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Impact of Pitting Corrosion on Corrosion Fatigue Crack Growth Under the Spectrum Loading

June 2000

Impact of Pitting Corrosion on Corrosion Fatigue Crack Growth Under the Spectrum Loading.

by
Svetlana P. Oshkai

A Thesis
Presented to the Graduate and Research Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science

in
Applied Mathematics
Department of Mechanical Engineering and Mechanics

Lehigh University

2000

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

May 4, 2000
Date

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ABSTRACT

The purpose of this research is to incorporate pitting corrosion into a life prediction model for corrosion fatigue crack growth in aluminum alloys. The original model implemented in the PMODGRO program uses a superposition model to account for corrosion effects on corrosion fatigue crack growth at the bore of fastener holes in aluminum alloy. In addition, temperature dependence is modeled as an Arrhenius formulation.

In the current study, the pitting is modeled by including an additional aspect in a simple corrosion-fatigue model. The pitting corrosion is based on a mechanistically based probabilistic model by Wei and Harlow (1993) for pitting corrosion and corrosion fatigue crack growth under constant amplitude loading. The influence of pitting corrosion on the residual life of the specimen under consideration is investigated. The results are compared to those obtained by previous investigators in the absence of pitting.

It was determined that including pitting corrosion decreases the predicted lifetime of an aluminum alloy specimen with a hole. The lifetime of a typical member was calculated to be from 3% to 95% shorter compared to the one predicted by the original model, depending on initial value of the fastener hole size, and initial damage size, as well as temperature values.

Onset of transition to pure corrosion fatigue, and completion of transition were established as the transition criteria to observe the influence of pitting corrosion on corrosion fatigue crack growth.

CHAPTER 1

INTRODUCTION

1.1 Purpose of the Study

The purpose of this research is to incorporate pitting corrosion into a life prediction model for corrosion fatigue crack growth in aluminum alloys.
The original method implemented in the PMODGRO program [by Chitang Li (1997)] uses a superposition model to account for corrosion effects. In addition, temperature dependence is modeled by an Arrhenius formulation. This program is then further modified into PCMODGRO (PCMODGRO =Pitting Corrosion PMODGRO) so that pitting corrosion can be incorporated. The influence of temperature, stress amplitude, random variables (initial pit size, corrosion fatigue crack growth coefficient, threshold driving force) and fastener hole size on fatigue life was studied in this research.

1.2 The Statement of Problem

The goal is to study the effect of including pitting corrosion into an existing model with thermal and chemical conditions that predict fatigue crack growth. This methodology is shown to be feasible through simplified modeling of an aluminum alloy plate with a hole. To maintain aging commercial and military aircraft units in safe operating conditions is important to schedule high cost inspections in suitable intervals.

1.3 Outline of Thesis

This dissertation contains 5 other chapters:

Chapter 2 gives detailed description of original fatigue crack growth model, introduces loading conditions and discusses influence of loading conditions and temperature effect on fatigue life.

Chapter 3 contains a review of the previous work done on fatigue crack growth and environmentally-assisted fatigue crack propagation including deterministic and probabilistic models. The governing equation assumed for fatigue crack growth rate is described and the methods that deal with mean stress as well as load interaction is discussed in detail in this chapter. The loading spectrum and temperature profiles coupled with loading spectrums, which have been used in PMODGRO, are also described. Structure of a new model discussed, plus, introduction to the new terms used to describe Transition criterion given. At the end of this chapter, the key variables, statistical distributions, and simulation methods have been discussed.

Chapter 4 contains detailed description of Transition criteria' used in presented work.

Chapter 5 presents the computation results including the influence on fatigue life due to different temperatures, loading interactions, random variables, initial pit and rivet hole sizes.

Chapter 6 is summary of presented by this thesis work, and discussion of possible in the future adjustments, and modifications of used program, model.

CHAPTER 2

BACKGROUND

2.1 Description of the original fatigue crack growth model.

Pitting corrosion and corrosion fatigue crack growth in an aluminum alloy are recognized as degradation mechanisms that affect reliability, integrity and durability of both commercial and military aircraft. To maintain aging aircraft units in safe operating conditions there is a need for scheduled inspections and repairs. Because of the extremely high cost of each inspection it is important to find suitable inspection intervals. Prediction of reliability or durability requires statistically accurate estimates of material response for loading and environmental conditions typically not included within available experimental observations. The desired estimates often involve extrapolations in time by factors of 10 or more. These can be made only if the fundamental random variables that affect the failure process can be identified and model by appropriate failure mechanisms. Thus, a mechanistically based probability model for the lifetime is being developed.

Cracking on an aircraft usually begins in the rivet holes (or in fasteners) which are located in the high stress regions of the fuselage (or wing). The rivets, subjected to high stress and more severe fatigue loading, are more likely to have cracks initiate and grow. The countersunk rivet, see Figure 1, is often used on aircraft to reduce drag.

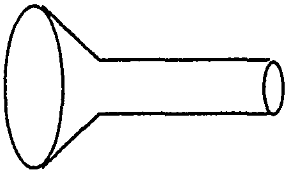


Figure 1: Schematic drawing of a rivet in airplane fuselage.

The skin around the rivets, however, is prone to fatigue cracks, which usually start in the skin below the surface of the rivet head and growth outward, see Figure 2.

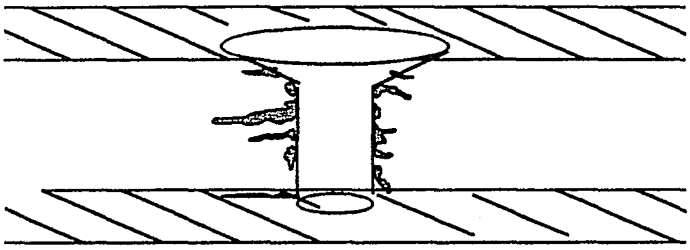


Figure 2: Initialization of fatigue and corrosion damage.

Li (1997) investigated the influence of the temperature, the random variables (such as the initial damage size, and the fatigue crack growth coefficient), and the affect of sequencing in the loading spectrum on fatigue life. To simplify the situation, only a double through thickness crack emanating from a fastener hole was considered in his study. The cracked panel located on the lower wing skin contained one hole subjected to uniaxial loading, which was perpendicular to the crack growth direction. The radius of the hole was assumed to be 3 mm, and the material was considered to be aluminum alloy 7075-T651.

The principal findings obtained by Li (1997) are the following:

1) The CDFs of the random variables significantly affect the distribution of fatigue crack growth life. It is important to quantitatively characterize the CDFs of the random variables so that the reliability and durability of fatigue critical engineering component can be assessed.
2) The predicted fatigue life of a double through-thickness crack emanating from a rivet hole subject to the FALSTAFF spectrum loading modeled with the generalized Willenborg model is 1.5 times longer that the one with no load interaction model for Al 7075-T651.
3) The test temperature has a significant influence on fatigue life inder constant stress amplitude loading condition.
4) The sequence of the loading spectrum does have an influence on fatigue life.

2.2 Loading conditions for fatigue crack growth model.

In order to simulate the loading condition that occurs during service in a more realistic manner, the standard loading spectrums for a fighter aircraft lower wing skin called FALSTAFF and ENSTAFF were used by Li (1997). FALSTAFF stands for Fighter Aircraft Loading Standard For Fatigue evaluation, which is for fatigue in the wing root area. ENSTAFF is Environmental FALSTAFF. The basic load factor history input were obtained from a Lockheed F-104G (German Air Force), a Fiat G-91 (German Air Force), a Lockheed F-104G (Royal Netherlands Air Force), a Northrop NF-5A (Royal Netherlands Air Force), and a Dassault Mirage III s (Swiss Air Force). See Van Dijk and De Jonge (1975). The load factor history mixture was converted into a corresponding stress history mixture using relatively simple well defined stress response relations, pertaining to an imaginary aircraft. More information on this subject can be found in Chapter 3, Part 5.

The established series of stress sequences in FALSTAFF representing 200 flights can be roughly classified into 3 different mission groups as follows:

I: Flights exhibiting a repetitive pattern of exercises severe maneuvering (e.g. conventional air-to-ground weapon training, close air support).

II: Flights exhibiting severe maneuvering without a repetitive pattern of exercises (e.g. air combat training, aerobatics functional check flights).

III: All other flights mainly involving moderate maneuvering or just incidental maneuvering (e.g. navigation flying, combat profile missions, special weapon deliveries).

Changing the sequential order of FALSTAFF means changing the load interaction between two individual flights. Therefore, the predicted fatigue lives from a different sequential order of FALSTAFF are different. In current work the load stress sequence applied to the panel remains the same, i.e. it is not randomized further.

It has been shown that FALSTAFF with a fixed sequence is a deterministic loading spectrum and does not reflect the variation in loading that occurs in different flights. FALSTAFF also does not consider different environment. The results show that the generalized Willenborg load interaction model is affected more than a no load interaction model. The stress concentration effect near hole also causes variation in predicted fatigue lives when the sequential order of loading spectrum changes. The reason is that the severe loading occurred near the hole results in a higher crack growth rate.

2.3 Influence of temperature on fatigue life.

As was mentioned earlier in this chapter, Li (1997) also studied the influence of Temperature and Stress Amplitude on Fatigue Life. It was shown that stress amplitude has a great influence on fatigue life. Even small increases of stress amplitude leads to significant decrease of a fatigue crack growth life (N). For example, if the stress amplitude changed from 20MPa to 60MPa, average fatigue live decreases by 80 times. A change in stress amplitude from 60MPa to 100MPa leads to a change in fatigue life average by 7.4 times. It's also appears that given the same loading condition, the same initial and final crack size changes in the temperature would have an appreciable affect on fatigue crack growth life. Fatigue life at average at T=213K is three times of the life at T=363K and twice of the life T=298K. Thus, the designing fatigue critical engineering components one should consider the temperature effect.

2.4 Summary.

The main conclusion from Li (1997) is that the existing model is a simplified model that needs further refinements to capture the damage behavior due to environmentally assisted fatigue crack growth. However, the influence of temperature, stress amplitude, random variables and random sequence of loading spectrum on fatigue life of Al 7075-T651 were considered and reasonably modeled.

CHAPTER 3

MODEL DESCRIPTION

3.1 Geometry.

One of the failure degradation mechanisms in aluminum alloy structures is pitting corrosion, which may have a significant effect on the component life. It is obvious, that the number and a size of constituent particles in aluminum alloy have a great influence on the rate of corrosion of an aluminum structure, because those particles are potential nucleation sites for corrosion pits. The nucleation and growth of corrosion pits is a very complicated process, which depends on the alloy's material properties and the environmental conditions to which the alloy is exposed. The rate of pit growth and it extension is determined by clusters of particles, and naturally, the larger clusters of particles lead to more severe damage [Harlow and Wei (1998)].

The model, used in the present study is motivated by the effect of environment on the surface of a hole in an alloy sheet, which would be bare, that is, no cladding or protective coating. As was mentioned before, the damage is assumed to begin by the formation of a corrosion pit on the hole surface. For simplicity of the model it was assumed, that when corrosion pit reached a critical size, a corrosion through-thickness crack nucleates from it, and then it grows until failure criterion is realized (Figure 3).

An original model by Wei and Harlow (1993) slightly differs from the model used in the current study: as soon as pitting corrosion continues to a critical size, a corrosion fatigue surface (thumbnail) crack nucleates from it and only then the surface crack ultimately transitions into a through (or through-thickness) crack. Therefore, in the original model damage was represented by three stages: pitting corrosion (Stage 1), corrosion fatigue surface crack growth (Stage2), and through-thickness corrosion fatigue crack growth (Stage 3). Stage 2 is not considered in present study. Corrosion fatigue surface crack growth under the spectrum loading is not simple to simulate. Plus, transition criteria from Stage 1 to Stage 2 is not known. Furthermore, the purpose of this study is not to learn more about surface cracking, but to consider the impact of pitting corrosion on life prediction using simple models for pitting corrosion and corrosion fatigue crack growth. The next aspect of the research will be to modify the model to make it more realistic, and in this new model a surface crack will be considered.

The next question that needs to be answered is why in the present work are only two pits, one on the each side of hole, considered. Of course, corrosion does not appear only on the surface of holes. But for this particular study corrosion on the surface of the plane has little influence on crack propagation, therefore, on the life. Figure 1 shows that a crack from a hole propagates perpendicularly to the applied stress. This study considers only those pits on the surface of the hole, which will later transition into a crack. Pits are assumed to have semi-cylindrical form, in order to avoid the consideration of surface crack (reasons for that were discussed earlier).

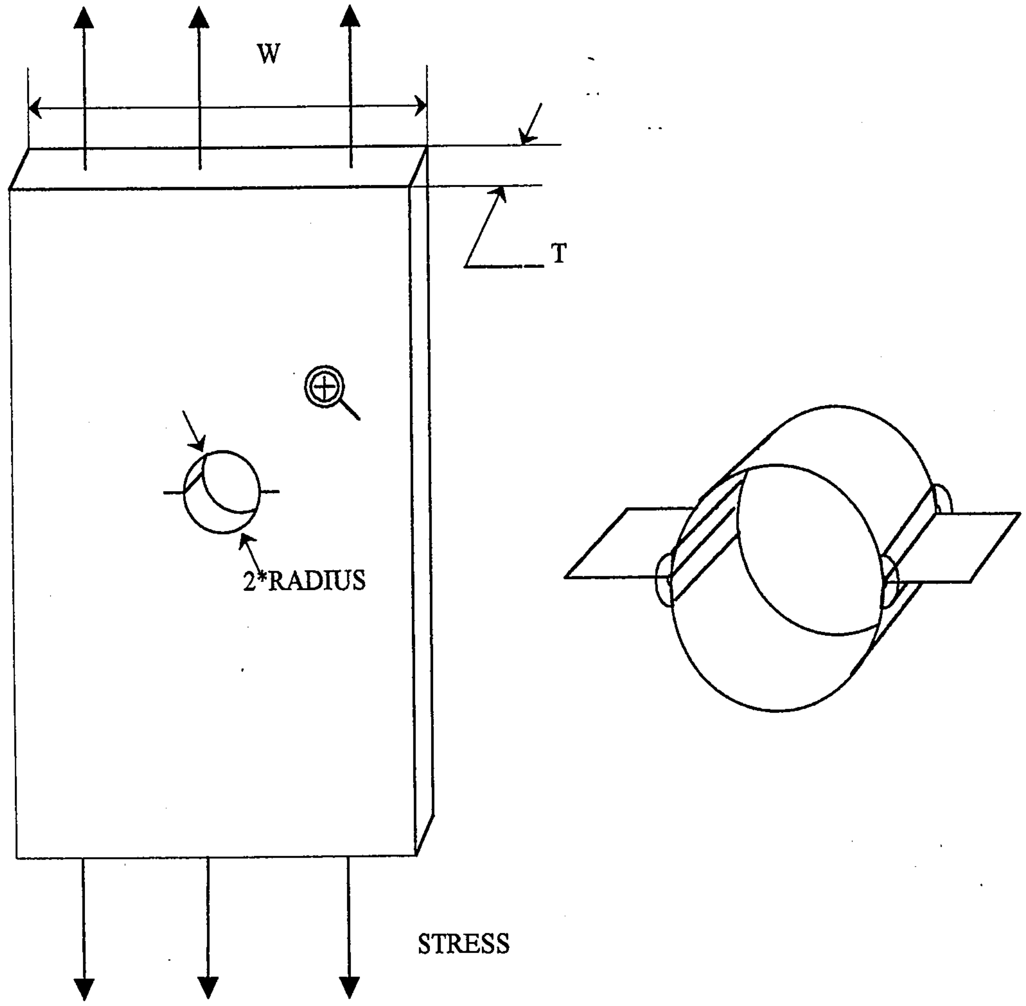


Figure 3: Center double-through crack at a Hole in a finite plate subjected to remote tension

3.2 Loading.

In order to simulate crack growth under spectrum loading the following two packages of data-files have been used:

1) FALSTAFF (Fighter Aircraft Loading Standard For Fatigue evaluation);
2) ENSTAFF = ENvironmental FALSTAFF.

Those data-files where obtained as a result of many loading cycles on fighter aircraft wing primarily during the maneuvers. To construct FALSTAFF as a primary input 200 flights were selected from different data sources (various aircraft, various operational circumstances). Later on those 200 load factor histories were transformed into a corresponding mixture of non-dimensional stress (strain or load) histories, what was finally classified into a bivariate statistical summary of stress ranges.

In selecting the basic load factor history input the following data sources were available, covering total of 324 individual flights:

Aircraft type	Operator
Lockheed F-104 G	German Air Force
Fiat G-91	German Air Force
Lockheed F-104 G	Royal Netherlands Air Force
Northrop NF-5A	Royal Netherlands Air Force
Dassault Mirage III S	Swiss Air Force

Consequently 40 individual flights were selected from each data set and after numerous transformations FALSTAFF was created. For more information on FALSTAFF consider Van Dijk and De Jonge (1975).

ENSTAFF is a standard load/temperature sequence considered to be representative for the load/temperature time history in the upper and lower wing skins near the wing root of a fighter aircraft. It combines, within a flight-by-flight type sequence, cyclic loads and associated temperature profiles representing typical flight missions of a combat aircraft. All details about ENSFAFF can be found in Gerharz (1987).

3.3 Pitting.

In 1993 Wei and Harlow introduced a probabilistic model for pitting corrosion under a constant load. Originally, Kondo (1989) and Kondo and Wei (1989) assumed that a growing pit remained hemispherical in shape and grew at a constant volumetric rate (dV/dt) given by formula:

$$\frac{dV}{dt} = 2\pi a^2 \frac{da}{dt} = \frac{MI_{P_0}}{nF\rho} \exp\left[-\frac{\Delta H}{RT}\right], \tag{1}$$

where a - pit radius;
M - molecular weight of the material;
n – valence;
F = 96514 coul/mol is Faraday's constant;
ρ - density;
ΔH - activation energy;
T - absolute temperature;
I_{P_0} – pitting current coefficient; (Arrhenius proportionality constant)

In current research the geometry was altered slightly. The assumption was that a growing pit remains semi-cylindrical in shape, with height equal to the thickness of a panel. (See Figure 3)

Therefore, formula (1) was modified into:

$$\frac{dV}{dt} = \pi a h \frac{da}{dt} = \frac{MI_{P_0}}{nF\rho} \exp\left[-\frac{\Delta H}{RT}\right], \qquad (2)$$

where h – thickness of the plate.

By simple integration, it was found that the time until transition from pitting to cracking could be evaluated by the formula:

$$t_{tr} = \frac{\pi h n F \rho}{2MI_{P_0}} \exp\left[\frac{\Delta H}{RT}\right]\left(a_{tr}^2 - a_0^2\right), \qquad (3)$$

where a_{tr} - pit radius at which a crack is initiated;

a_0 - initial pit radius;

The other way to express transition pit radius a_{tr} is in terms of the threshold driving force ΔK_{th} via the crack growth mechanism [Kondo (1989),Kondo and Wei (1989)]. For simplicity, in present study it was assumed that:

$$\Delta K_{th} = K_t \Delta\sigma \sqrt{\pi a_{th}}, \qquad (4)$$

where $\Delta\sigma$ - far field stress range, and $K_t = 3$ is assumed for a very small semi-cylindrical flaw along a circular hole in an infinite plate. K_t is a function of the rivet hole radius and width of the plane W (see Figure 3). More information on this can be found in Beer and Johnston (1981).

Thus, by rewriting equation (4) :

$$a_{tr} = \frac{1}{\pi}\left(\frac{\Delta K_{tr}}{3\Delta\sigma}\right)^2. \tag{5}$$

During the ground time pit growth was modeled by using formula (3). Than, transition pit size a_{tr} was substituted into equation (5), and assuming that the threshold driving force ΔK_{th} is known, far field stress range $\Delta\sigma$ could be found. Later $\Delta\sigma$ is going to be used in Chapter 4 for Transition criteria I.

3.4 Introduction of the new terms needed to describe Transition criteria.

For the problem of pitting corrosion evolving into a crack two transition criteria are needed.

Transition criteria:

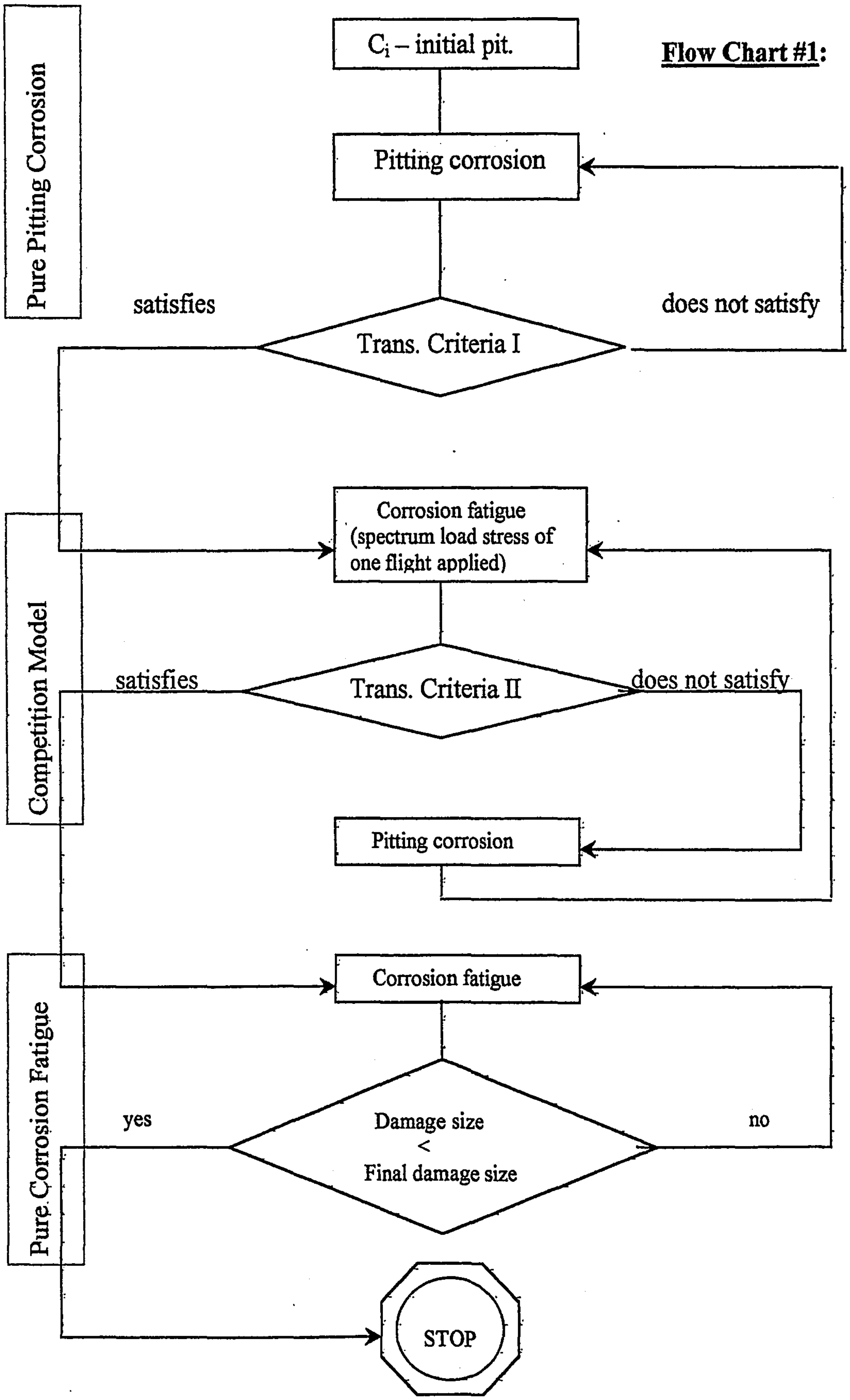
(I) from pitting to cracking, transition which initiates a Competition model;

(II) from the Competition model to Pure Corrosion fatigue.

To illustrate, introduced in the present study are the new terms “Pure pitting corrosion”, “Competition model” and “Pure corrosion fatigue”. (See Flow chart #1) Simulation starts with the assumption that the plate in under no stress (plane is on the ground). The period named as “Pure pitting corrosion” describes damage caused by pitting corrosion that is not large enough for a crack to initiate and grow during a flight cycle. The first appearance of a crack initiates the “Competition model”. During this period of time a pit and a crack alternate in causing damage growth. See Figure 4. At some moment in the simulation the crack size will dominate thereafter. This period is the “Pure corrosion fatigue”.

If in case (I) need for transition criteria is obvious (how to define moment of the appearance of a crack), in case (II) it’s not so simple. On the Figure 4 it is obvious that after some point in time the crack always dominates over the pit. On the close-up it becomes clear why transition to "Pure corrosion fatigue" can not be defined from the physical point of view: because of the loading spectrum pit and crack alternate in causing a damage growth.

Flow Chart #1:


Pure Pitting Corrosion
C_i – initial pit.
Pitting corrosion
satisfies
Trans. Criteria I
does not satisfy
Competition Model
Corrosion fatigue (spectrum load stress of one flight applied)
satisfies
Trans. Criteria II
does not satisfy
Pitting corrosion
Pure Corrosion Fatigue
Corrosion fatigue
yes
Damage size < Final damage size
no
STOP

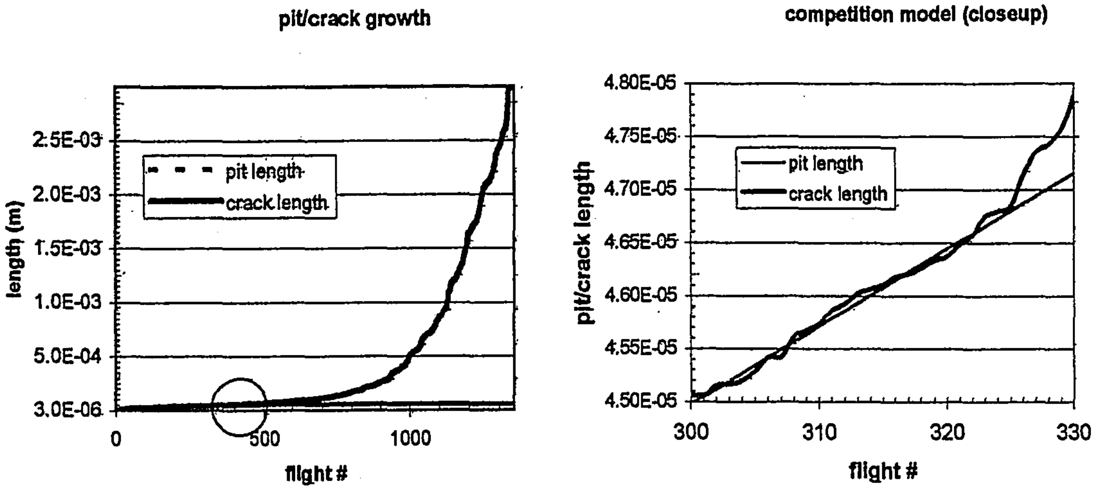


Figure 4: Pit and crack sizes recorded before each next flight simulation.

So far there is no physical process know to author that signifies transition to "Pure corrosion fatigue". Transition criteria II was incorporated into model due to a time crisis problem, to cut unneeded calculations of pit growth, therefore shorten time of computer simulations.

As it was mentioned in part 3.1 of the thesis, it is assumed that the original defects are 2 semi-cylindrical pits on the surface of a hole (see Figure 5).

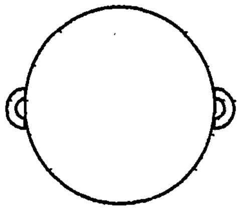


Figure 5: Two-dimensional projection of fastener hole and 2 semi-cylindrical pits.

At the beginning, only those 2 pits exist, meaning, no cracking at all. Obviously, the appearance of a crack needs to be defined. For this particular study there were 23 hours of "ground time" with pitting corrosion taking place, and 1 hour of "air time" with crack growth, if the stress was high enough to advance the damage. See Figure 6.

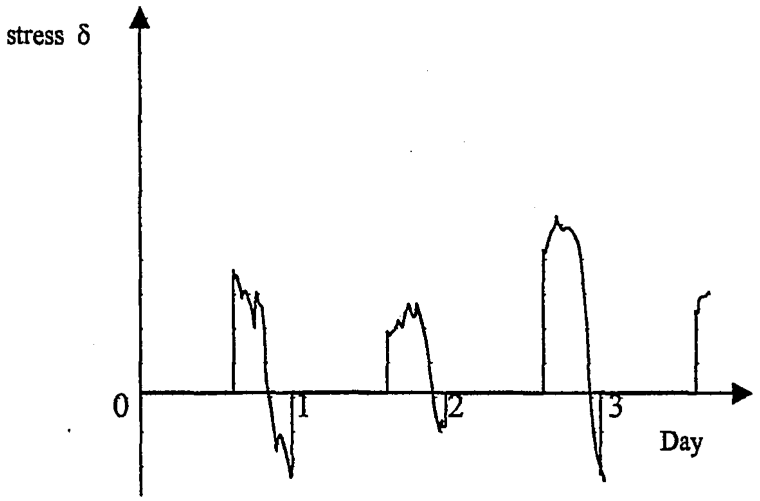


Figure 6: Schematic of a load stress during a time on the ground and during flights.

Therefore, depending on the original radius of pits such long periods of time on the ground will lead to considerably fast growth of damage size (in terms of pits sizes). At some point damage size will be large enough for a crack to start and grow. Transition criteria I will be discussed in great details in Chapter 4.

To find Transition criteria II was extremely important. For calculations of pit and crack growth, it became obvious that after some time the damage size no longer depends on the pit size. Therefore, Transition criteria II was introduced. In case with spectrum load stress there is no natural way (using known formula) to find moment starting which pit will always be smaller then crack. Conclusion of the study of a pit and a crack growth behavior is that pit or crack size can not be compared with any single number to successfully determine stopping point of pit growth calculation. Meaning, there is no any reasonably small number ξ^* such that after comparing pit size with it (with ξ^*) or crack size with it, would be possible to conclude that the crack never again will be overgrown by the pit.

Another tested idea was to count number of flights sense the last switch from pitting to cracking acquired. However, there is no rational justification for the number of flights to be considered.

After numerous test runs it became obvious that if pit larger then crack by some small value δ^* it is safe to assume that starting this moment pit will be not able to consume the crack.

Both Transitions criteria will be discusses in greater details in Chapter 4.

3.5 Corrosion fatigue growth.

The computer program PMODGRO, which has been used as basis in this work has been written to integrate thermal and chemical considerations and probabilistic methods into a life prediction model for corrosion fatigue crack growth. Therefore, in this part of the chapter a short presentation of fatigue crack growth modeling based on the loading conditions, environment (corrosion fatigue), thermal effect, and probabilistic approach to a problem will be introduced.

The main components, which were assumed for the fatigue crack growth model, are:

1. Fatigue crack growth based model : Paris-Erdogan model
2. Stress ration effect : Walker's expression
3. Load interaction model : generalized Willenborg model
4. Numerical technique : cycle-by-cycle integration procedure and Vroman integration method.
5. Loading input : spectrum loading (FALSTAFF)
6. Temperature dependent corrosion fatigue crack growth model (added to part 1)

3.5.1 Fatigue crack growth model based on loading conditions.

One of the important points in fatigue design is developing reliable models for characterizing the fatigue crack growth rate (*da/dN*), where *a* is a crack length and *N* is number of cycles of remote cycles loading applied to the crack, by using proper loading parameters. The fatigue crack growth rate shall be able to reflect the actual resistance of the material under different conditions of applied stress, specimen and crack geometry.

Paris, Gomes and Anderson (1961) showed that the fatigue crack growth rate *da/dt* is related to the stress intensity factor range by the power law relationship

$$\frac{da}{dN} = A(\Delta K)^p, \tag{6}$$

where ΔK is stress intensity factor, A and p are empirical constants. Equation (6) is called the Paris or Paris-Erdogan equation. These constants are influences by such variables as the material microstructure, cyclic load frequency, environment test temperature and stress ratio, R', which is defined as

$$R' = \frac{\sigma_{\min}}{\sigma_{\max}} = \frac{K_{\min}}{K_{\max}}, \tag{7}$$

Paris and Erdogan (1963) showed the validity of equation (6) on aluminum alloys with different combinations of stress ranges and crack length and with different specimen geometries.

Fracture occurs as the maximum cyclic stress intensity approaches some critical value, K_c, Since $K_{max}=\Delta K/(1-R')$, Forman, Kearney and Engle (1967), expanded the simple Paris-Erdogan power law to take care of this phenomenon by

$$\frac{da}{dN} = \frac{A(\Delta K)^p}{(1-R')K_c - \Delta K}, \tag{8}$$

To incorporate the effect of stress ratio such that all constant-amplitude data of various stress ratios may be represented by single curve, K.Walker (1970) introduced the idea of the effective stress, σ', defined as

$$\sigma' = (1-R')^m \sigma_{\max}, \tag{9}$$

where m is an empirical constant that is material dependent. In terms of the effective stress the fatigue crack growth rate equation based on equation (6) can be written as

$$\frac{da}{dN} = A[(1-R')^m \sigma_{\max}\sqrt{\pi a}]^p = A[(1-R')^{m-1}\Delta K]^p, \tag{10}$$

The constant m is typically around 0.5 , but varies from approximately 0.3 to nearly 1 for many materials. Decreasing values of m imply a stronger effect of R'. In case where $R'<0$, ΔK is set equal to $K_{\max}$. This is because the stress intensity factor is not defined for a stress that does not open the crack.

Besides the Paris-Erdogan equation, researchers have developed some more sophisticated equations to fit the fatigue crack growth rate data, but due to the simplicity of the Paris-Erdogan equation, it is the most frequently used expression in the analysis of fatigue crack growth for a wide spectrum of materials and fatigue test conditions.

In conclusion it is need to be said that, to predict the fatigue crack growth behavior, the following must be available:

1. The stress-intensity factor, described as a function of crack size, for the relevant structural and crack geometry;
2. The stress-time (load-time) history, described for the structural location, component or structure under consideration;

3. The constant amplitude crack growth rate data, described as a function of the stress-intensity factor, for the material and for the relevant environment ;
4. A damage integration routine that integrates the crack growth rate to produce a crack growth curve, using the proper stress-time history, the proper stress-intensity formulation, and an appropriate integration rule.

For a given material and set of test conditions, the fatigue crack growth rate can be written in Paris-Erdogan form of equation (6). Equation (10) is employed in this research to account for the mean stress effect.

3.5.2 The stress intensity function.

Because of the phenomenon of the stress concentration effect, the stress distribution around the rivet hole is much higher than remote stress field. The stress intensity factor for a crack growing form the edge of the hole needs to be modified to take the stress concentration effect into account. Bowie's solution was the first solution proposed. Newman and Raju (1981) presented a approximation of the Bowie's solution by taking advantage of three-dimensional finite element method.

The stress intensity factor takes the form of equation

$$\Delta K = F \Delta \sigma \sqrt{\pi a} = F(\sigma_{\max} - \sigma_{\min})\sqrt{\pi a}, \tag{11}$$

where F is a geometrical factor which depends upon the crack configuration, and $\sigma_{\max}$ and $\sigma_{\min}$ are the maximum and minimum values, respectively, of the remote fatigue stress during each cycle.

The approximation by Newman and Raju is given below

$$F = 1 - M_1(0.15 - M_1(3.46 - M_1(4.47 - 3.52M_1))), \tag{12}$$

where

$$M_1 = \frac{1}{1+\frac{a}{r}}, \tag{13}$$

and where r and a are radius and half crack length, respectively.

3.5.3 Load interaction.

It is obvious that an aircraft structural component experiences in service has variable amplitudes. Therefore, the crack growth behavior under variable amplitude cycling is greatly complicated by interaction effects of high and low loads. A high load occurring in a sequence of low-amplitude cycles significantly reduces the rate of crack growth during the cycles applied subsequently to the overload. This phenomenon is called *retardation.* Retardation results from the plastic deformations that occur as the crack propagates. During loading, the material at the crack tip is plastically deformed, and a tensile plastic zone formed. Upon load release, the surrounding material is elastically unloaded, and a part of the plastic zone experiences compressive stresses. The larger the load, the larger the zone of compressive stresses. The high loads occurred in service are beneficial to fatigue life of engineering components. The fatigue crack growth tests of aluminum alloy under flight-simulation loading showed that reducing the magnitude of high loads in the flight-simulation loading shortened the fatigue life [Schijve, Vlutters, Ichsan and Provo′ Kluit (1985)]. In order to account for he load interaction effect in fatigue crack growth life prediction, the generalized Willenborg retardation model is used in this study.

The original Willenborg model made use of plastic enclave formed at the overload as depicted in Figure 7:

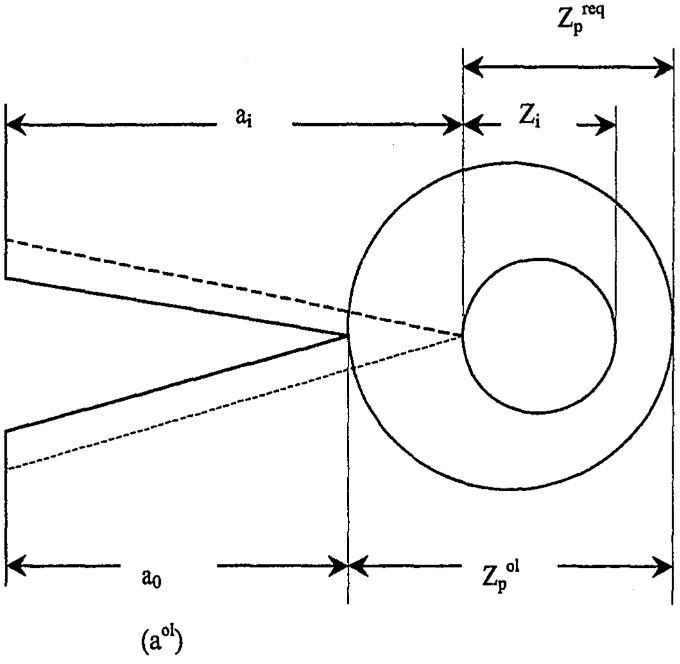


Figure 7: Load interaction model, schematic illustration.

The overload σ_{max}^{ol} created a plastic zone Z_p^{ol} which will cause retardation for the following stress cycles, if following conditions is met:

$$a_i + Z_i < a^{ol} + Z_p^{ol}$$

where a^{ol} and a_i - half crack lengths to which the overload σ_{max}^{ol} is applied and the subsequent remote stress $\sigma_{max,i}$ is applied respectively;Z_i it the plastic zone size generated by $\sigma_{max,i}$.

Detailed description of original Willenborg model can be found in Li's (1997) dissertation, or Willenborg (1971).

3.5.4 Superposition model for environmentally assisted fatigue crack growth.

To take into account contribution of sustained load on environmentally assisted fatigue crack growth in big strength steels a superposition model was proposed by Wei and Landes (1969). This first model ignores the contribution of a cycle dependent terms and later was modified [Wei (1979)].

After numerous times been modified (see paper by Wei and Gao (1983)) superposition model recognized the fact that fatigue and corrosion fatigue operate as concurrent process:

$$\left(\frac{da}{dN}\right)_e = \left(\frac{da}{dN}\right)_r (1-\Phi) + \left(\frac{da}{dN}\right)^*_{cf,s} \Phi,$$

where $\left(\frac{da}{dN}\right)_e$ is mechanical fatigue rate,

$\left(\frac{da}{dN}\right)^*_{cf,s}$ is "pure" corrosion fatigue rate,

Φ is fractional area of crack that is undergoing pure corrosion fatigue.

In the limit, for $\phi = 0$ or for test in an inert environment

$$\left(\frac{da}{dN}\right)_e = \left(\frac{da}{dN}\right)_r,$$

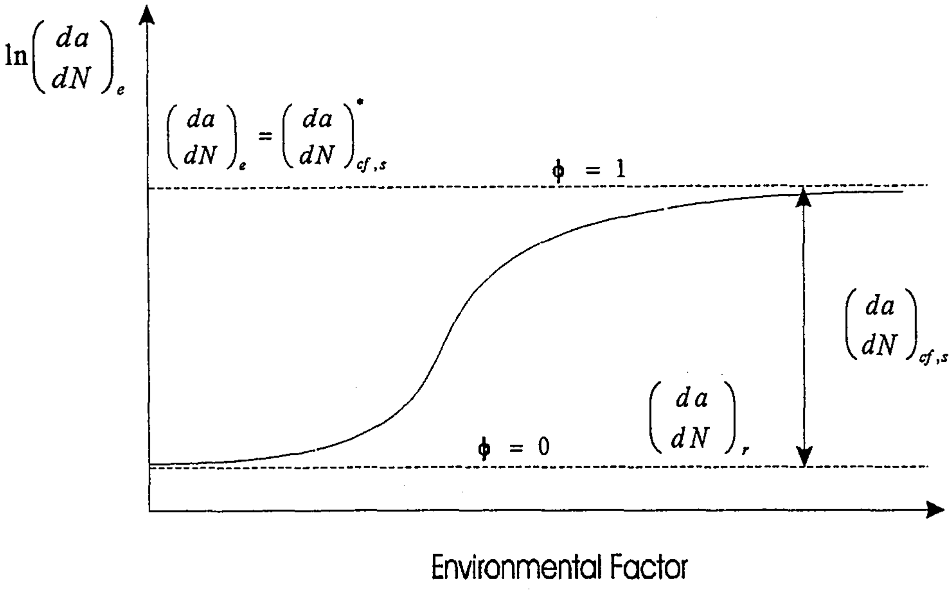
which corresponds to pure fatigue.

For $\phi = 1$, corresponding to saturation [Weir, Hart, Simmons, and Wei (1980)]

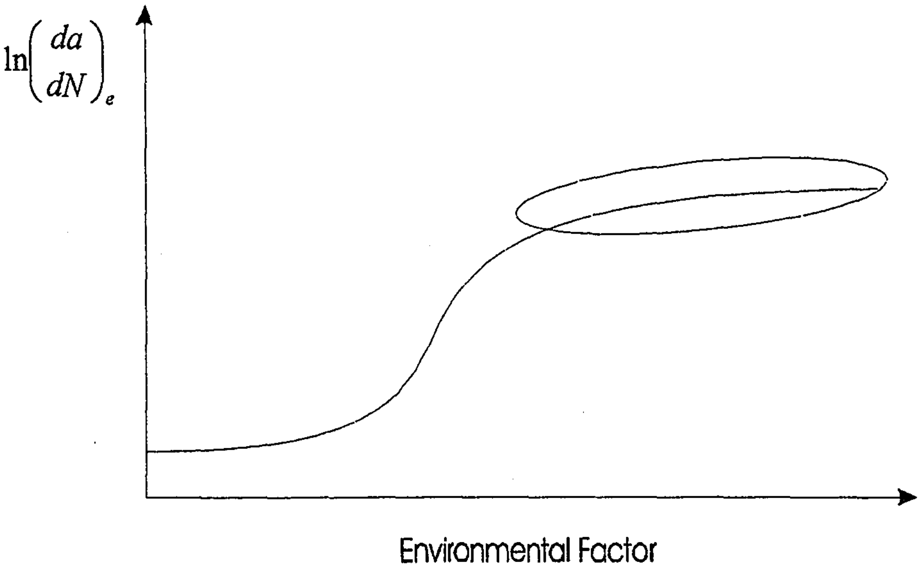
$$\left(\frac{da}{dN}\right)_e = \left(\frac{da}{dN}\right)^*_{cf,s},$$

measured growth rate is corresponding to the pure corrosion fatigue rates.

Thus, relationship between environmental factor and environmentally assisted fatigue crack growth can be schematically drawn as:



Low region of the graph represents pure mechanical fatigue (meaning: no environment influence - vacuum). In the upper region – is pure corrosion fatigue (what the environment costs). Material that is considered in this study is aluminum allow. This material under the normal conditions is going to be under environmental effect. Therefore, in current study interest lies in upper region of the curve, where $(da/dN)_e \rightarrow (da/dN)_{cf,s}$


$\ln\left(\frac{da}{dN}\right)_e$
Environmental Factor

CHAPTER 4

TRANSITION CRITERION.

One of the purposes of this study was to determine the influence of the pitting corrosion on the fatigue crack growth. This chapter projects theoretical work that was done to achieve this goal.

4.1 Transition criteria I.

As it was mentioned in Chapter 3 Part 4, Transition criteria I is the condition of transition in the model from pure pitting corrosion to corrosion fatigue, or initialization of the Competition model. This transition criterion was first introduced by Wei and Harlow (1993). In that work, the plane was subjected to the constant amplitude loading. Under such condition pitting controls the damage growth until corrosion fatigue crack growth dominates.

Transition was characterized by a system of equations:

$$\Delta K \geq \Delta K_{th}, \tag{14}$$

$$\left(\frac{da}{dt}\right)_{crack} \geq \left(\frac{da}{dt}\right)_{pit}, \tag{15}$$

where ΔK - driving force for a crack in infinite plate

ΔK_{th} - threshold driving force

and the derivatives are the corrosion fatigue crack growth or pit growth rates, respectively.

Schematic representation of pitting corrosion and corrosion fatigue (see figure below) shows that in case of constant amplitude loading there will be no competition between crack and pit growth. As soon as a crack nucleates there will be no more influence of pitting corrosion on the defect size. Therefore, under constant amplitude loading, starting from the moment of crack initiation, only crack growth defines residual life length of the plane.

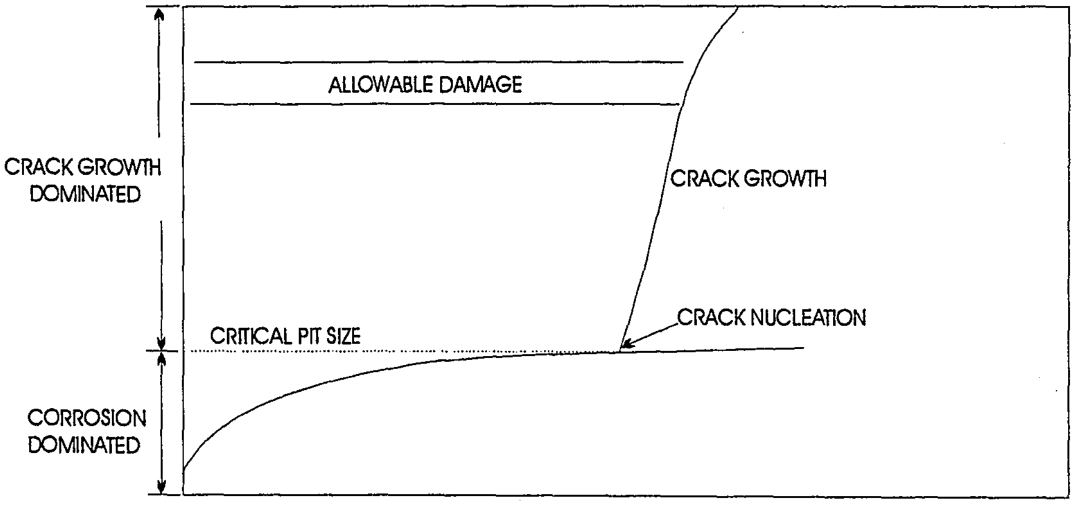


Figure 8: Pitting and cracking under the constant amplitude load.

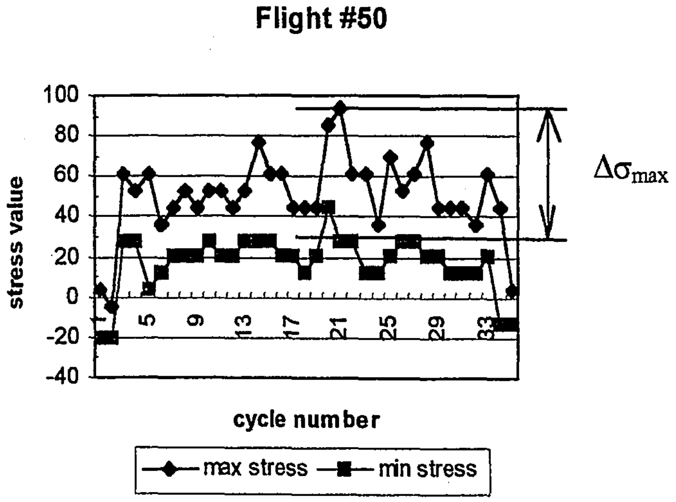
Condition (15), which defines correspondence between the speed of the growth of pit and crack, is typically the more critical condition. Since the pit growth rate continuously decreases with time, and since the crack growth rate continuously increases, assuming that condition (14) satisfied, then there is a unique time at which the crack will grow faster then existing pit. So, from that moment the crack only will influence defect size.

Keeping in mind that under a spectrum load stress $(\partial a/\partial t)_{crack}$ will not be continuously increasing, we are forced in the present work to alter condition (15). Condition (14), however, is exactly condition that's needed in a new model for spectrum load stress as a transition criteria from pitting corrosion to cracking (or corrosion fatigue).

Finally, Transition criteria I for the model with spectrum loading was found:

$$\Delta\sigma_{\max} \geq \Delta\sigma_{pit}, \tag{16}$$

where $\Delta\sigma_{\max}$ - maximum amplitude of load stress during current flight (see plot of load for flight #50 below), $\Delta\sigma_{pit}$ - stress range for given pit size, calculated by formula (4) (see Chapter 3, Part 1).



Therefore, if Transition criteria I is satisfied then a crack will appear during this particular flight, and probably grow. Furthermore, there is no guarantee, that, by the end of the next "ground" cycle, a pit will not grow larger then the current crack (simply, the crack is consumed by pit growth). If the crack is consumed, then model will be in the "pure corrosion" stage again, until the next flight when Transition criteria I will be used again to determine whether maximum amplitude of load stress is high enough for crack to appear or not.

4.2 Transition criteria II.

In Chapter 3 Part 4 a description of the term “Competition model” can be found. The last flight in which pit determines the damage growth is taken to be the end of the Competition model, since only cracking causes subsequent damage growth. Calculations of pit growth become unnecessary. Numerous simulations (or test-runs) were considered. A general observation is that before Pure corrosion fatigue starts, anywhere from less than 1% to 30% of the total life time of the plane passes.

Next set of graphs (Figure 9) shows that the time of transition from the Competition model to the Pure corrosion fatigue model is not easy to predict. Transition to Pure corrosion fatigue greatly depends on the initial pit size, and on the maximum stress during each flight. That makes it impossible to find a reasonable, common for all different cases period of time, at the end of one there will be no dough that pitting corrosion does not play any role in growth of damage size. For example, even after considerably long period of time with small initial pit size or with a plane under a low load, a pit could grow big enough to consume a small crack.

A second approach was to count the number of flights since last time that pitting dominated the damage growth. After some number of flights, say $\mathbf{N_1}$, assume that because the pit was not able to consume the crack for such a long period of time, transition to Pure corrosion fatigue had occurred. Question: what should **N₁** be chosen equal to?

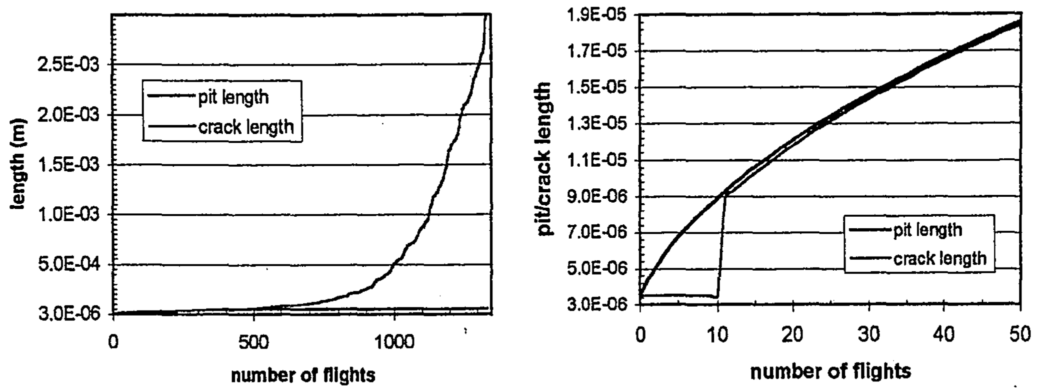
Finally, the decision was to search for transition criteria that takes into account both pit and crack sizes. Test-runs were done for a variety of cases, from very little to large initial pit sizes. Observations from those results gave a rise to a simple, but effective and safe transition criteria. If the difference between the crack size and the pit size appears to be larger then δ^* =1.e-5 m it is assumed that transition to Pure corrosion fatigue occurred. In other words, Transition criteria II:

$$a_{pit} - a_{crack} \geq \delta^*, \tag{17}$$

where a_{pit}, a_{crack} – pit size and crack size correspondingly.

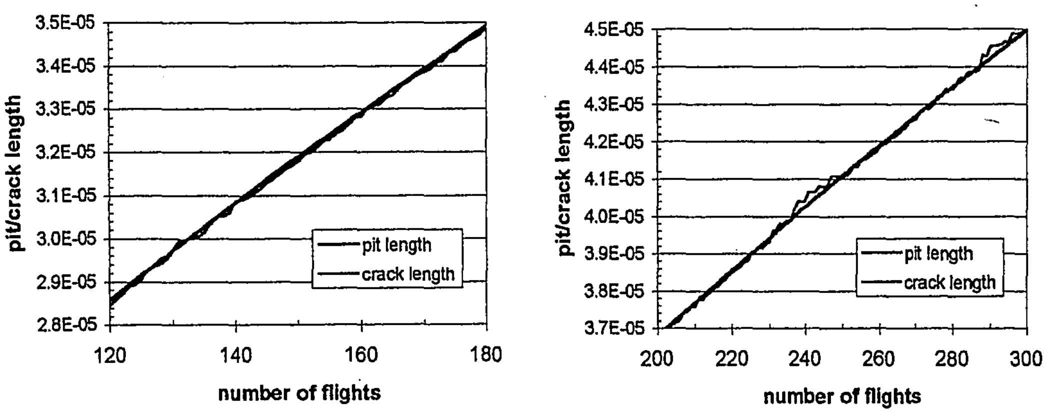
Based on the loading conditions, initial sizes of the pits, observations and on the experience this tolerance δ^* =1.e-5 m is a good choice for the Transition criteria II for all considered cases. Of course, if random variables such as initial pit size, stress intensity factor, e.g. have a completely different distribution, Transition criteria II should be checked and possibly adapted. Incorporating Transition criteria II shortened the computational time approximately from 10% to 85% depending upon the initial conditions of each problem.

Figure 9: Different stages of pit and crack growth.



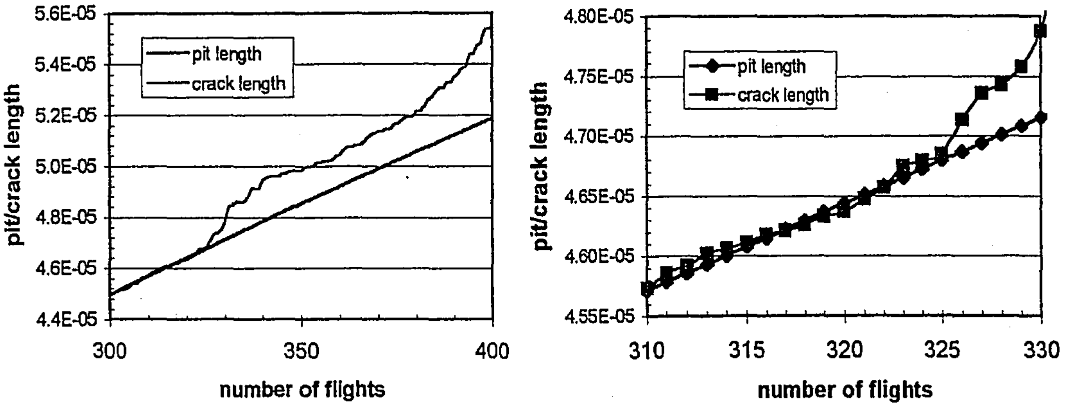
a) pit/crack growth

b) Transition Criteria I



c) competition model (closeup 1)

d) competition model (closeup 2)



e) Last consumption of the crack by the pit

f) Last consuming of the crack (closeup)

Figure 9 shows different stages of the pit and crack growth in one of single point simulations. Single hole with two pits was considered (Figure 3). Application of the loading sequence (flying time) alternated with effect of the environment (ground time). See Chapter 3 Part 4. Figure 9(a) reflex overall view on pit and crack growth during those simulations. General form very much the same with the Figure 8 (for the constant amplitude loading). Closer look at the results (see Figure 9(c) and 9(d)) illustrates the difference between crack growth under the constant amplitude loading and under the spectrum loading: the pit is consuming the crack, then the crack starts growing again.

Figure 9(b) illustrates the moment of the first appearance of the crack. Figure 9(e) and 9(f) capture the moment when the pit consumed the crack for the last time.

CHAPTER 5

RESULTS

5.1 Effect of pitting corrosion an initial pit size on the results.

To fully explore the impact of pitting corrosion on the damage growth eight different combinations of initial settings were considered:

series	Rivet hole size	Average initial damage size	Pitting corrosion
A_p	0.01 m (L)	1.5e-4 m (L)	included
A_f	0.01m (L)	1.5e-4 m (L)	Not included
B_p	0.01 m (L)	4.5e-6 m (S)	included
B_f	0.01 m (L)	4.5e-6 m (S)	Not included
C_p	0.003 m (S)	1.5e-4 m (L)	included
C_f	0.003 m (S)	1.5e-4 m (L)	Not included
D_p	0.003 m (S)	4.5e-6 m (S)	included
D_f	0.003 m (S)	4.5e-6 m (S)	Not included

where L = Large, S = Small sizes.

With the temperature fixed at T=25° C (or 298K) eight test-runs were made: four runs included pitting corrosion in the model, and four others did not. Each of those test-runs was an average of 10 runs with 100 cases of different initial damage sizes each to produce general results. Initial defect size, obviously, plays incredibly large role in final results. Series' with large initial damage size (A_p, A_f) and (C_p, C_f) show almost no difference in life length of plane as result of inclusion of pitting corrosion in original model. On the other hand, series' with small initial damage size (B_p, B_f) and (D_p, D_f) have dramatic difference in fatigue life as result of pitting corrosion (p.c.) incorporation into the model. (See Figure 10 through Figure 15)

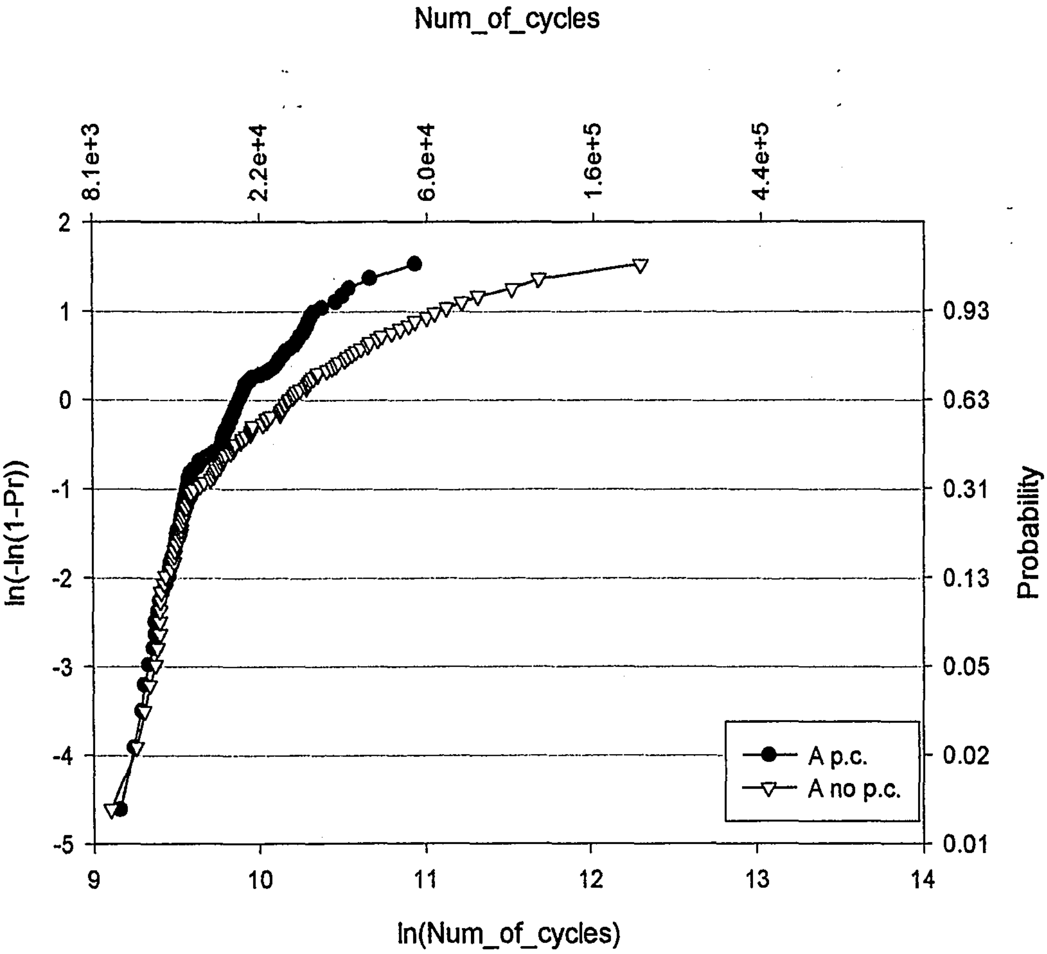


Figure 10: The influence of pitting corrosion on the fatigue life. Case A.

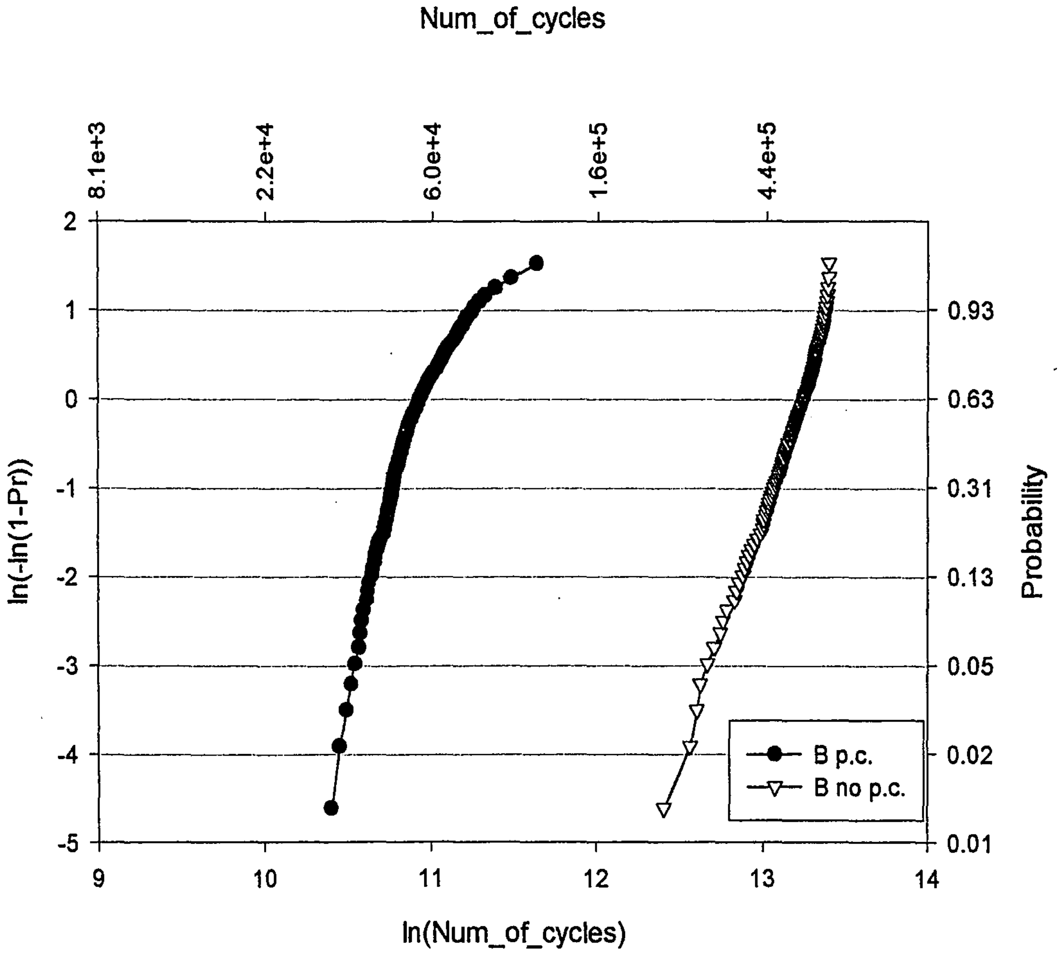


Figure 11: The influence of pitting corrosion on the fatigue life. Case B.

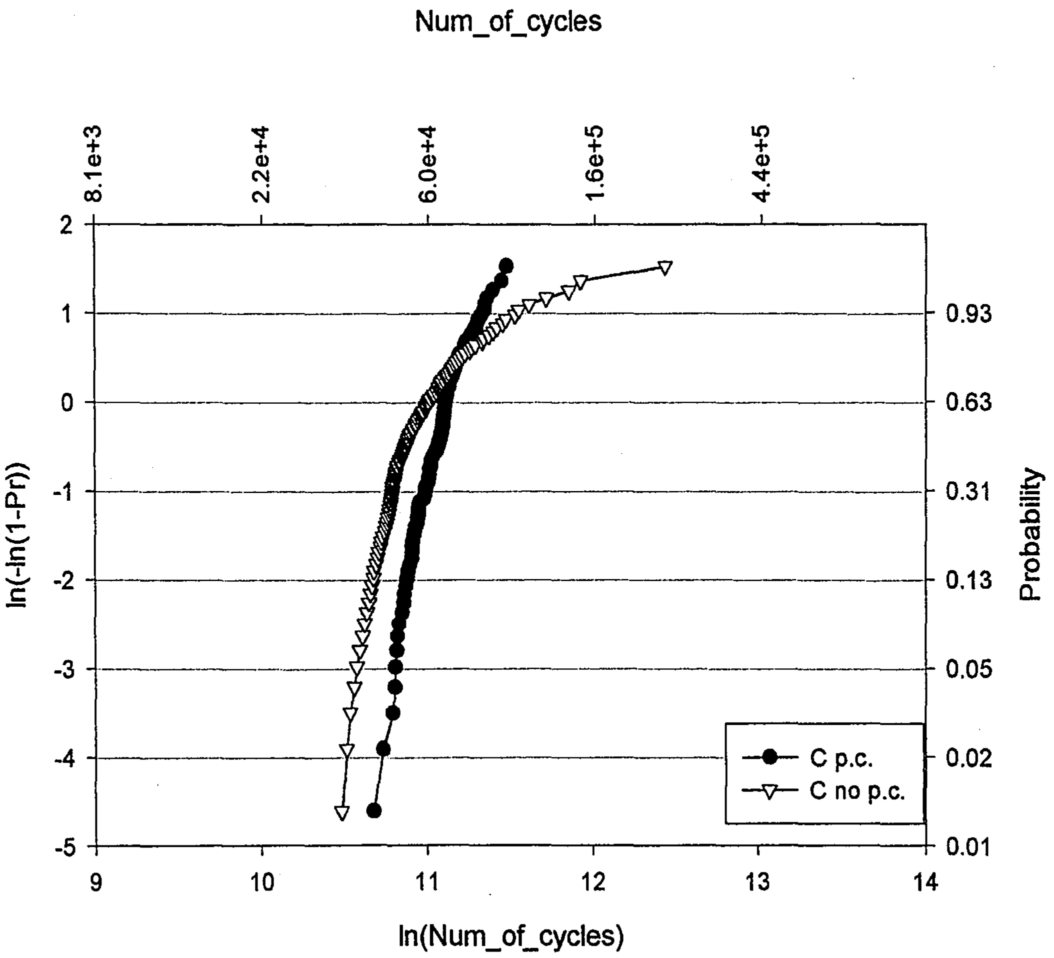


Figure 12: The influence of pitting corrosion on the fatigue life. Case C.

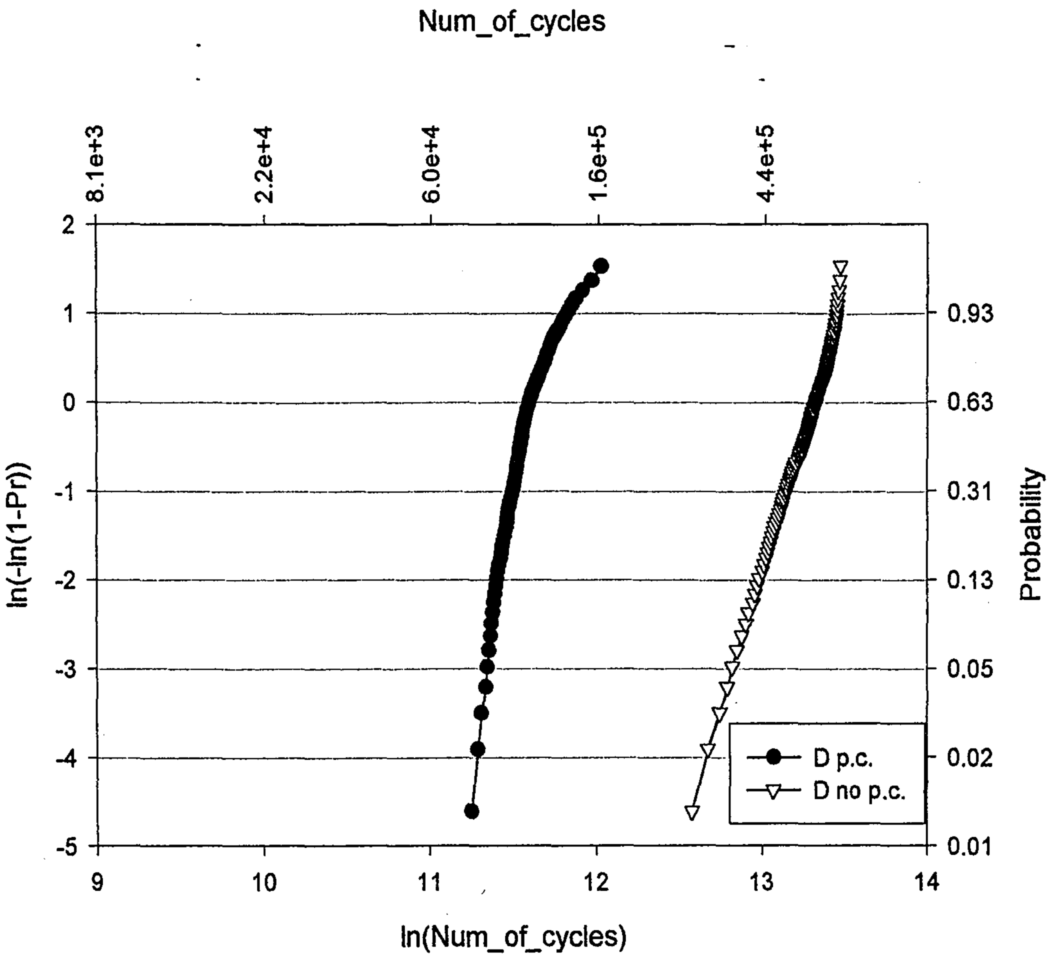


Figure 13: The influence of pitting corrosion on the fatigue life. Case D.

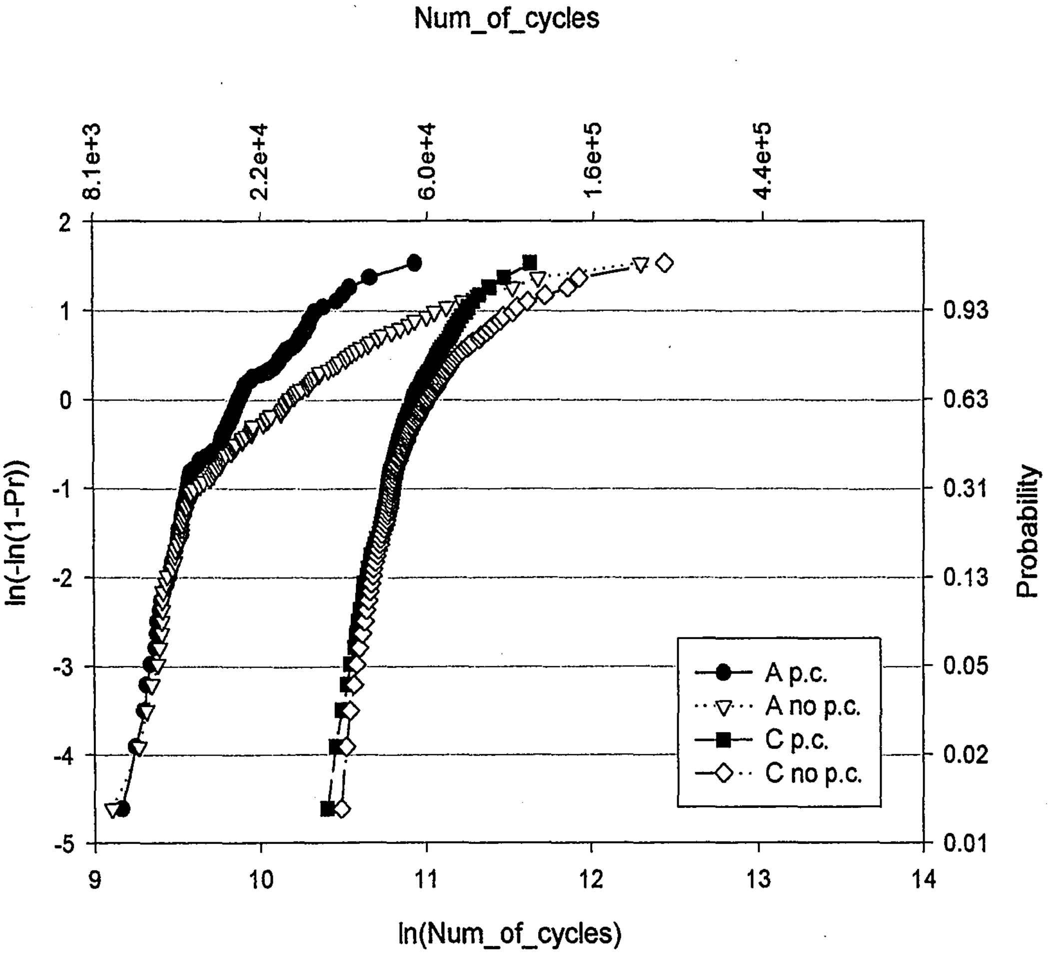


Figure 14: The influence of pitting corrosion and fasetener hole size on the fatigue life. Cases A and C.

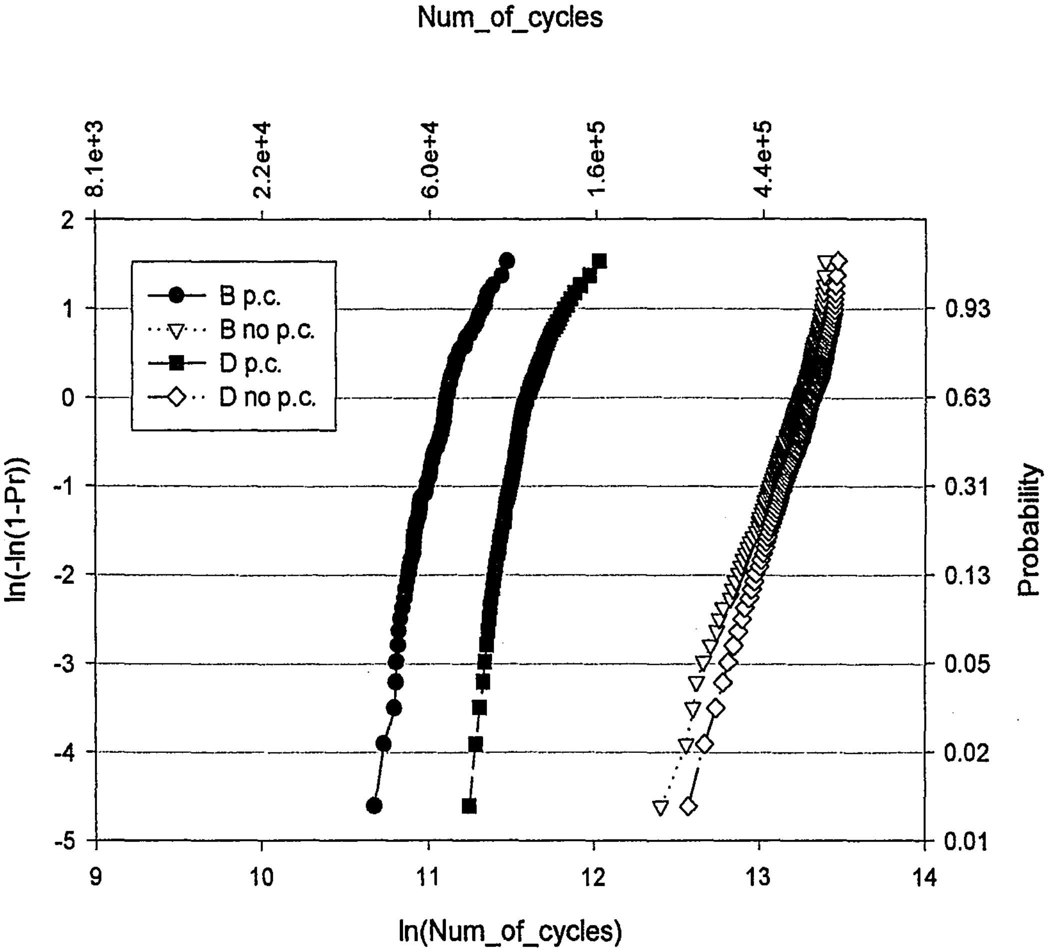


Figure 15: The influence of pitting corrosion and fasetener hole size on the fatigue life. Cases B and D.

Fatigue life is shortened by pitting corrosion for cases with small initial pit sizes. This is a reasonable expectation: the rate of pit growth at appropriate temperatures will be much higher than the rate of tip crack corrosion. Pitting corrosion will still have an impact in cases A and C no matter that the crack was nucleated immediately in the first flight. In cases of large initial damage sizes pit with larger size will not increase by 100% it's own original size as fast as smaller pit will, but numerically it will grow much faster then smaller pit, and will lead damage size grow for some very short time. (Figure 16 illustrates it)

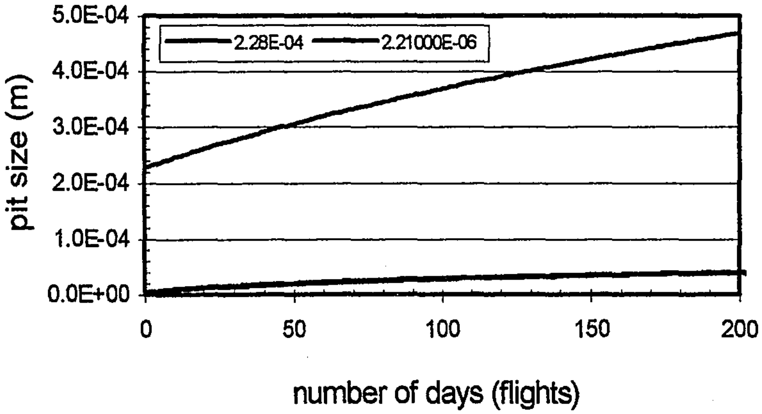


Figure 16: Rates of small pit and large pit growth.

The shape of the curves also have been affected: curves become less spread on the top of the graphs A and C. Random variable "pit size" in both those cases, comparing to cases B and D, have widely spread distribution. (See parameters for those random variables in part 4 of this chapter.) Therefore, all longer lasting points from the top on the curve, were the smallest ones. With pitting corrosion exactly such points will be effected the most.

5.2 The influence of temperature on fatigue life with pitting corrosion incorporated.

Early detection of a crack from the holes is crucial and pitting corrosion has proven to be influential especially in cases with small pits. Therefore, to study the temperature effect test runs were done using series D (small rivet hole, small pits). The temperature varies: T_1= -40° C (or 233K), T_2 =25° C (or 298K), T_3- (temperatures, used in ENSTAFF temperature profiles), T_4=75° C (or 348K). Results where consistent with results obtained by Li (1997): with temperature increasing fatigue life length shortens rapidly. (Figure 17)

All though the results appear to be consistent with Li's (1997) study direct comparison of the two results where not possible, because Li used the model C_f in his calculations. New calculations were made, with same temperature profiles, but with a large initial pit size and small hole size (series' C with and without pitting corrosion). See Figure 18 trough Figure 20

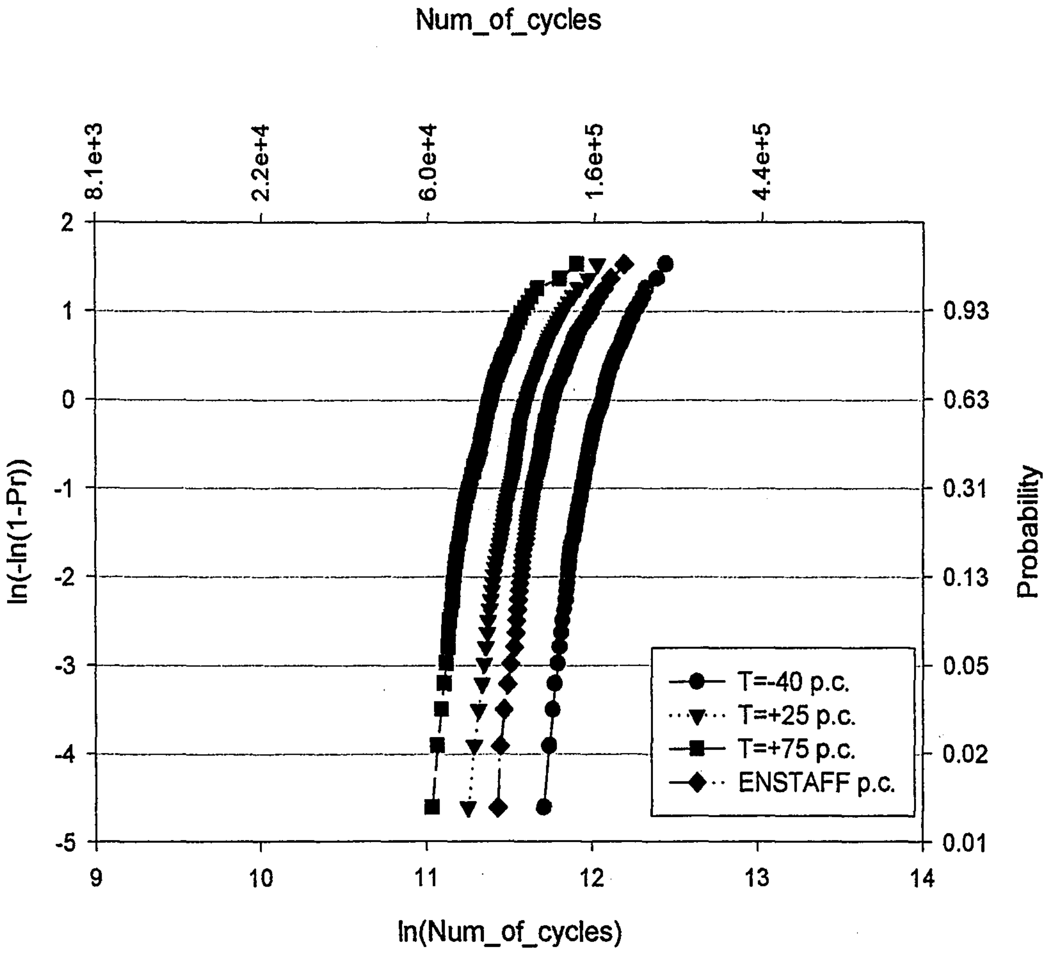


Figure 17: Comparison of the influence of ENSTAFF temperature profiles and of FALSTAFF at various temperature conditions on fatigue life. Case D, pitting corrosion included in all 4 cases.

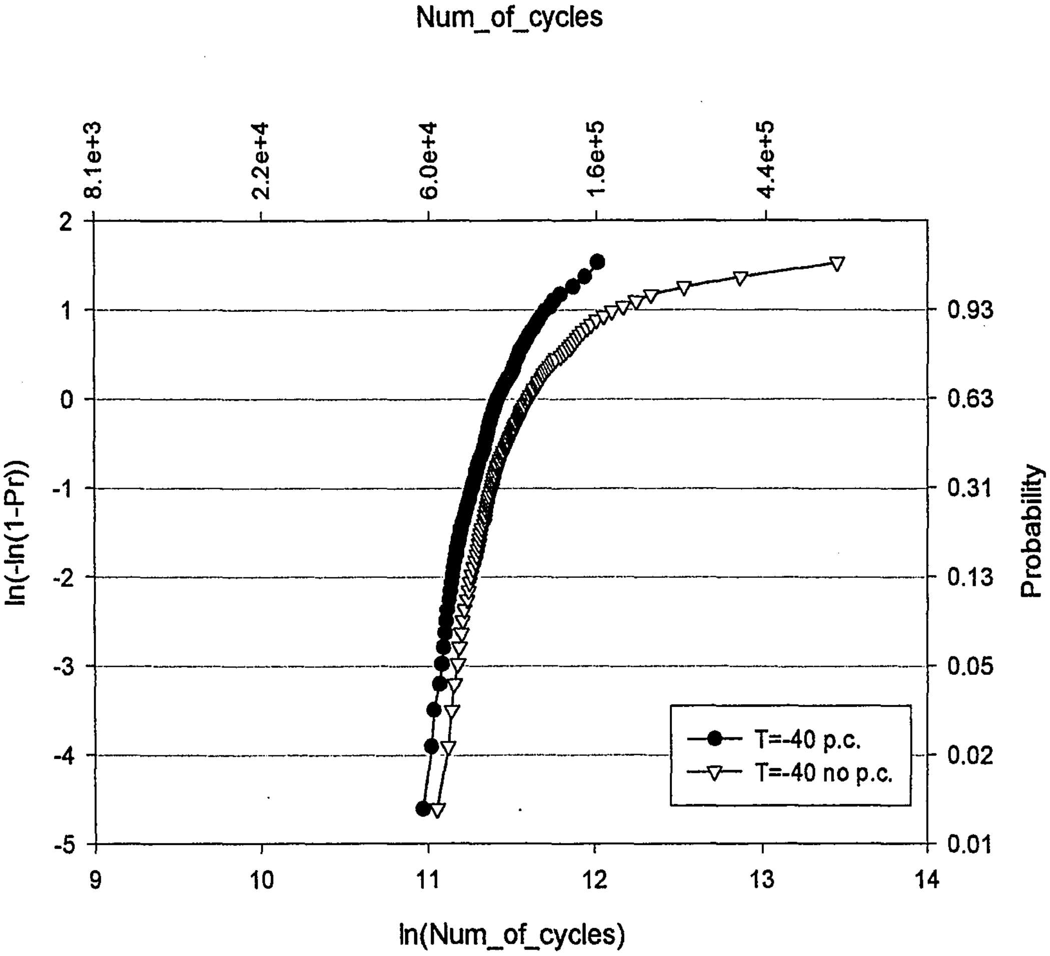


Figure 18: Influence of FALSTAFF at low temperature (-40 C) on the fatigue life (two models considered: with pitting corrosion and without pitting corrosion).

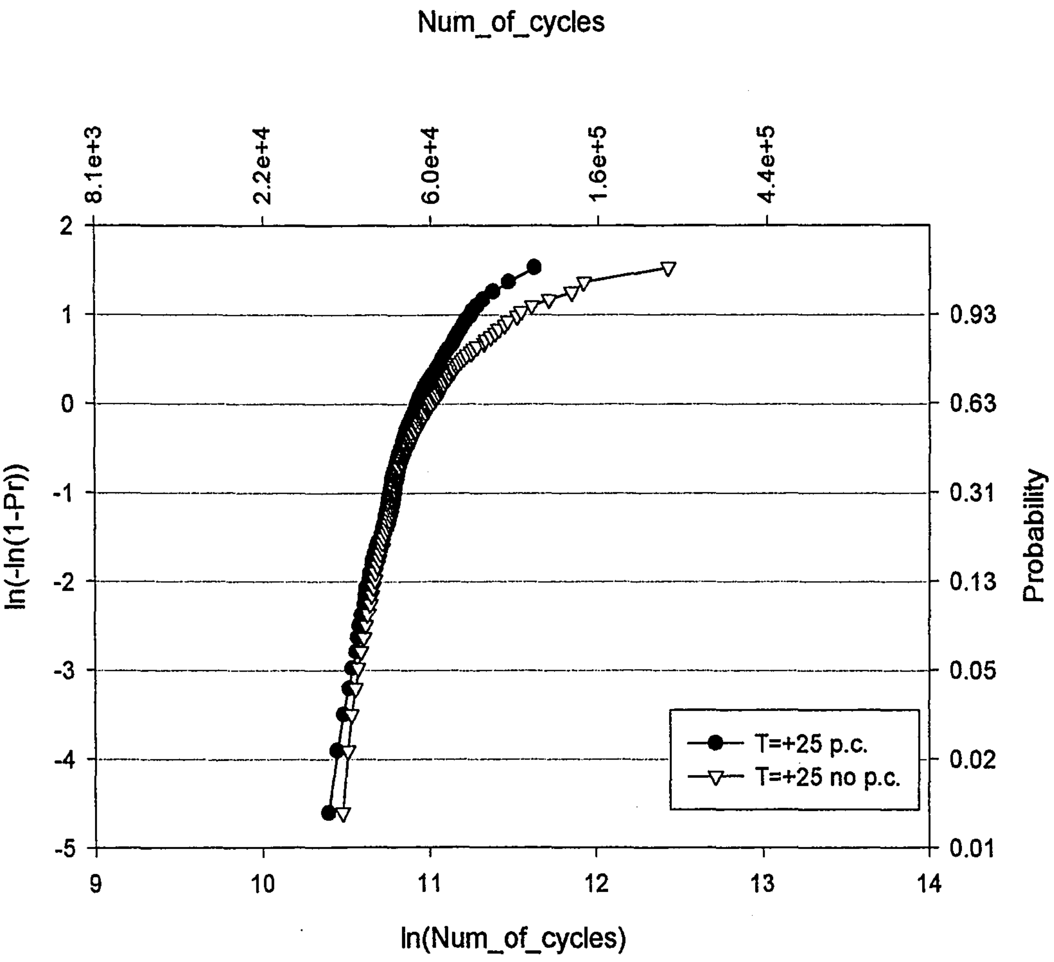


Figure 19: Influence of FALSTAFF at room temperature (+25 C) on the fatigue life (two models considered: with pitting corrosion and without pitting corrosion).

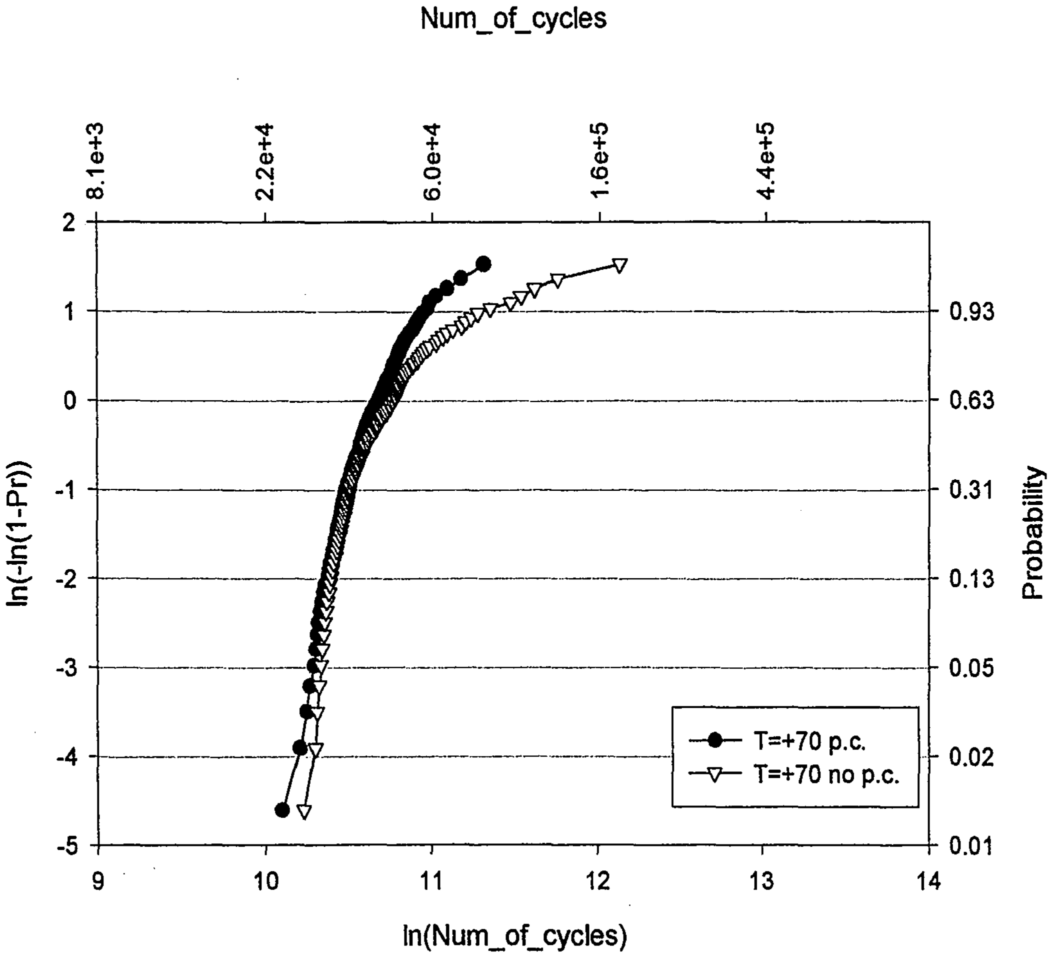


Figure 20: Influence of FALSTAFF at high temperature (+70 C) on the fatigue life (two models considered: with pitting corrosion and without pitting corrosion).

Middle area (with probability $\in(0.04, 0.8)$) in each of 3 last plots (Figure 18 - Figure 20) shows almost no difference between cases with and without corrosion. The reason for that is the initial pit size: comparing to the previous case D pits are approximately 33 times larger, so crack growth starts within the first flight. Therefore, there is almost no impact of pitting corrosion on fatigue life. On the other hand, in upper and low region of each of 3 plots difference between two cases is dramatic. Recalling that in each run 100 points (pits or cracks) with different initial radiuses were generated. Now sizes of damage vary a lot, because of the specific of CDF. Smaller damage needs larger stress for a crack to grow, consequently, transition to corrosion fatigue may not appear in one of the first flights, meaning that a pit will have more influence than in cases with large initial damage size. Talking about bottom of the plots (probability near 0), we again considering CDF: closer to the limits of random variable distribution generated pits or cracks tend to vary in sizes dramatically. Next table (see Table 1) contains 3 smallest and 3 largest values of initial damage sizes simulated in 10 independent program runs. Obviously, more then 10 runs should be used to calculate true average for 3 largest values of the damage size.

Table 1: Distribution of an initial pit sizes at extreme values.

Interval	Number of points in each of the 10 runs that belong to the interval									
0-1.00E-05	0	2	0	1	0	0	0	2	1	0
//-2.00E-05	2	1	0	1	2	1	0	0	1	3
//-3.00E-05	3	2	2	1	3	3	1	1	2	3
//-2.50E-04	1	1	1	0	1	3	1	0	0	3
//-2.60E-04	0	0	1	2	1	0	1	2	1	0
//-2.70E-04	2	0	2	1	0	1	0	1	2	0
//-2.80E-04	0	1	1	1	0	0	0	1	0	1
//-2.90E-04	0	0	1	0	0	0	2	1	1	0
//-3.00E-04	0	1	0	2	1	1	1	0	0	0
//-3.10E-04	0	1	0	1	0	0	1	0	1	1
//-3.20E-04	0	1	1	0	1	0	0	0	1	0
//-3.30E-04	2	1	0	0	0	0	0	1	0	0
//-3.40E-04	0	0	1	1	0	0	1	0	0	0
//-3.50E-04	0	0	1	0	0	0	0	0	1	0
//-3.60E-04	0	0	0	0	0	0	1	0	0	0
//-3.70E-04	0	0	0	0	0	0	0	1	0	0
//-3.80E-04	0	0	0	0	0	0	0	0	0	0
//-3.90E-04	0	0	0	0	0	0	0	0	0	0
//-4.00E-04	0	0	0	0	0	0	0	0	0	0
//-4.10E-04	0	0	0	0	0	0	0	0	0	0
//-4.20E-04	0	0	0	0	0	0	0	0	0	0
//-4.30E-04	0	0	0	0	0	1	1	0	0	0

5.3 Discussion on behavior of pitting corrosion model at low temperature.

Close examination of different plots led to a discovery of the clear indication of the influence of pitting corrosion on the fatigue life length at extremely low temperatures [at T=-40° C (or 233K)]. Experiments show that pitting corrosion is arrested at the low temperatures (Lee (1999), Dolley (1999)). Computer simulation of damage growth with and without pitting corrosion in the model where run for two cases of temperatures: T_1=+75° C (or 348K) and T_2=-40° C (or 233K). (See Figure 21)

On the next plot (Figure 22) it is obvious that with pitting corrosion included in the model at the low temperature fatigue life is much shorter than in the model without pitting corrosion and at the higher temperatures. The reason is in the rate of pitting corrosion: pit growth rate at T=-40° C (or 233K) is very slow, but because the initial pit size is chosen to be very small transition to cracking does not happened for quite some time. The rate of pit growth appears to be higher than the environmental corrosion fatigue growth rate.

Therefore, the model is proven to be temperature sensitive: at normal to high temperatures, the model describes the physical phenomenon close to the experimental tests, but at the low temperature results are not as close as expected.

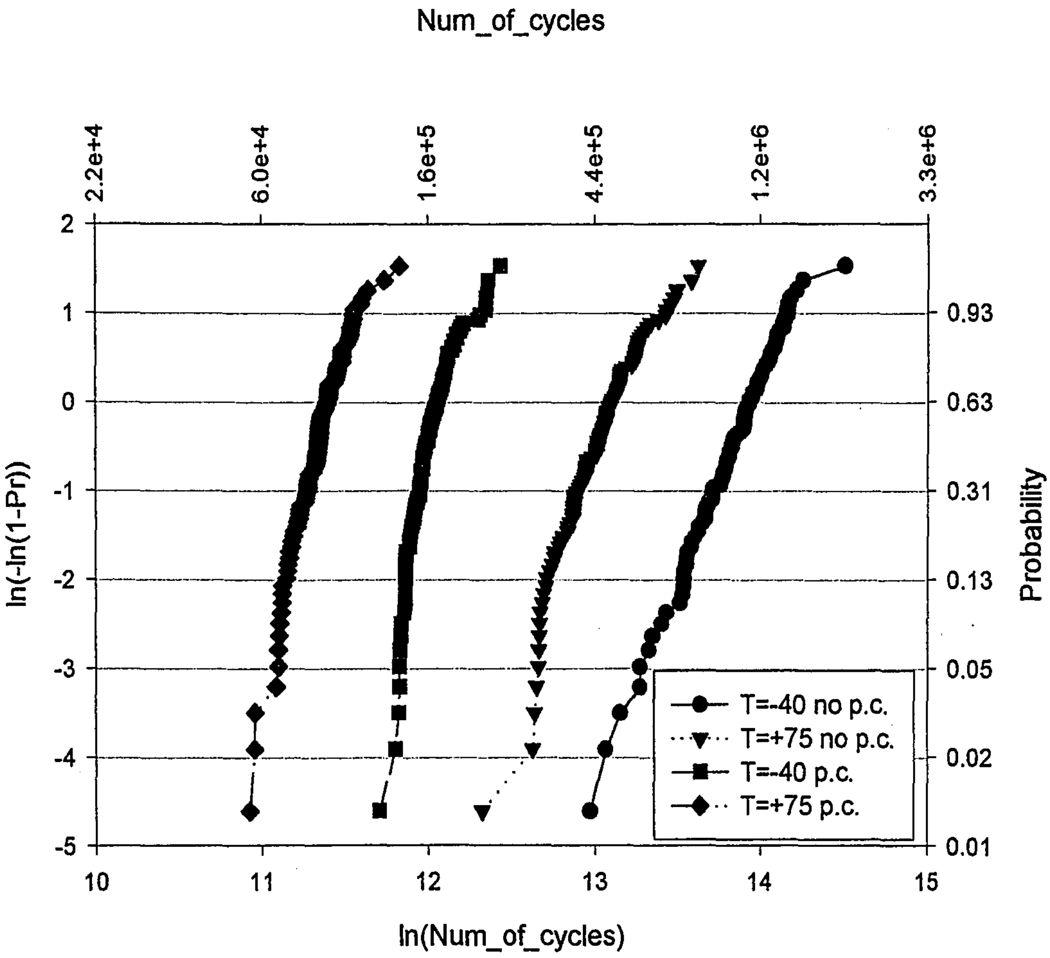


Figure 21: Impact of pitting corrosion on fatigue life at low temperature, comparing to the case without pitting corrosion at high temperature . Case D, with and without pitting corrosion.

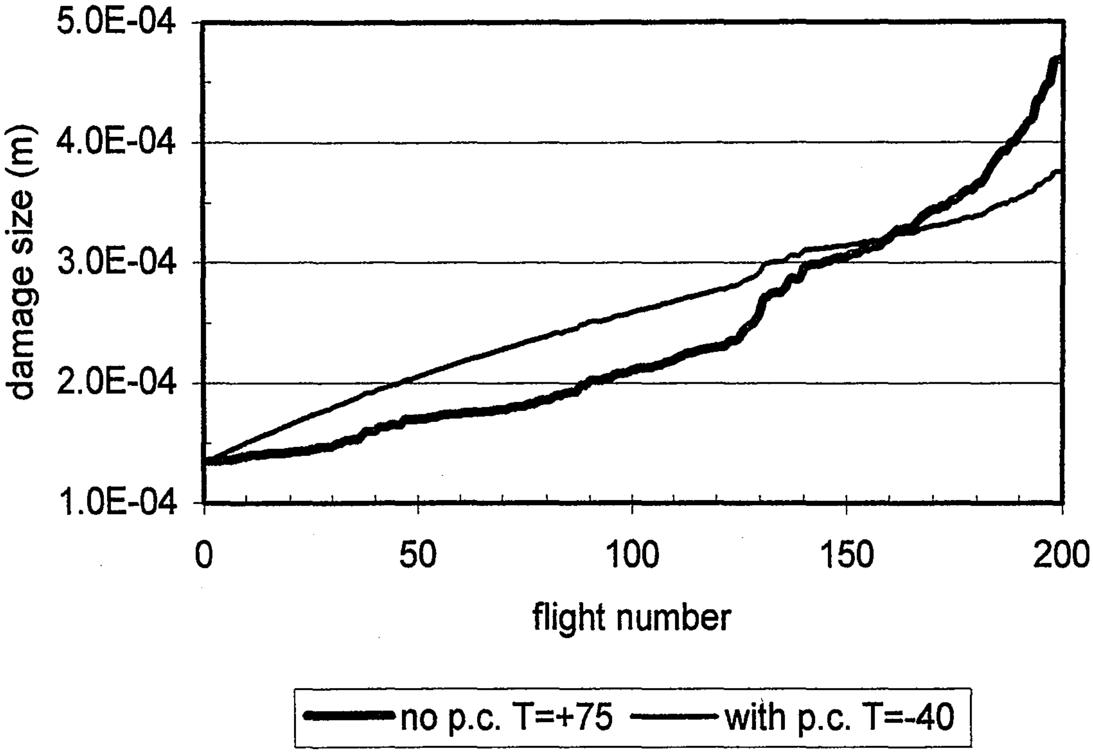


Figure 22: Phenomenon of the low temperature pitting corrosion.

5.4 Influence of the random variables on fatigue life under spectrum load.

Flight loading spectrums were constructed to simulate the service loads that an airplane will encounter during the service time. Although the wing loading of a fighter airplane is not totally random, it is subject to certain uncertainties. The uncertainties in developing spectrum loading include variation in mission profiles and due to the usage of an individual airplane. To take into account influence of those uncertainties the random variables where included into the model.

The impact of each random variable on fatigue lives subjected to spectrum loading differs from the rest. Impact of threshold driving force (ΔK_{th}) is minimal, almost none at all. Opposite to ΔK_{th} influences of fatigue crack growth coefficient (A_c) shown to be great. (See Figure 23) In order to select in the future more appropriate CDF (cumulative distribution function) extensive experimental work should be done to gather statistical information.

Because distribution functions are unknown, it was assumed that the Weibull CDF sufficiently robust to adequately estimate the statistical character of all of the random variables. In cases with pitting corrosion incorporated in model "c" is an initial pit radius, where in cases without pitting corrosion "c" is an initial crack length. Detailed information on this subject can be found in Harlow and Wei (1998).

The three-parameter Weibull CDF , given by:

$$F(x) = 1 - \exp\left(-\left[\frac{(x-\gamma)^{\alpha}}{\beta}\right]\right), \qquad x \geq \gamma, \tag{18}$$

where all estimated parameters given in Table 2.

Table 2 – Weibull parameters used in the model.

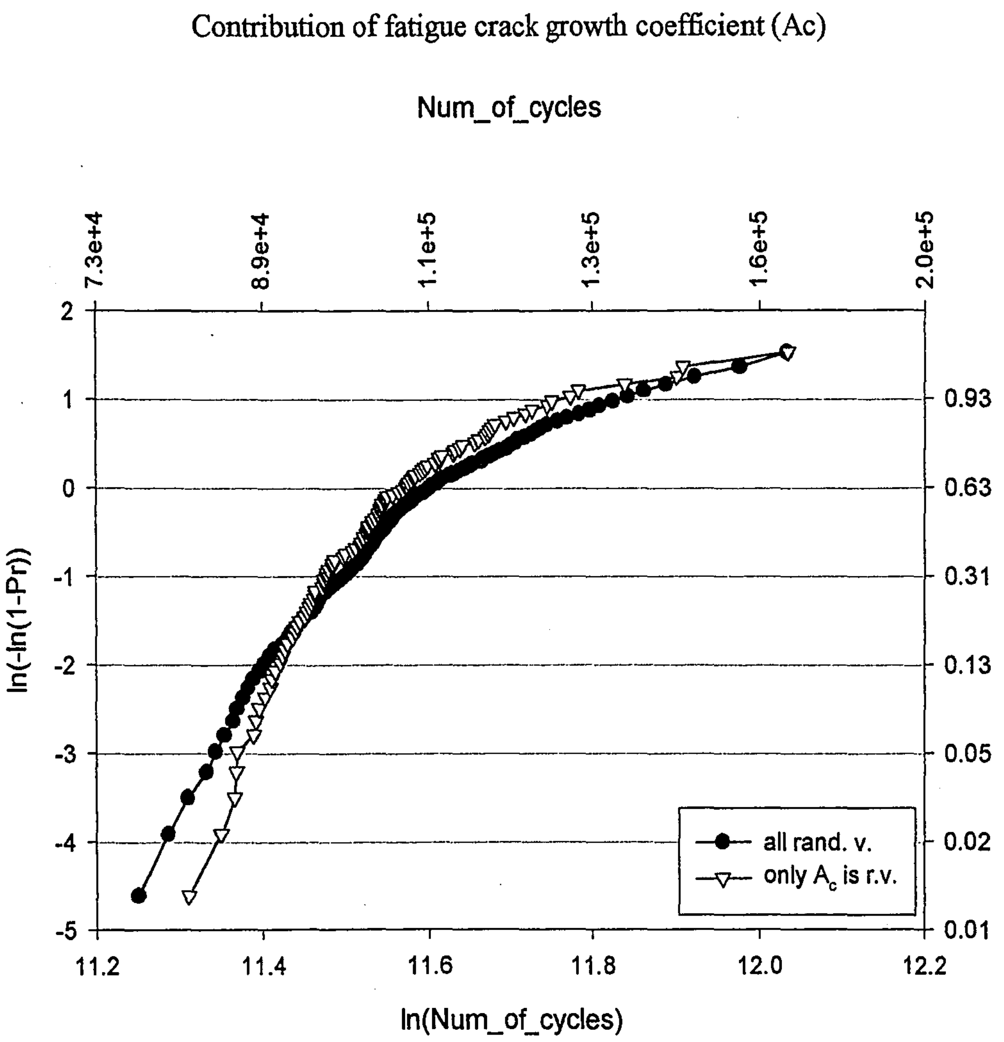
Random variable	α	β	γ
A_c	8	2.5e-10 (m/cycle)/[MPa(m)$^{0.5}$]$^{-4}$	0
c_i (large)	2	1.5e-4 (m)	0
c_i (small)	1.008	1.286e-6	3.5e-6
i_p	2.591	0.806	0.30
ΔK_{th}	2.093	0.351	2.010

where A_c – fatigue coefficient,

c_i – initial pit radius

i_p – Arrhenius proportionality constant

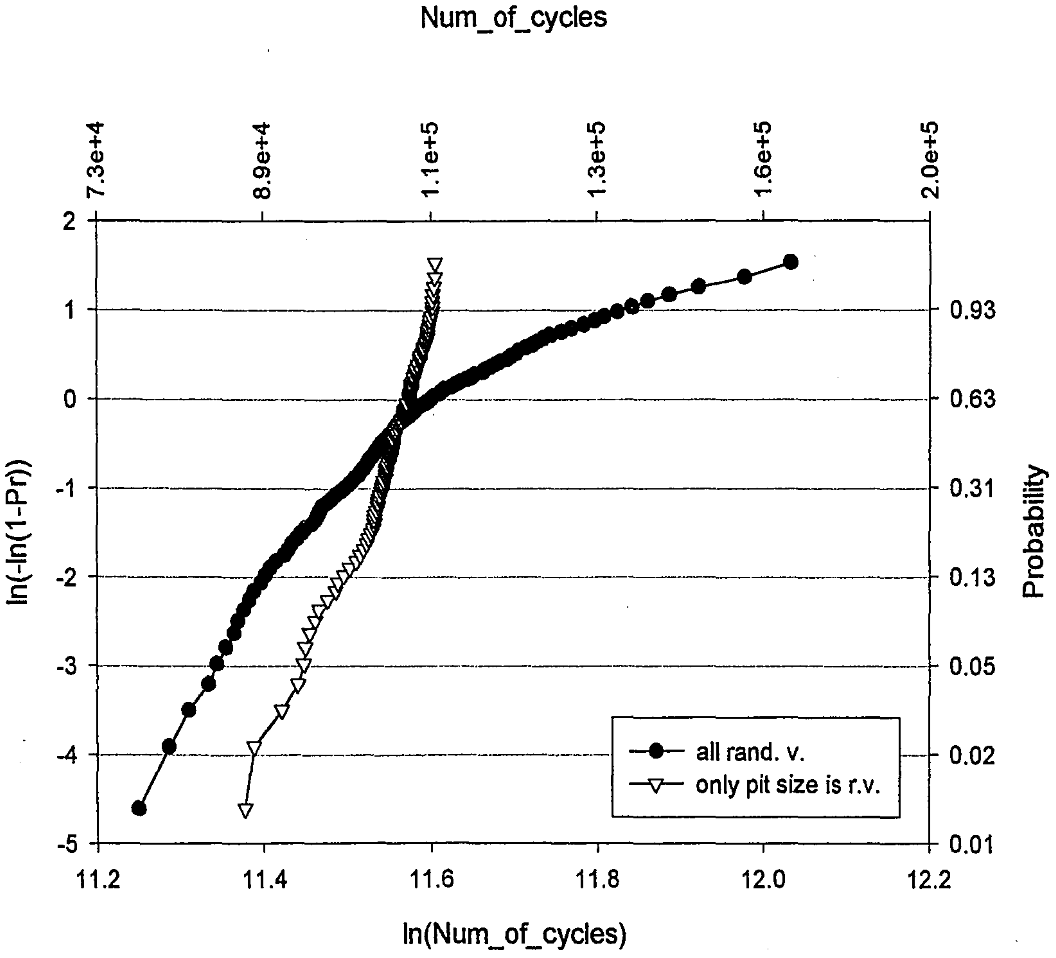
ΔK_{th} – threshold driving force



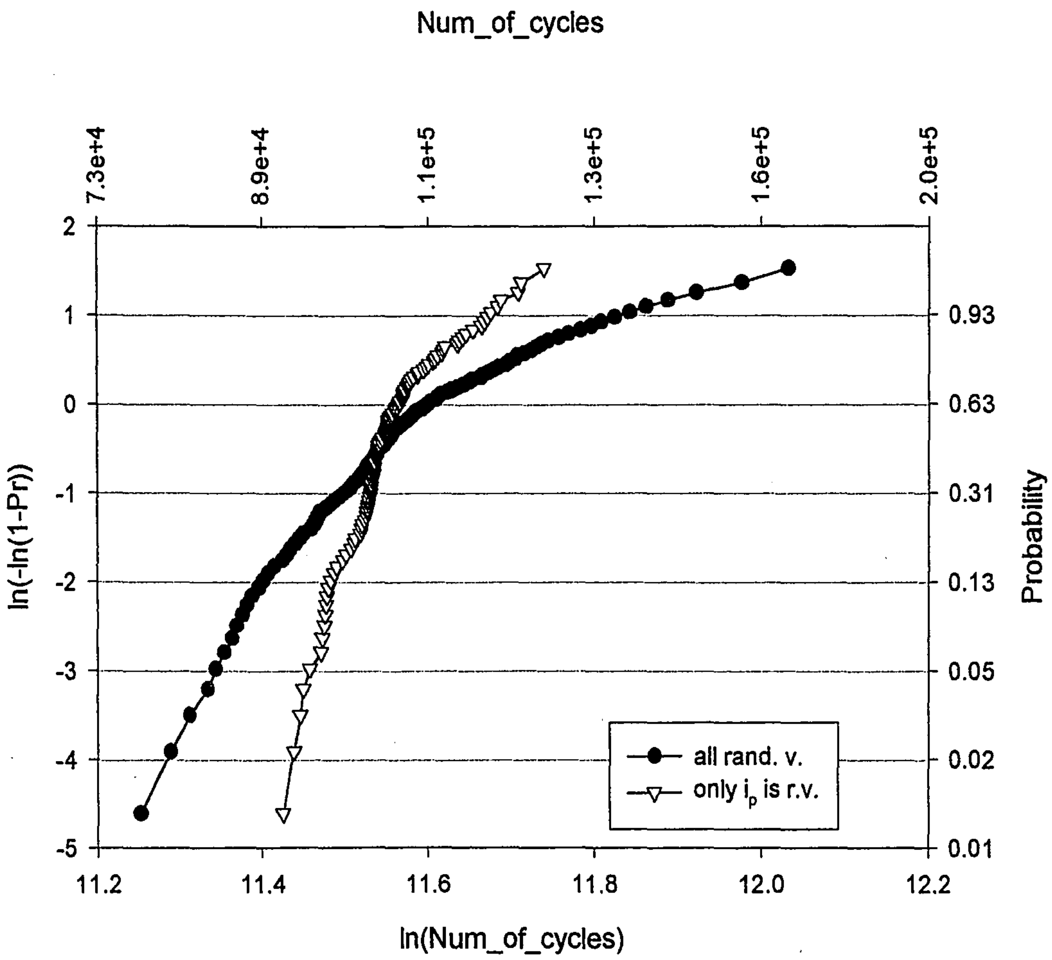
Contribution of fatigue crack growth coefficient (Ac)

Fugure 23a: Influence of random variable A_c on fatigue life.

Contribution of the initial pit size (c)



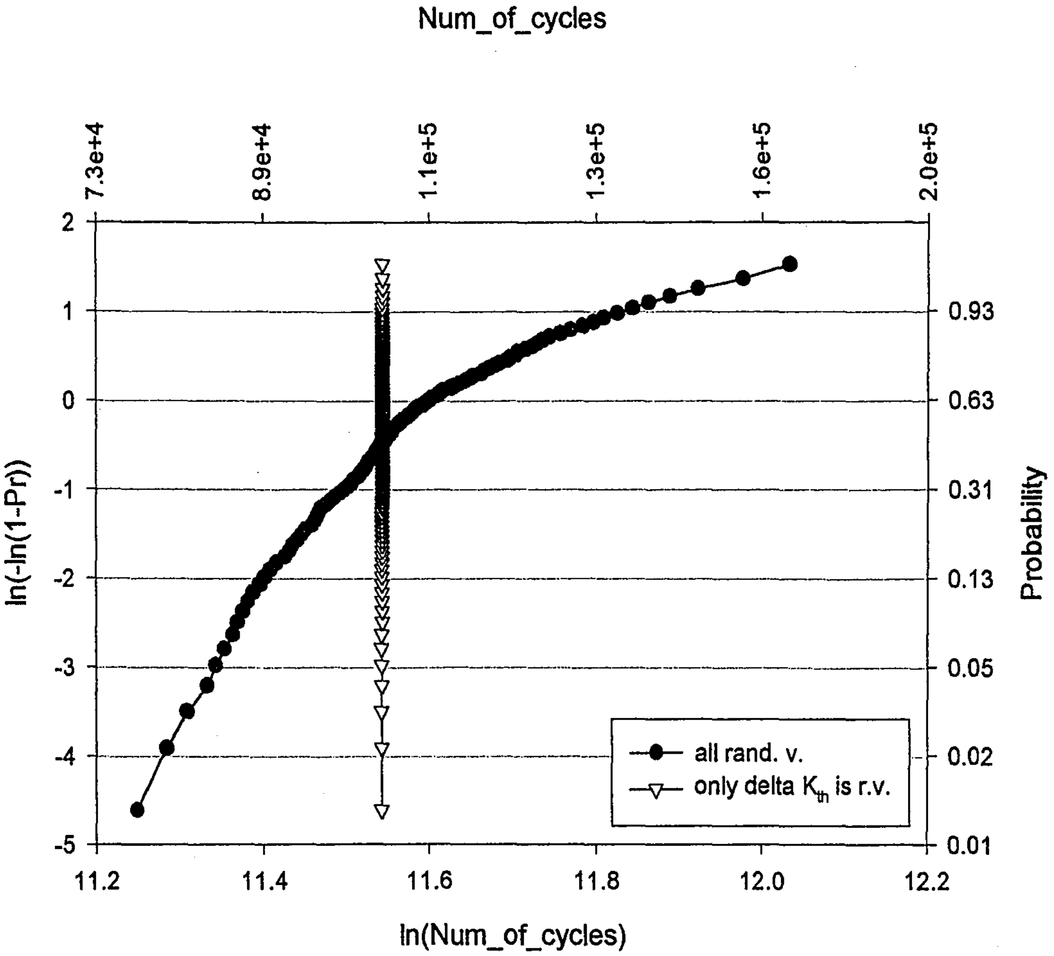
Fugure 23b: Influence of random variable **c** on fatigue life.



Contribution of the pitting current (i_p)

Fugure 23c: Influence of random variable $\mathbf{i_p}$ on fatigue life.

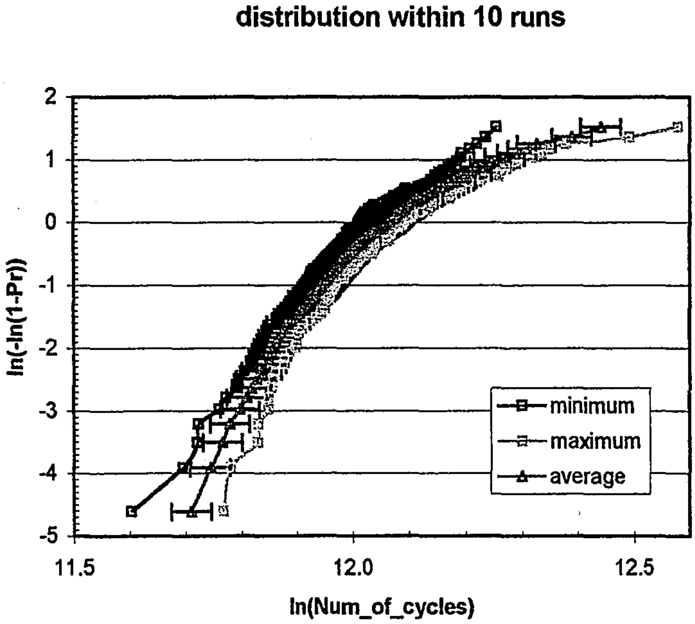
Contribution of the threshold driving force (delta K_{th})



Fugure 23d: Influence of random variable **delta K_{th}** on fatigue life.

5.5 Simulation confidence.

To produce results true for the general case, most of the graphs presented in Chapter 6 are average of 10 runs 100 points each. Dispersion of results depends on the influence of each random variable (such as initial crack/pit size) see Part 4 Chapter 6, and also on distribution of each random variable during a test run. To study confidence of plots 10 random runs were considered. Values of resulting lifetime inside of each run were rearranged into an ascending order. Next plot shows minimum and maximum deviation of the lifetime for every outcome from the mean lifetime.



It appeared that any single run can be expected to fall in ± 3.5% of the area of a 10 runs average values. (See Figure 24)

5.5 Simulation confidence.

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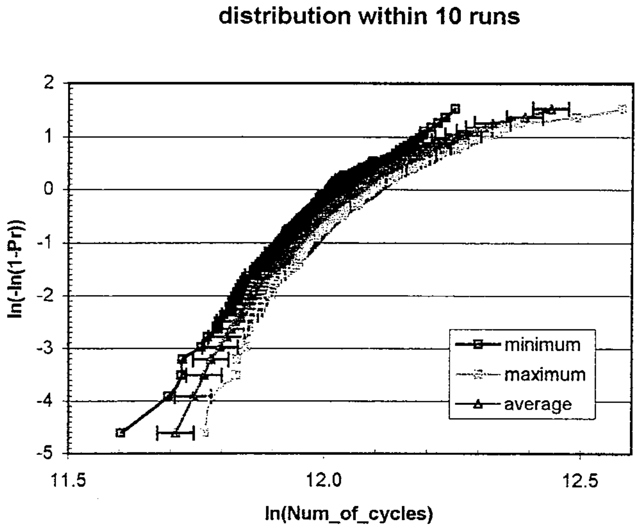
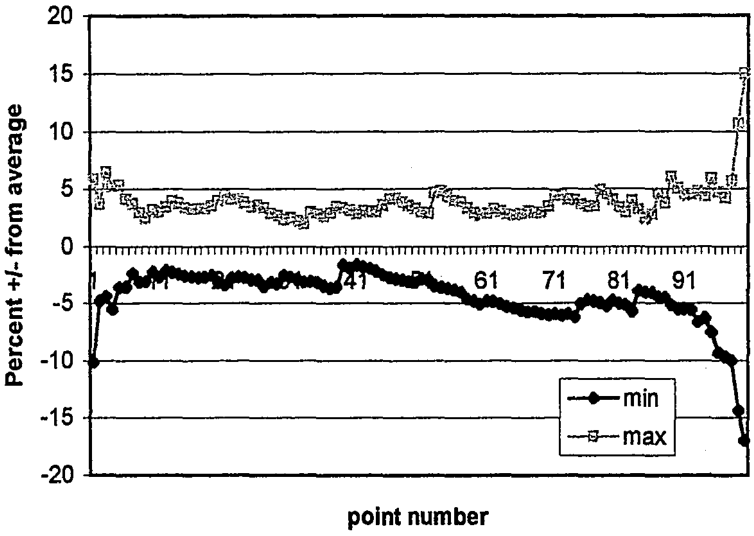
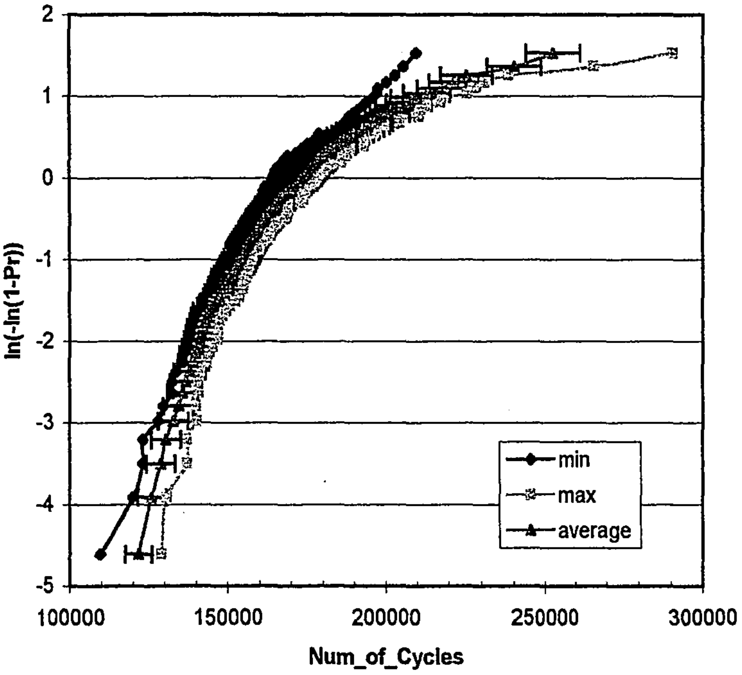


It appeared that any single run can be expected to fall in ± 3.5% of the area of a 10 runs average values. (See Figure 24)



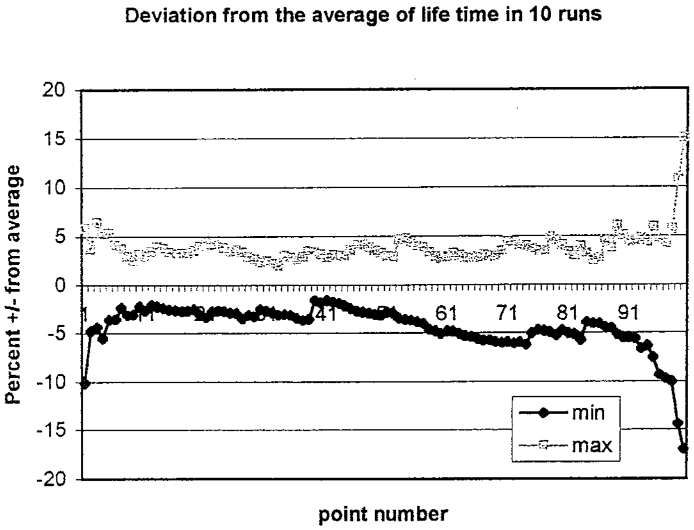
Deviation from the average of life time in 10 runs



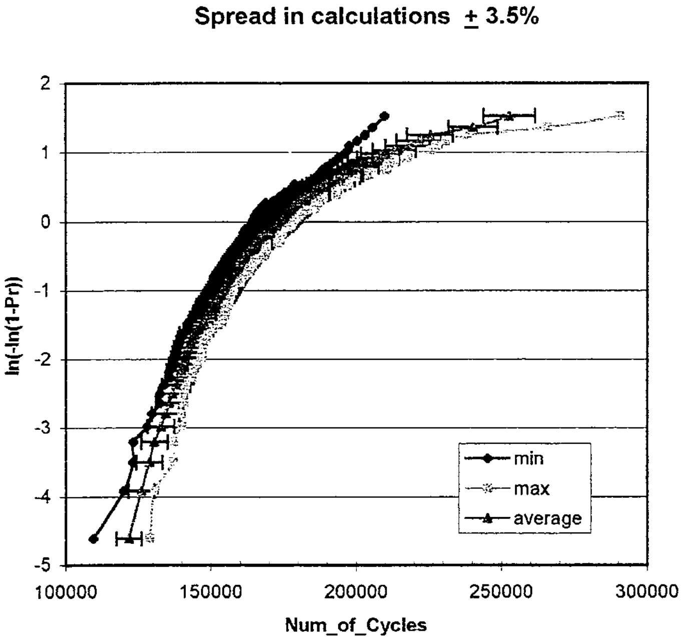
Spread in calculations ± 3.5%

Figure 24: Simulation confidence.

INTENTIONAL SECOND EXPOSURE



Deviation from the average of life time in 10 runs



Spread in calculations ± 3.5%

Figure 24: Simulation confidence.

CHAPTER 6

Conclusion and Future work.

This research has shown the importance of incorporating pitting corrosion into a model for calculating damage occurring under spectrum loading.

Influence of temperature has proven to be very important, because temperature is one of the influential parameters for pitting corrosion. That is why the difference between cases considered by Li (1997) and cases in this study (for temperature influence) is so great.

Established transition criteria (onset of transition to pure corrosion fatigue, and completion of transition) allows determination of the moment when pit size becomes insignificant compared to crack size. In other words, knowing the moment of completion of transition it is now possible to observe the influence of the pitting corrosion on the fatigue crack growth.

Although the model used for this project is simplified, the outcome of this work unmistakably shows the importance of continuation of studies in this field.

Possible aspects that could be examined in future studies:

1) changing the pit shape from semi-cylindrical to hemispherical;
2) more pits, not just the two could be considered. That brings in the question of 2-D or 3-D distribution law for pits in aluminum alloys;
3) the model for pit growth under low temperature should be rechecked and possibly corrected;
4) the sequence of the loading factors needs to be randomized for real life projection of the stress applied on aircraft;

5) multiple crack initiation sites could be studied, and new complete model of the underlying process for fatigue life estimation could be developed.

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APPENDIX: PROGRAM DESCRIPTION.

The original model MODGRO (also known as AFGROW) is basis of the computer program used for the simulation in the presented study. It was first modified by Li (1997). (program PMODGRO). All codes are written in Turbo PASCAL and program runs mainly on an IBM RISC 6000 workstation. The next schematic diagrams show the flow of the input information necessary to run computer simulation.

Input for P2BT.RAS (reading out oh file infstaf) :

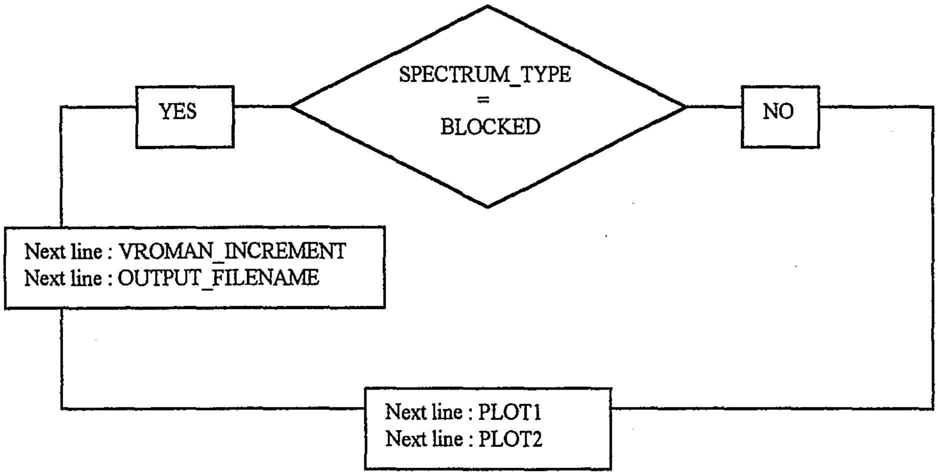
First line	affl	-temperature data (real);
Second line	rdex	-multiplier (to multiply total number of flights of a flight spectrum for permutation) (integer);
Third line	random_seed	-seed for random number (integer);
	trial	-number of iterations (integer);
	data_point	-number of data points,generated per iteraton (integer);
	a_f	-final crack length (real);
Fourth line	aci0	-α value for initial crack flaw (real);
Fifth line	awc0[1]	-α value for corrosion fatigue crack growth rate coefficient (real);
Sixth line	*****.da2	-PMODGRO original material data file name with extension (*****.da2; text)

Stop reading out of file infstaf, start reading out of file *****.da2 .
After reading all information out of file *****.da2 go back to file infstaf and read line seven.

Seventh line	***	-loading spectrum file name without extension (text);

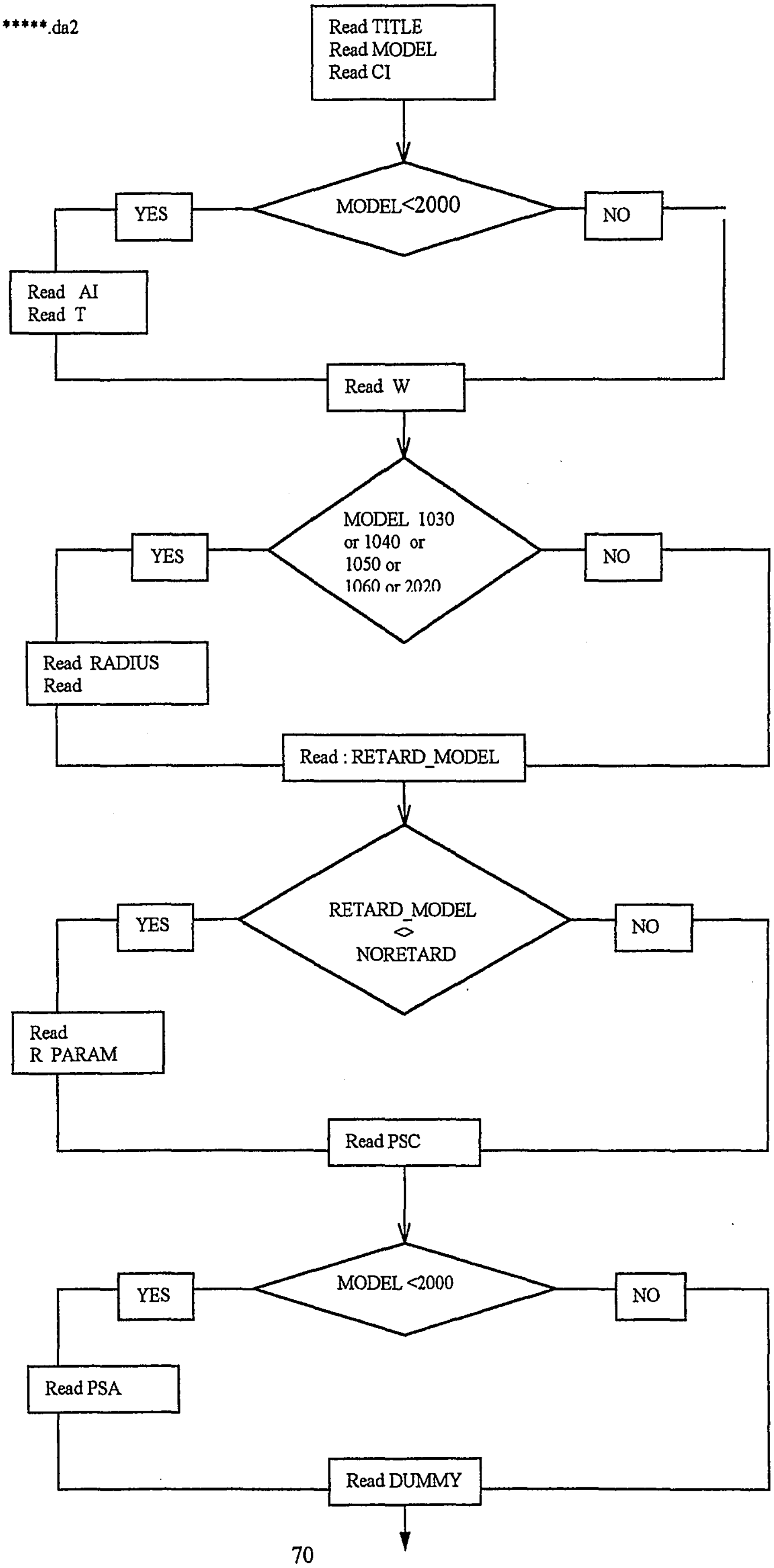
Now go to file ***.sp2 and read information out of this file.
After closing file ***.sp2 return to file infstaf and read next line.

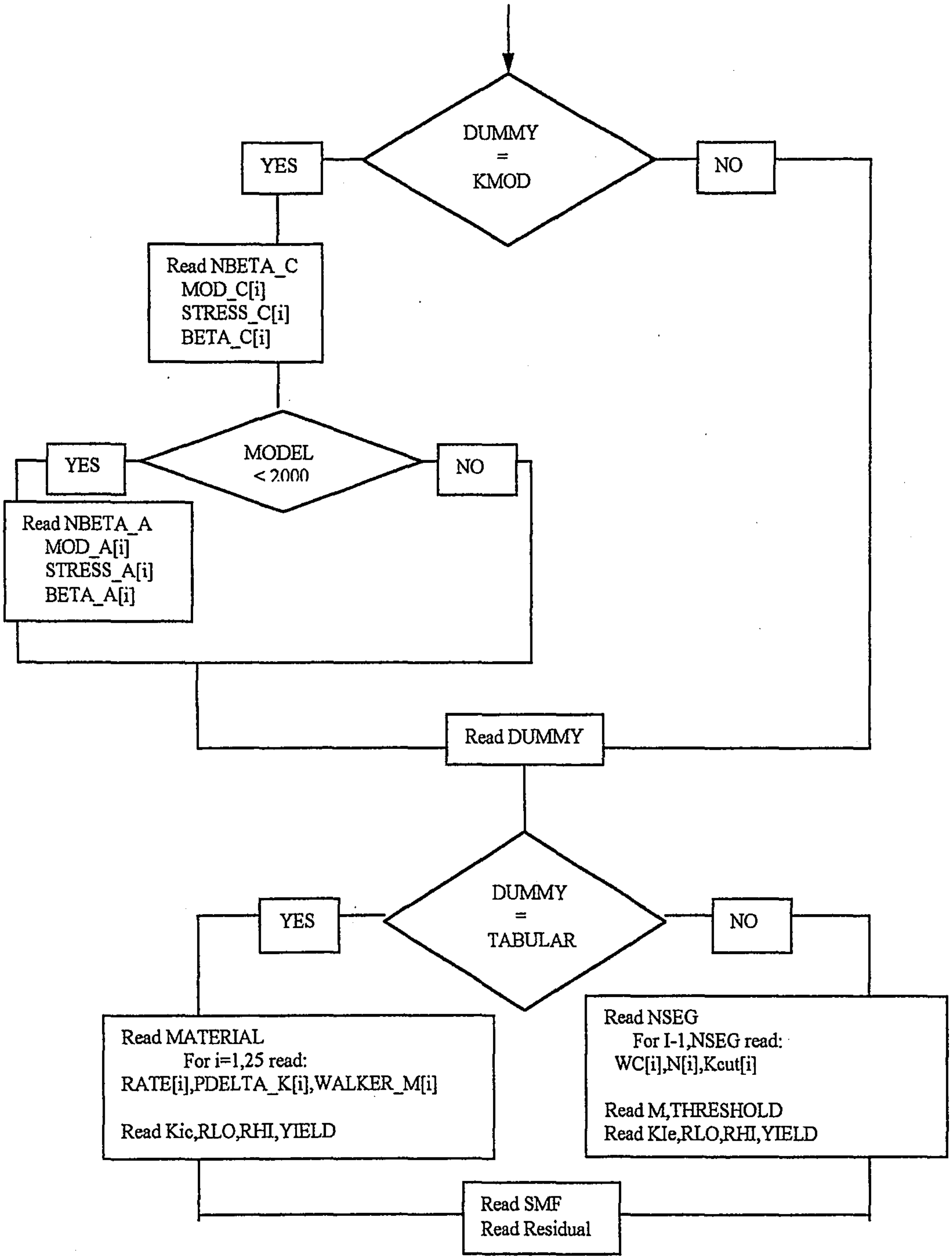
Eighth line	ALLOWED_PASSES	-maximum number of allowed passes or runs (integer);



****
Comments: VROMAN_ INCREMENT - % of the currant crack length ,over which it doesn't increment over crack growth.
PLOT1 & PLOT2 -special names for output files (****.dat);

Reading out of file *****.da2





→ Stop reading out of file *****.da2

Reading out of file ***.sp2 :

First line	SPECTRUM_TITLE
Second line	SPECTRUM_UNITS
Third line	SPECTRUM_TYPE
Forth line	No_of_Files

Close file ***.sp2 .

Comments:	TITLE	-information about test (text);
	MODEL	-code, which contains information about the geometry of a test
	CI	-initial surface crack length (real);
	W	-width of the panel (integer ; in meters);
	RADIUS	-hole radius (real);
	LOAD_XFER	-load transfer ;
	R_PARAM	-Willenborg shut-off ratio (real);
	PSC	-stress state in the 'C' direction (real);
	NSEG	- number of segments (integer);
	wc[i]	-C
	N[i]	-n
	M	-Walker M;
	RLO	-Lower R Value Boundary;
	RHI	-Upper R Value Boundary;
	KIc	-Plane Strain Fracture Toughness (real);
	YIELD	-Yield Stress (real);
	SMF	-Spectrum Multiplication Factor (real; in MPa)

VITA

Svetlana Oshkai was born to Galina and Peter Novokov on September 20, 1974 in Voronezh, Russia.

In 1991 Svetlana Oshkai was accepted as a student to the Department of Applied Mathematics and Mechanics of Voronezh State University, and completed her studies in June 1995, earning Bachelor's degree.

In January 1997 Svetlana Oshkai was accepted to the graduate school of Lehigh University. During her work towards the Master's degree, Svetlana Oshkai was awarded several teaching and research assistantships. Current research resulted in the following presentation:

"Impact of Pitting Corrosion and Corrosion Fatigue Crack Growth Spectrum Load Fatigue Life" To be presented at the 4th Joint DoD/FAA/NASA Conference on Aging Aircraft, St. Louis, MO, May 15-18, 2000.

END OF TITLE