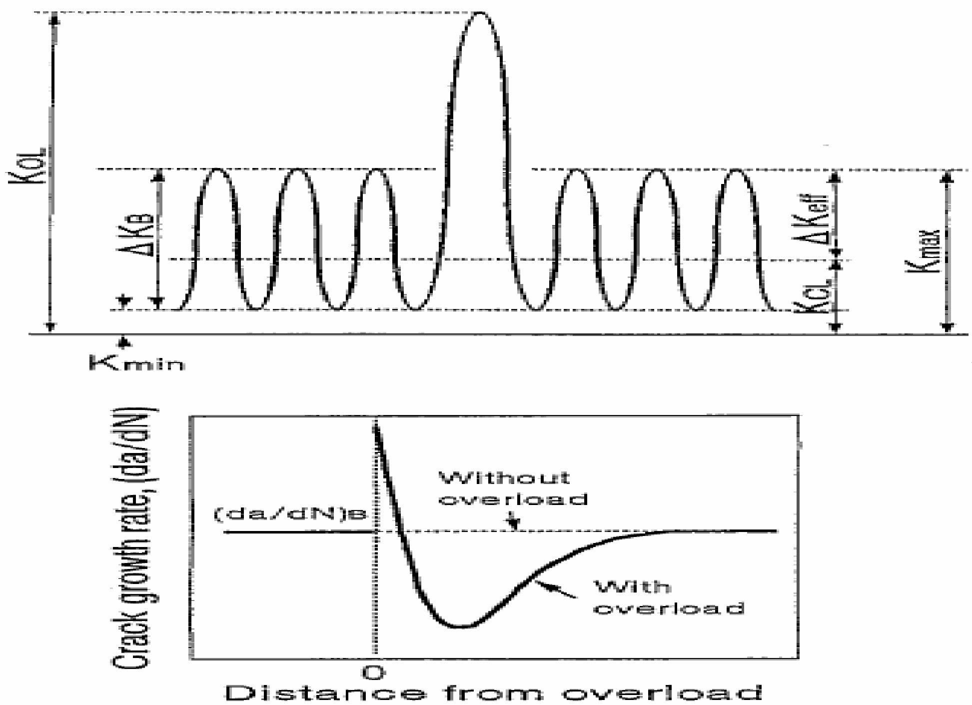


Fig 2.9: specimen overloading

In [6], a finite element analysis using ANSYS 5.7 was conducted to simulate the crack-growth retardation due to the single-peak overload under cyclic loadings. The objective of simulation was to predict the crack-growth retardation due to the influence of overload in Aluminum Alloy with a center pre-cracked specimen. The compressive residual stress at crack-tip after the overload is the major factor causing retardation (figure 2.9). Residual stresses are produced when one region of a part experiences permanent plastic deformation while other regions of the same part either remain elastic or are plastically deformed to a different degree. The overload introduces a large plastic zone in which the material experiences permanent deformation. Upon unloading, the surrounding elastic material attempts to resume its original size (the plastic zone is permanently deformed) and by doing so, exerts compressive stresses on the plastically deformed material at the crack tip (figure 2.10). When the crack has grown through the region (compressive plastic zone) of residual stresses after a further period of cyclic loadings, the crack growth resumes at the propagation rate expected under constant amplitude cyclic loadings. It means that if compressive residual stress is introduced by the controlled yielding (overload), the fatigue life of a component will be significantly increased. This enhancement of fatigue life depends on the peak and magnitude of the overload ratio.

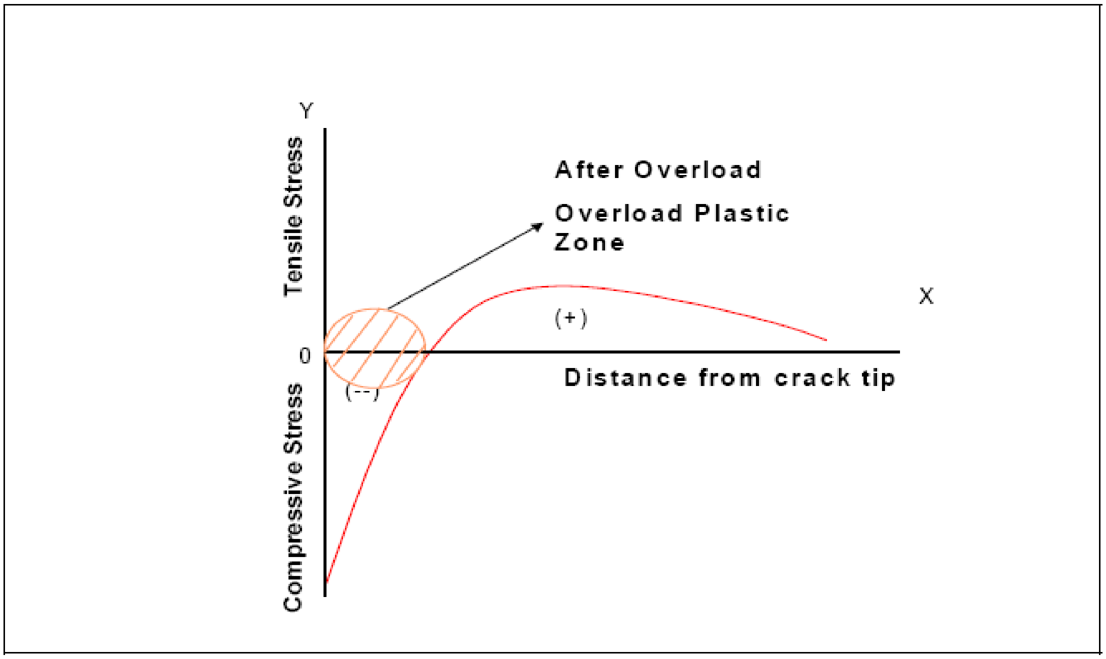


Figure 2.10: residual compressive stresses ahead of crack tip

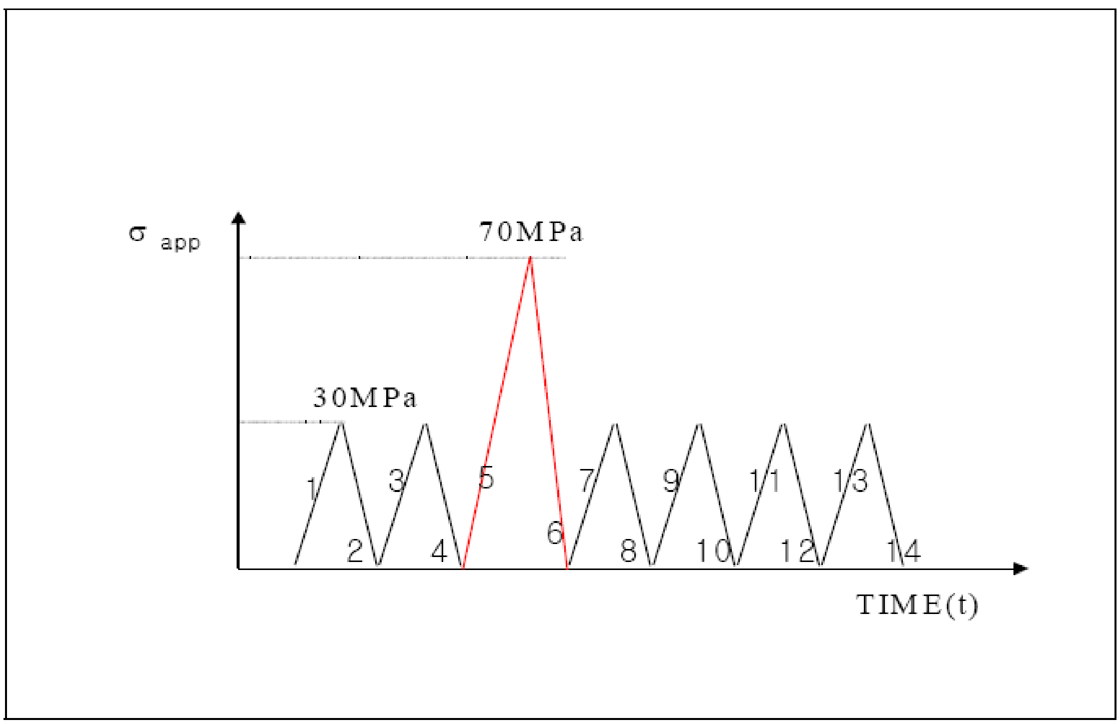


Fig 2.11: overloading in cyclic loading

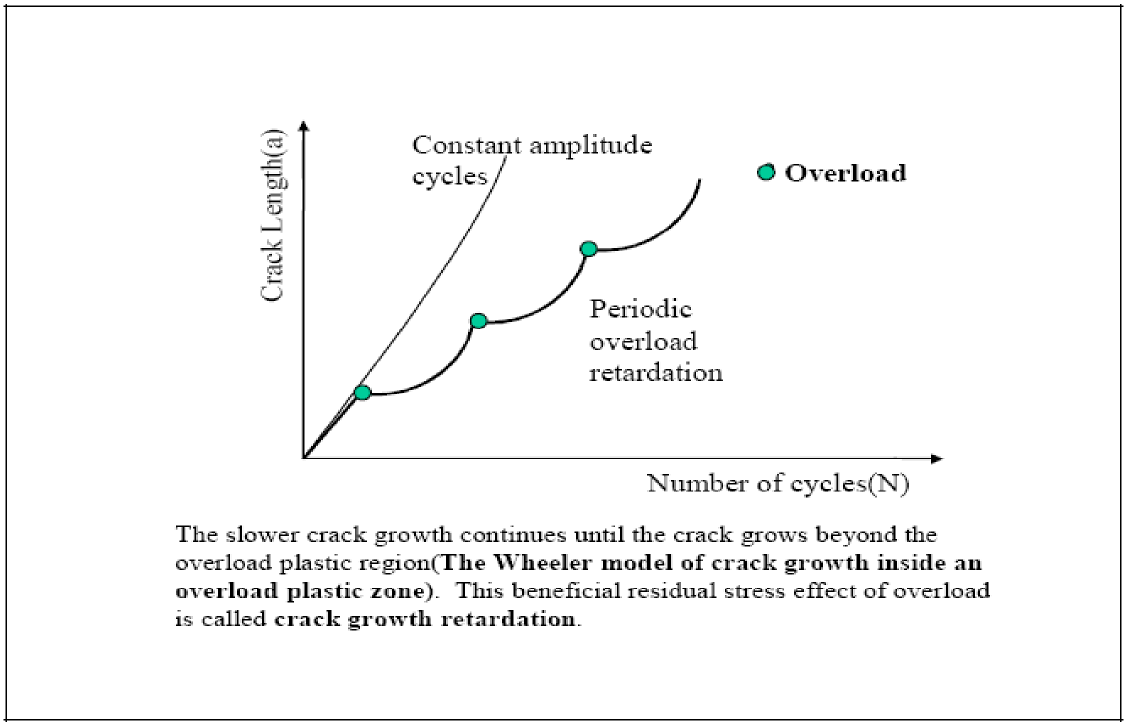


Figure 2.12: fatigue life enhancement due to overloads

During the crack propagation, the crack growth is affected by environmental conditions, material properties, and loading conditions including the magnitude and stress ratio of overload. Careful attention must be given to a series of critical decisions about element type, mesh method (Mapped mesh, Free mesh), element length size, the selection of material behaviors, model design (geometry of the specimen, symmetric boundary condition or loading condition) and crack tip modeling (singular point) if the analysis is to be reliable. A model for the elastic-plastic finite element simulation in plane stress is presented by running a nonlinear analysis with ANSYS 5.7. The bilinear inelastic isotropic hardening (an elastic-plastic model) is considered as element material behavior. Large deformation effects were also considered during the nonlinear analysis. The crack growth simulation was based on the stress-strain curve of the node point near crack-tip. The displacement near crack-tip, the stress-strain curve and stress redistribution along the crack plane after overload were investigated during cyclic loadings. The specific results that are being aimed for are the effects of overload induced residual compressive stresses on the crack growth near the crack tip.

Chapter 3

EXPERIMENTAL PROCEDURE

Experimental procedure:

The machine used for the fatigue test is INSTRON-8502. It is a fully computerized servo hydraulic type machine having Instron da/dN software for measurement and recording (online data logging) of fatigue crack propagation.

3.1 Materials and fabrication:

3.1.1 Specimen material:

The material used for study is Aluminum alloy of thickness 6.5mm. The chemical composition is given in the following table.

The chemical composition of aluminum alloy is given in Table1:

Table 3.1.Composition (%) of the aluminum alloy

Si	Fe	Mn	Mg	Cu	Zn	Ti	Al
0.22	0.37	0.46	1.2	0.05	4.6	0.008	93.1

3.1.2 Fixture material:

Material used for the fixture (Mode I & mode II) is EN24 steel whose composition is as follows.

Table 3.2. Composition (%) of the fixture material

C	Mn	Ni	Si	Cr	Mo
0.35-0.45	0.40-0.70	1.25-1.75	0.10-0.35	0.90-1.30	0.20-0.35

3.1.3 Pin material and its manufacturing:

Pin material used is Mild steel and Manufacturing done by turning and heat treated at 950^{o}C for one hour and then oil quenched.

3.2. DIMENSIONS:

3.2.1. DIMENSIONS OF THE SPECIMEN:

The dimension of the single edge notch specimen is shown in the following fig.

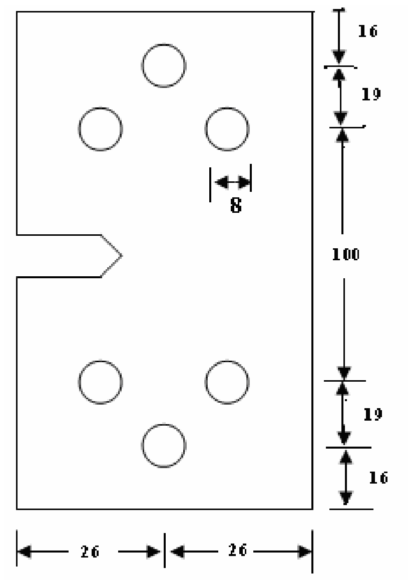


Fig 3.1 Dimensions of the specimen used

3.2.2. FIXTURE DESIGN FOR MODE I LOADING:

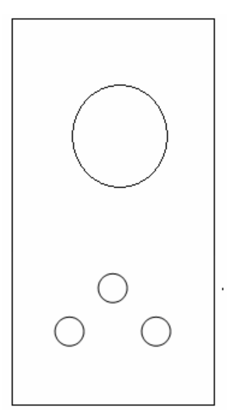


Fig 3.2 Fixture design for mode I loading

3.2.3. FIXTURE DESIGN FOR MIXED MODE AND MODE II LOADING:

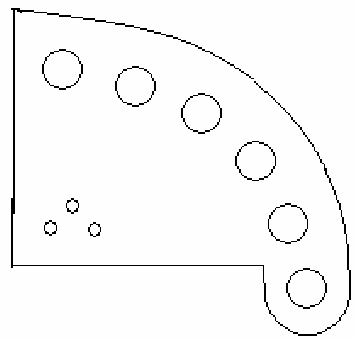


Fig.3.3. Fixture design for Mode II loading

3.2.4 SET UP SHOWS THE SPECIMEN HELD IN MIXED MODE OVERLOADING FIXTURE:

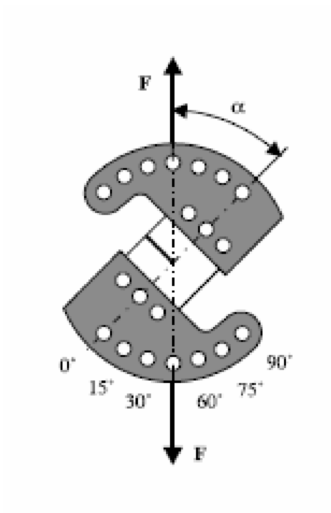


Fig 3.4 Setup showing specimen in mixed mode overloading fixture

3.3 Experimental procedure:

The material used in the present investigation was aluminum alloy (Zn-4.6, Mg-1.4, Mn-0.5, Cr-0.1, Zr-0.1, Ti-0.03) known Al 7005 having yield strength of 250 MPa. Single edge notched specimens of dimensions 52 mm*170 mm*6.5 mm were prepared in the

LT- direction. The notches were of flat type cut with jewellary saw up to a length of 15mm. Before the fatigue test, the notched specimens were precracked up to a length of 16mm. The fatigue tests were carried out in tension-tension constant stress amplitude mode using sinusoidal loading conditions in an Instron-1603 electromagnetic resonance (EMR) machine. The tests were performed at a stress ratio R=0.1 and loading range of ΔP=7000 Newtons.

For the values obtained from the experiments we get the graphs in the form of the figure **1**.

With out overload:

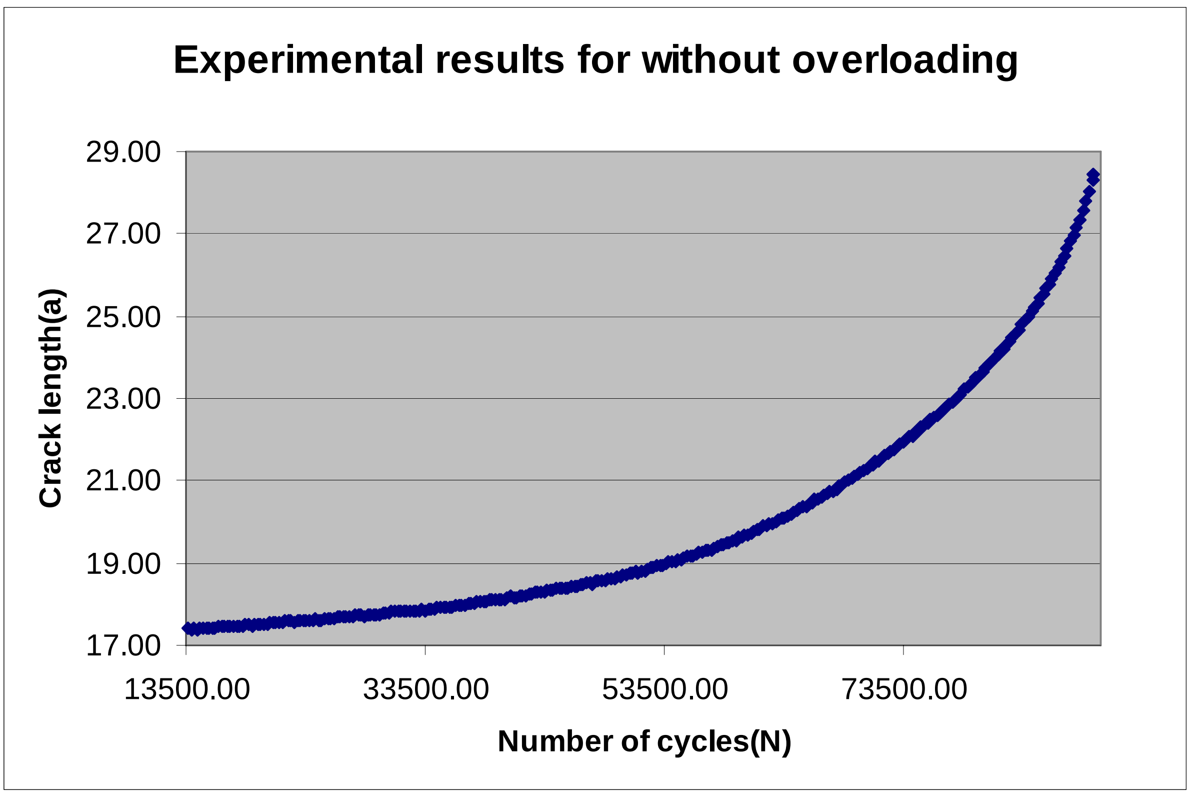


Fig 3.5 experimental results for the with out overloading case

Experimental results with 2.5 overloading case:

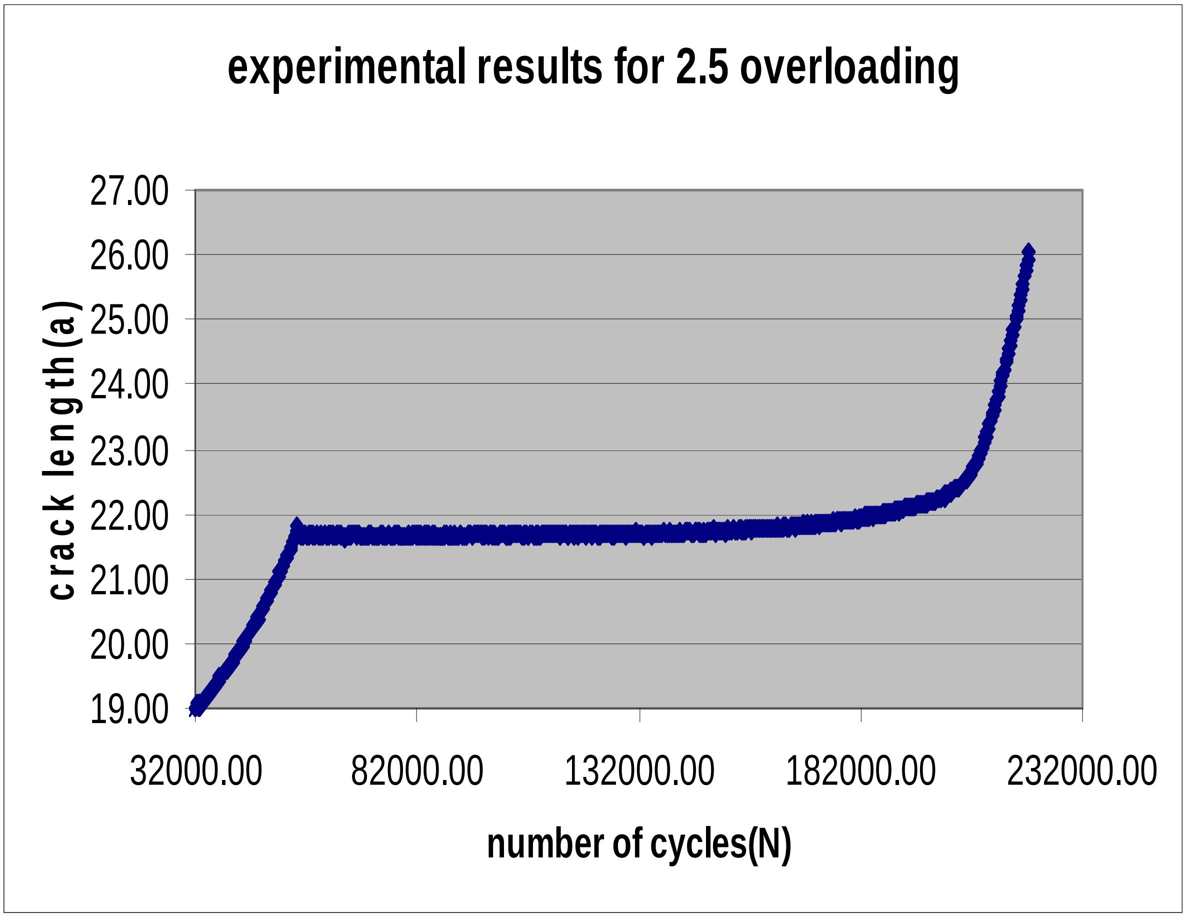


Fig 3.6 experimental results for the overloading case

Chapter 4

SIMULATION PROCEDURE

SIMULATION PROCEDURE

4.1. ASSUMPTION:

To simulate the behavior of crack growth on the specimen some assumptions and approximations are required. Here analysis was undertaken based on the assumption that the tensile load is acting uniformly on the specimen perpendicular to the crack propagation.

4.2 MODELING PROCEDURE:

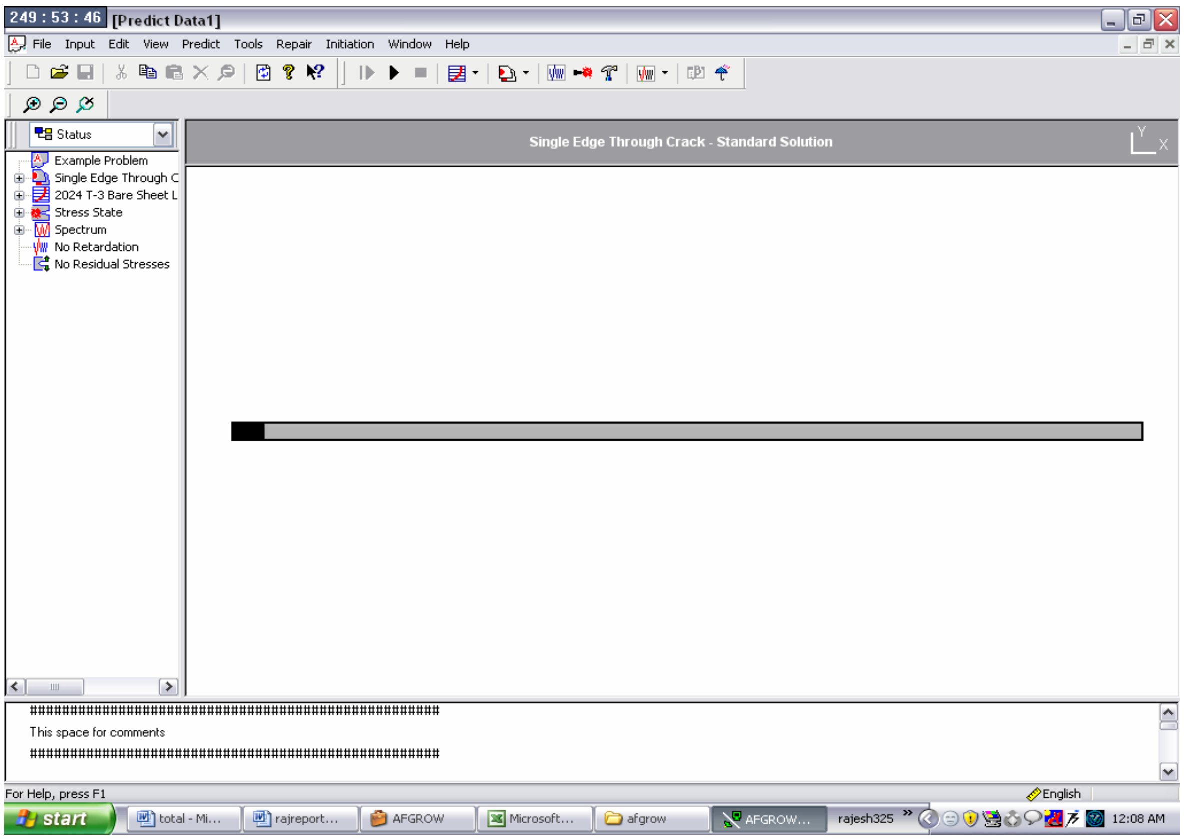


FIG 4.1 AFGROW SIMAULATION WINDOW

4.3. DESCRIPTION OF LOADS:

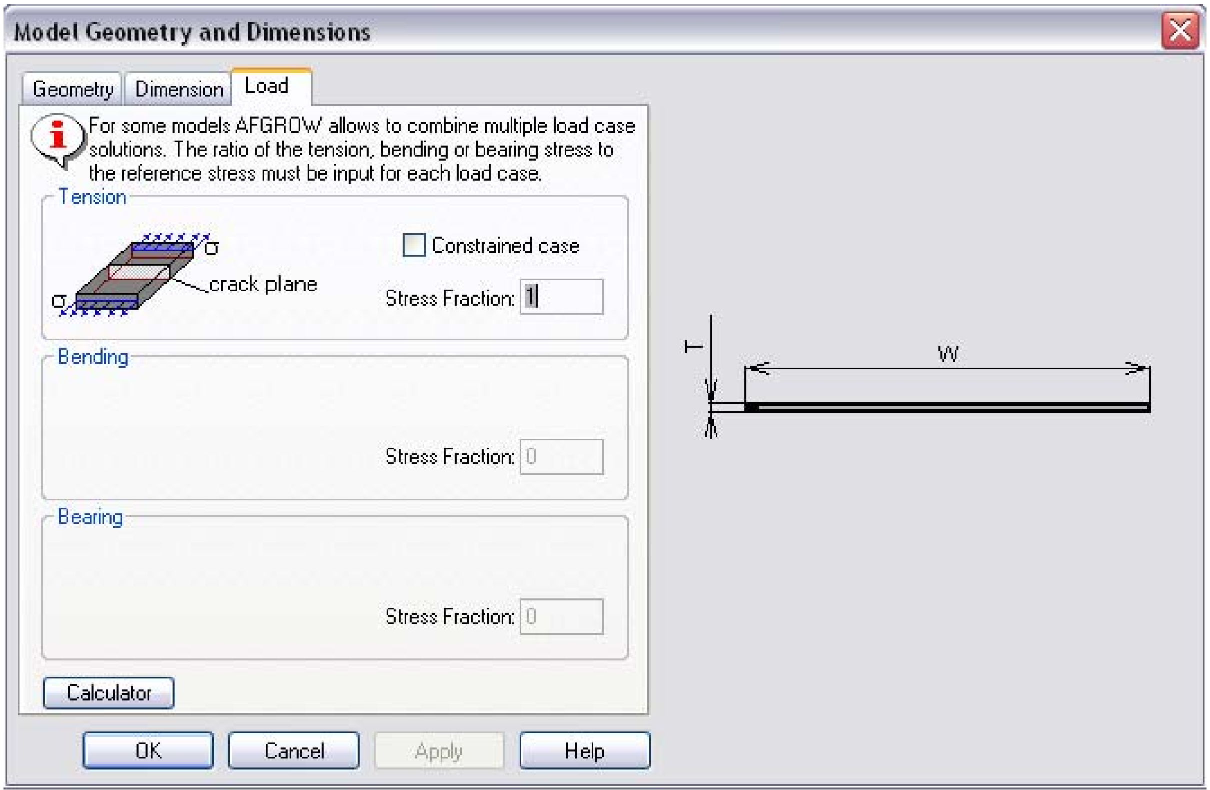


Fig 4.2 load distribution on specimen in AFGROW

4.4. MATERIAL PROPERTIES:

The properties of model used in the present study are shown in following table

Properties of the model:

Material type	isotropic
Young's modulus	2e5
Poison's ratio	0.33
Yield stress	303 MPa
Plain strain toughness	52 MPa
Coefficient of thermal expansion	6.7e-5
Delta K threshold	2.198
Plane stress toughness	300 MPa
Paris exponent(n)	3.001

Table 4.1 properties of the material for the simulation process

Fig 4.3 AFGROW results for the case of without overloading:

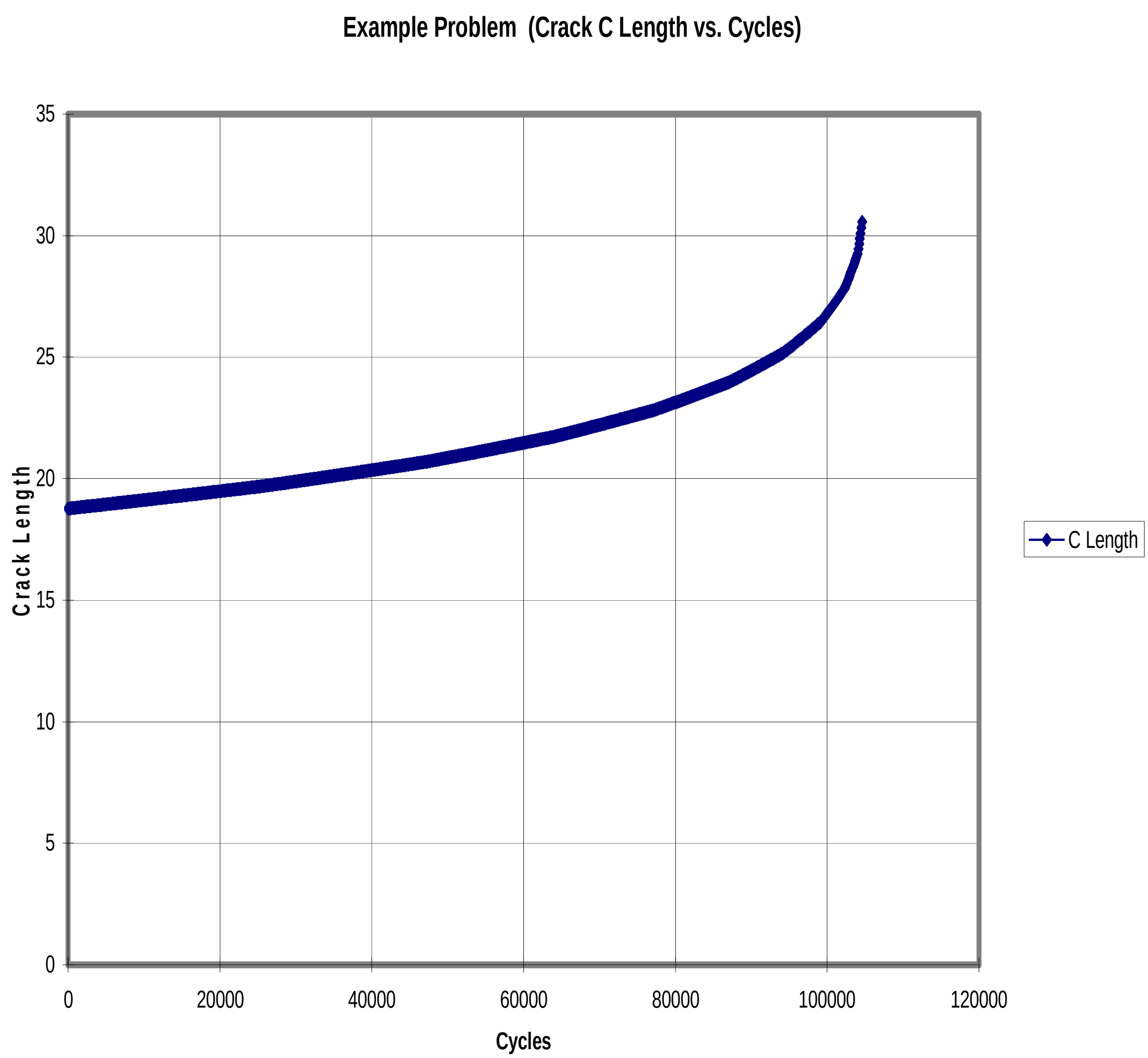
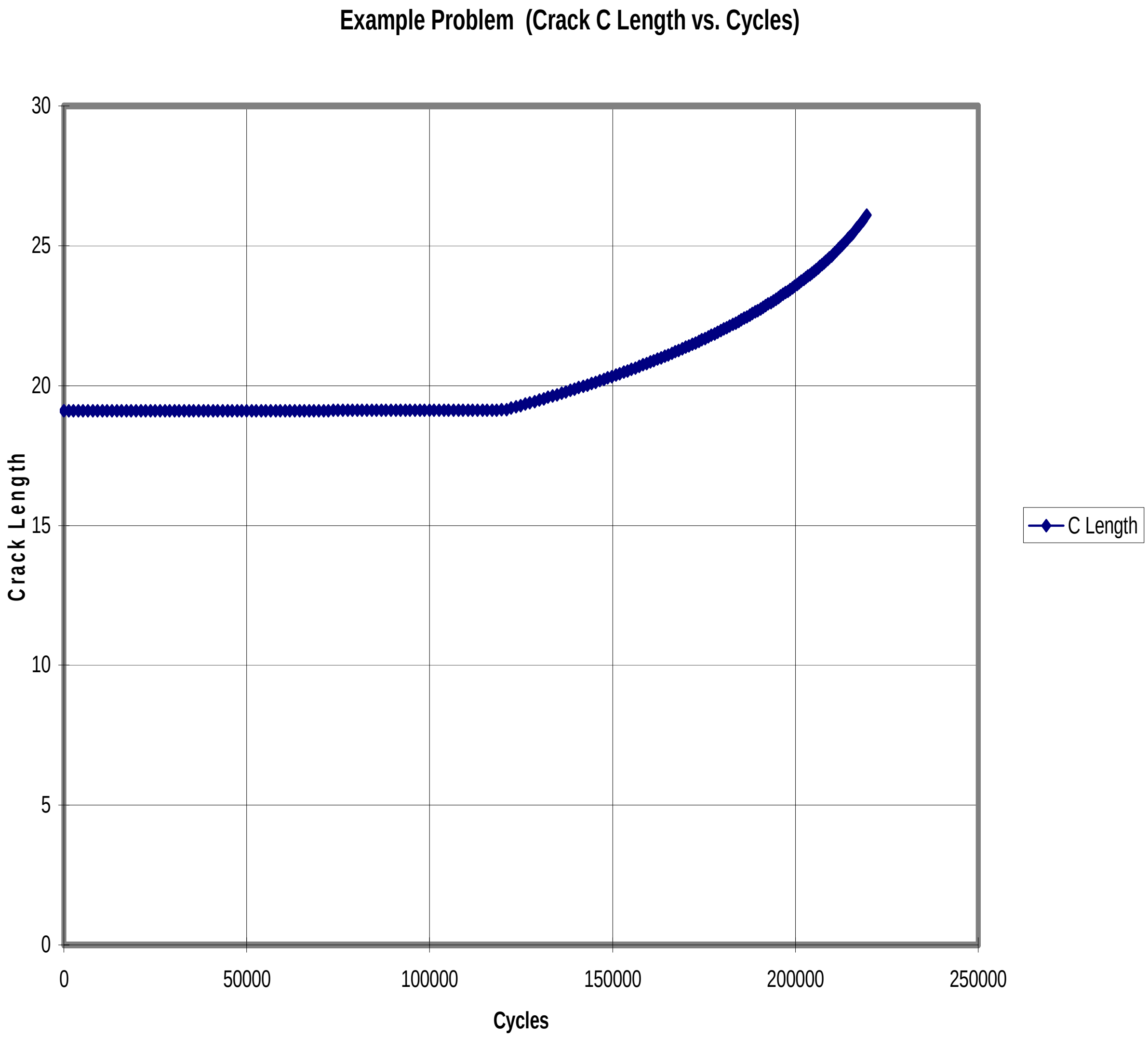


Fig 4.4 AFGROW results for the case overload (2.5 Pmax):



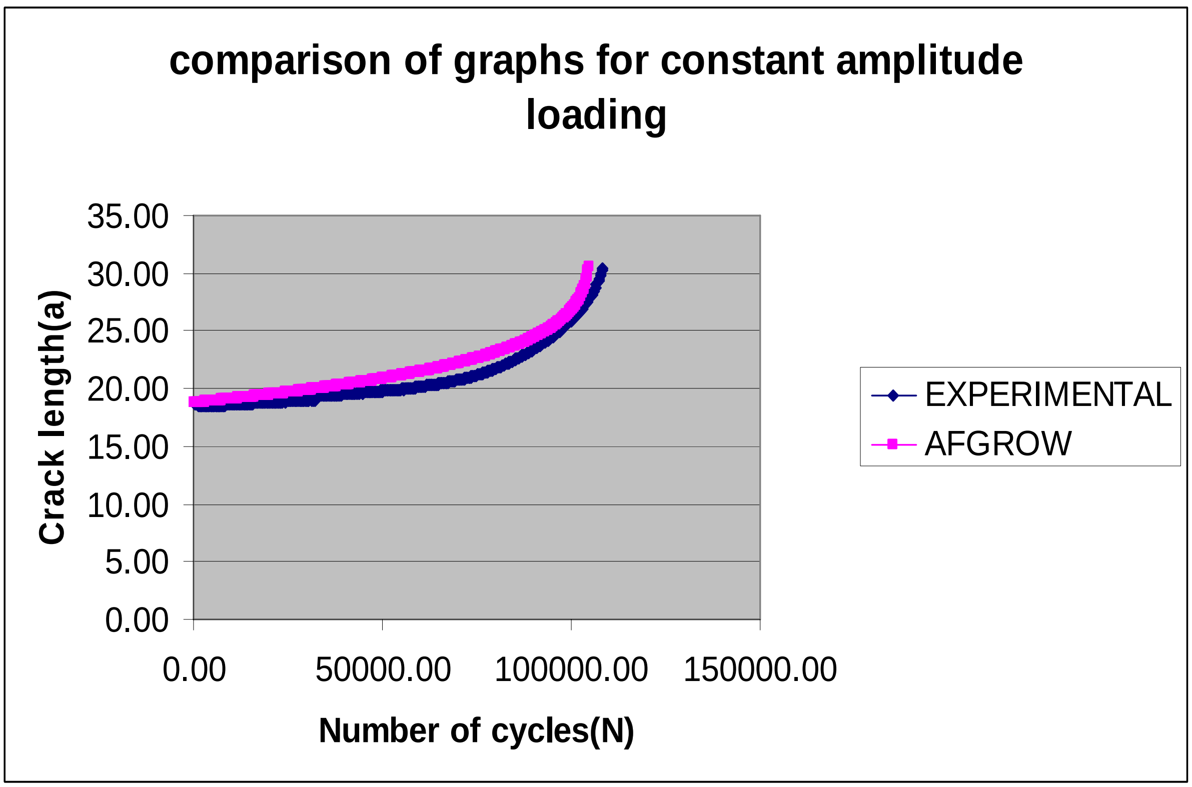
Chapter 5

RESULTS AND DISCUSSION

RESULTS AND DISCUSSIONS:

5.1. MODE I FATIGUE CRACK PROPAGATION TEST:

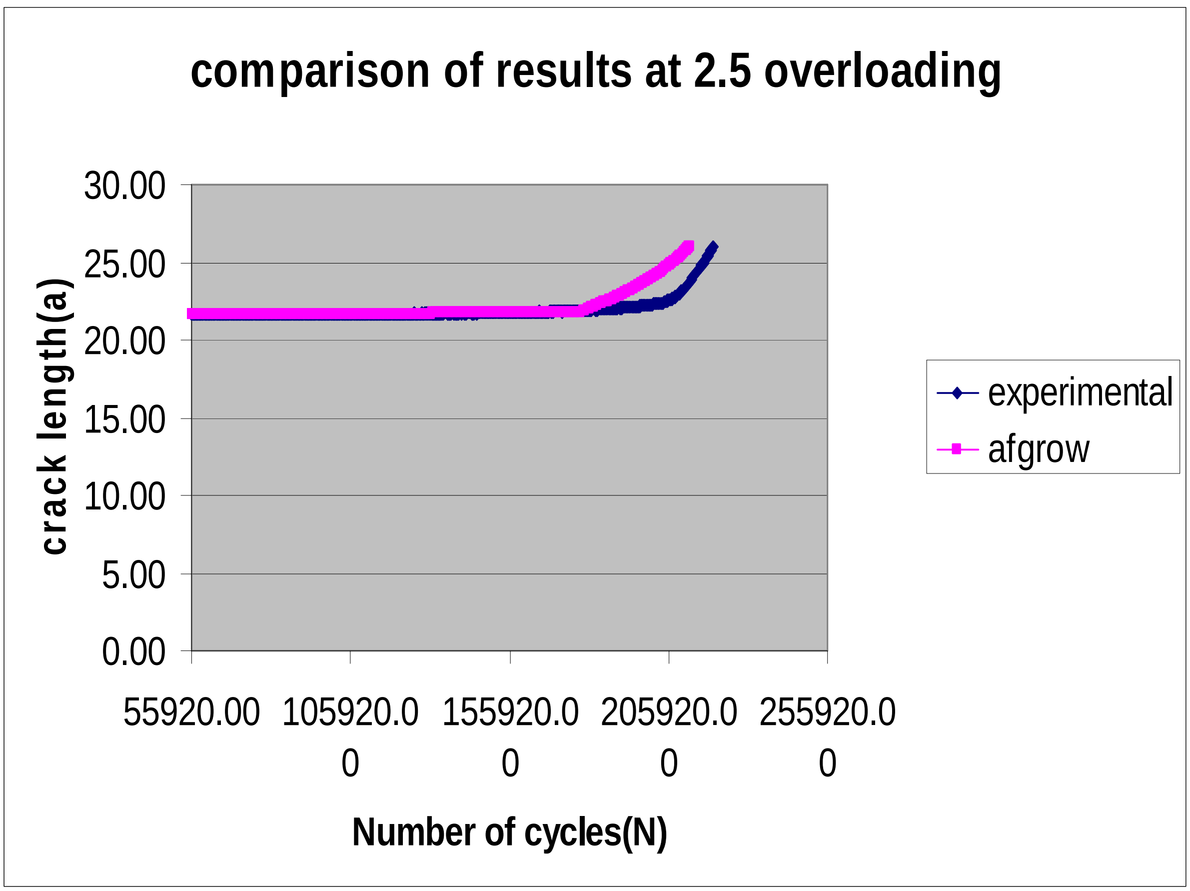
Fatigue crack propagation under constant amplitude loading without overload formed the basis of comparison. Variation of crack length with number of cycles under constant amplitude loading at stress ratio R=0.1 is shown in figure.**5.2.** and is compared with the simulation results graph which is obtained from the software AFGROW is shown below.



5.1. Imposing of experimental and simulation *a* Vs N curves for constant amplitude loading of Mode I fatigue test

5.2 Mode I fatigue crack growth propagation test with mode I overload:

In this test, *a* Vs N curve showed similar behavior as that of previous specimen till the point of application of overload. The overload was 2.5 times P_{max}, when the crack length attained 21.6mm. The crack propagation was retarded over a certain period of time. The number of cycles for propagating a crack of a particular length was observed to be greater in this case than that of the former. The comparison of the experimental and the simulation results is shown in the following figure with overload of 2.5 Pmax.



5.2. Imposing of experimental and simulation *a* Vs N curves for Variable amplitude loading of Mode I fatigue test

5.3 Calculations to find the plastic Zone size:

Application of an overload spike or band overload during constant amplitude high cycle fatigue retards a propagating fatigue crack. The overload introduces a large plastic zone and hence enhances the magnitude and size of compressive residual stress field in the vicinity of the crack tip. This enhanced compressive residual stress field reduces the available crack tip driving force, thus causing a reduction in fatigue crack growth rate (FCGR). The extent of retardation is usually expressed in terms of the total number of cycles involved during retardation (called delay cycle, N_D) and the overload affected total retarded crack length, a_D. These retardation parameters are shown in figure 1.

5.3.1 Experimental procedure:

For the values obtained from the experiments *a*-N curves are obtained in the form of the figure 1. To obtain equations for *a*-N, curve fitting is done in segments 1, 2, 3 as shown in figure below. The curve fitting is done using the MATLAB Tool box.

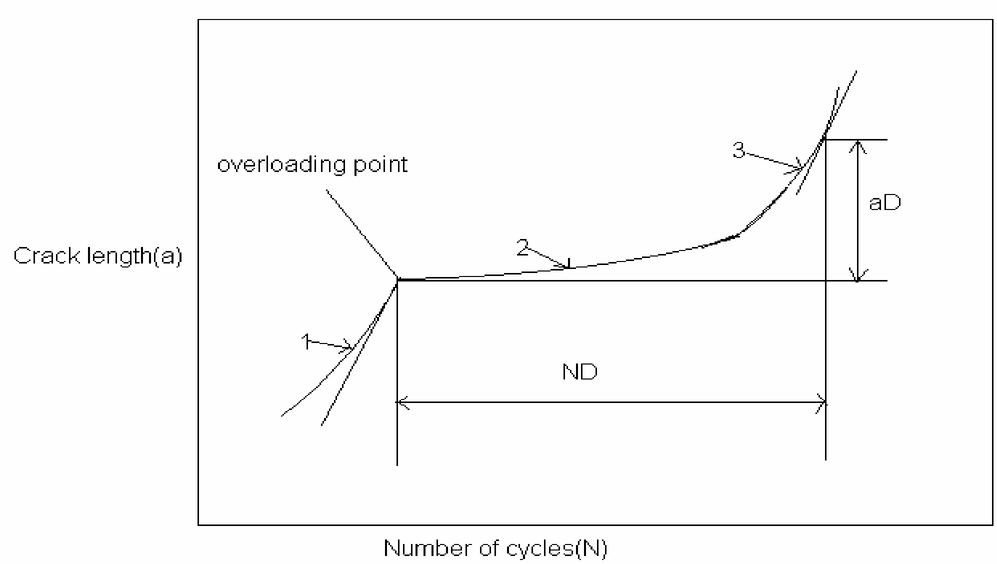
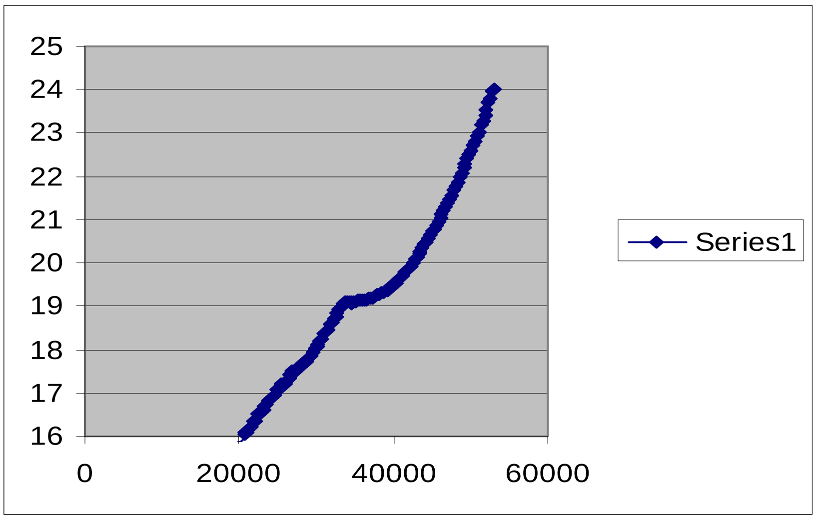


Fig 5.3: Schematic representation of retardation parameters

Overload ratio (OLR)-2:

The experimental data is obtained from the experiments **(shown in the figure)** and the fitting curves for the regions 1, 2, 3 are found out using MATLAB at 95% confidence bounds.

Fig 5.4: experimental results for Overload 2:



For the region 1:

The general polynomial is

a = p1*N^2 + p2*N + p3

the three coefficients of the polynomial are found by the MATLAB as

Coefficients (with 95% confidence bounds):

p1 = 9.37e-009 (4.147e-009, 1.459e-008)

p2 = -0.0003736 (-0.0007071, -4.018e-005)

p3 = 24.06 (18.77, 29.36)

For the region 2:

Coefficients (with 95% confidence bounds):

p1 = 1.464e-008 (1.421e-008, 1.507e-008)

p2 = -0.001103 (-0.00114, -0.001066)

p3 = 43.35 (42.56, 44.14)

For the region 3:

Coefficients (with 95% confidence bounds):

p1 = 1.319e-008 (1.277e-008, 1.36e-008)

p2 = -0.0009618 (-0.001004, -0.00092)

p3 = 39.91 (38.86, 40.96)

The retardation parameters a_D and N_D are now obtained by equating the slope of curve 1 to that of curve 3 and obtaining the value of N.

Calculation of cyclic plastic zone size:

Wheeler model gives the overloading plastic zone size is as

a_D + cyclic plastic zone size= overloading plastic zone size

$a_D+Z_D=Z_{ST}$

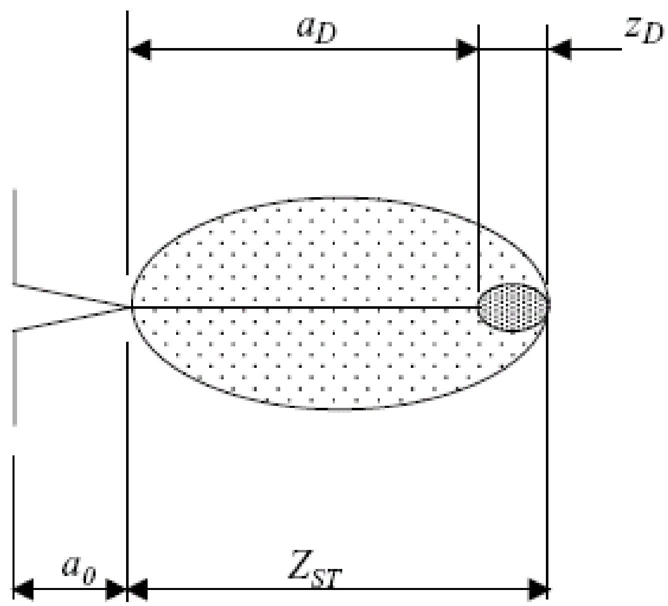


Fig 5.5: End of retardation

Formula used for the calculation of cyclic plastic zone size is

$Z_{ST}=(1/3.14)*(\Delta K/\sigma y)^2$

$\Delta K=f(g)*\Delta\sigma*(3.14*a)^\wedge(1/2)$

$f(g)=1.12-0.231*(a/w)+10.55(a/w)^2-21.72(a/w)^3+30.39(a/w)^4$

$\Delta\sigma=\Delta P/(w*b)$

Yield strength σy=250 MPa

The constants used to calculate the above parameters for the experimental specimen are as

Crack length (a)=23.84mm

Width w=52mm

Breadth b=6.5 mm

ΔP=7000 N

From the above equation the cyclic plastic zone size is obtained as

Z_{ST}= 1.00mm

The overload plastic zone size is as

Overload plastic zone size= a_D+Z_{ST} =2.33mm

Plastic zone sizes for the OLR of 2.25 and 2.5 are obtained similarly.

Fig 5.6: experimental results for Overload 2.25:

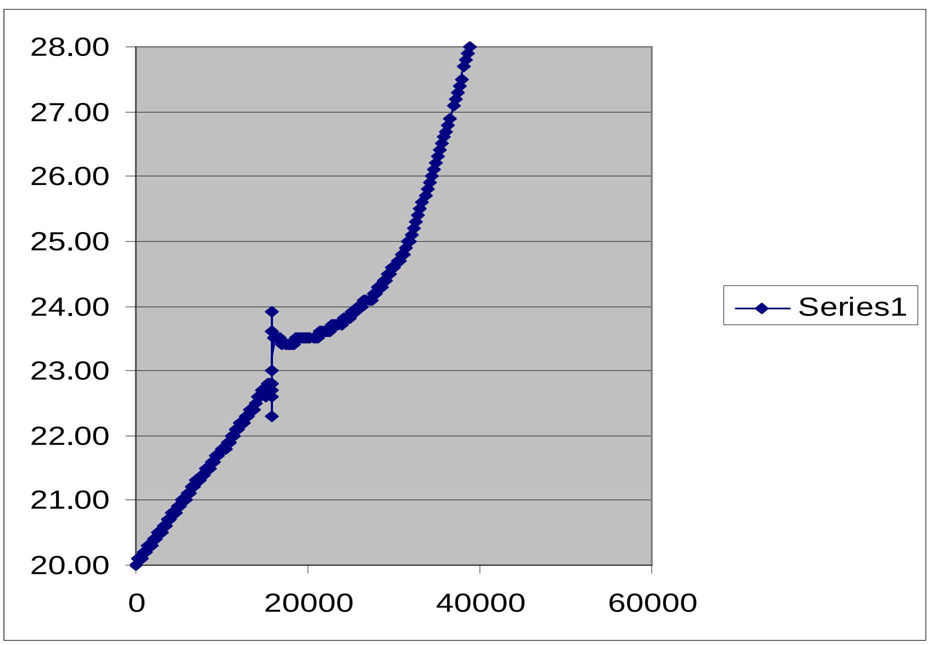
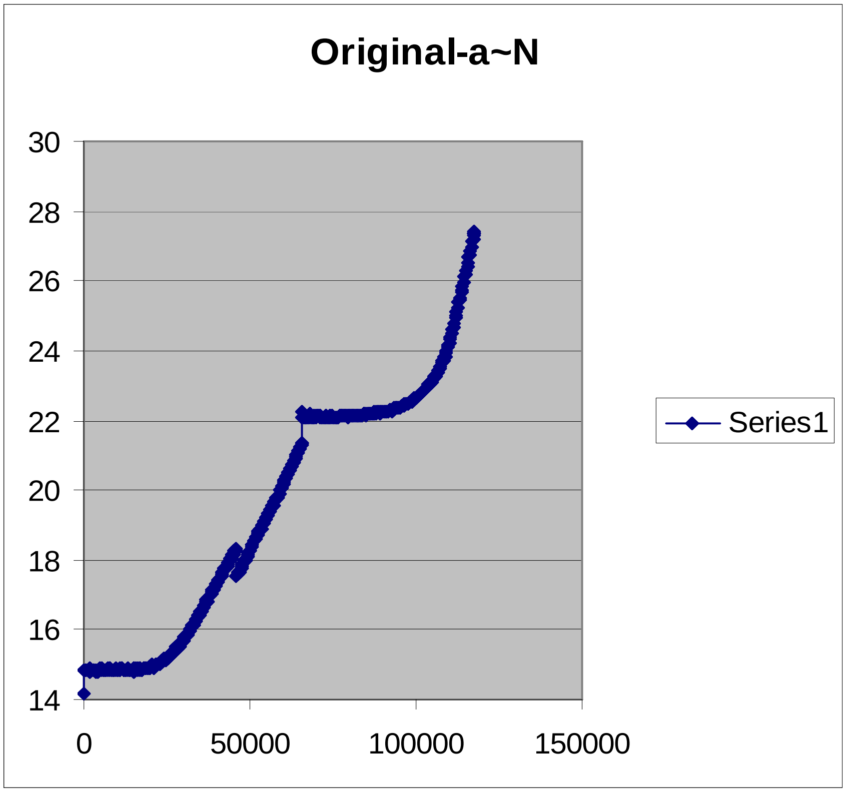


Fig 5.7: experimental results for overload 2.5:



5.3.2 Plastic zone size calculations by using stress analysis:

For the plane problem, the leading terms for mode I stress fields in Cartesian coordinates are

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix} = KI*\cos(\theta/2)/((2*3.14*r)^\wedge(1/2)) \begin{Bmatrix} 1-\sin(\theta/2)*\sin(3\theta/2) \\ 1+\sin(\theta/2)*\sin(3\theta/2) \\ \sin(\theta/2)*\cos(3\theta/2) \end{Bmatrix}$$

It is been assumed that the von-mises criterion for yielding holds good, while determining the stress distribution. The Von-mises criterion for yielding is,

$\sigma 1,2=(\sigma_x+\sigma_y)/2\pm\sqrt{[\{\sigma_x-\sigma_y)/2\}2+\sigma_{xy}^2]}$

$\sigma=1/\sqrt{2}[(\sigma 1-\sigma 2)^2+(\sigma 2-\sigma 3)^2+(\sigma 3-\sigma 1)^2]$

Now σx, σy, σxy have different values for different modes these values depend on the value of stress intensity factor (K), the stress intensity factor which is different for different modes of loading. In the following discussion K was calculated for different OLR values and the expression for von-mises was derived.

$K^{Ol} = f(g)*\sigma^{ol}*\sqrt{(\prod *a)}$

Kol= stress intensity factor at overload

$\sigma^{ol} = \sigma max*OLR$

a= crack length at the overloading point

For the OLR 2:

a=22.51mm

f(g)=2.302(by the above formula)

σ_{max}=7777.7778 N

Stress intensity factor at overload Kol=28.17Mpa√m

Using Von-mises criterion and substituting σ1, σ2 in the expression for σ

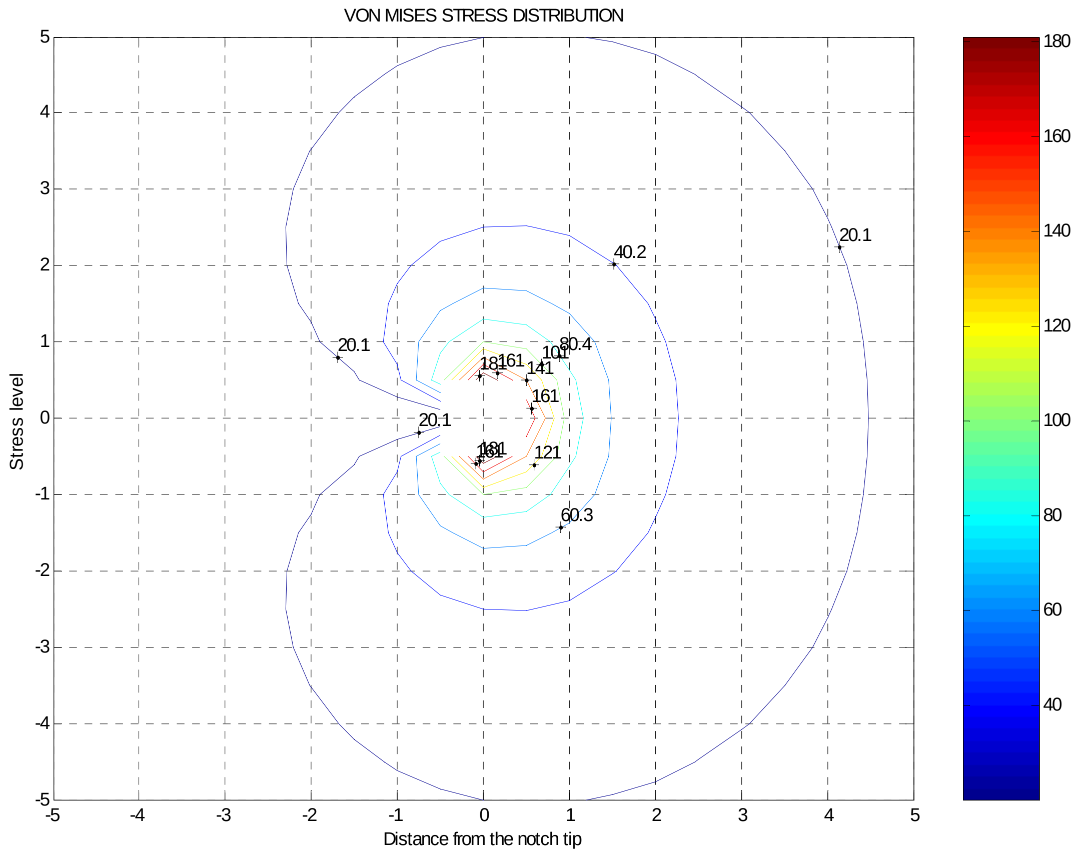
$\sigma=(KI/\sqrt{(2*\prod *r)})*\sqrt{[\sin^2\theta+\{(1+\cos\theta)/2\}^2]}$

The Von-mises σ was plotted against the r,θ to determine the variation of stress around the crack tip. Various contours of stresses appeared in the stress distribution and this then helped in determining the size of the plastic zone. It is known that the stress is maximum at the crack tip and decreases gradually as one move away from the crack tip; the contour with the stress value of yield strength is in fact the plastic zone size.

Using the MATLAB toolbox as shown below drew the plot

The stress contours are shown in the following figure

Fig 5.8 von mises stress distribution for the mode I loading



This σ was plotted against the X-axis along the direction in which the crack propagates. Thus, these plots gave an understanding of the stress level at different crack lengths and that to in cylindrical coordinates.

Take $x=r\cos\theta$

$y=r\sin\theta$

$r=\sqrt{(x^2+y^2)}$

to find the plastic zone size put y=0, θ=180 and r=x in the equation of σ in terms of cylindrical coordinates.

Put σ_{ys}=250Mpa

On simplification we get that $\sigma=KI/\sqrt{(2*\prod*x)}$

From the above formula we get that as

x=2.02mm

The above procedure is done for one case that is OLR-2.same procedure will be carried out for the cases of 2.25, and 2.5 also. The following table shows the plastic zone sizes obtained by experimentally and by using stress analysis calculations.

Table 5.1: Comparison of plastic zone sizes

Overload ratio (OLR)	Experimental (mm) [using Wheeler model]	Stress calculations (mm)
2	2.33	2.02
2.25	2.68	2.98
2.5	3.135	2.96

Chapter 6

CONCLUSION & SCOPE OF FURTHUR WORK

6.1 Conclusion:

1. It is possible to obtain retardation models using AFGROW software by proper selection of experimental parameters.
2. The plastic zone sizes calculated using Wheeler model from the experimental values match with the results obtained by stress analysis technique using Von-Mises yield criterion.

6.2 Scope of further work:

Similar work can be carried out for the mode II and for the mixed mode overloads. The retardation model taken for the fatigue crack growth prediction in overloading is Wheeler's model in this work. Different retardation models for the above cases can also be tried out.

Chapter 7

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