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**FATIGUE CRACK COALESCENCE and SHAPE
DEVELOPMENT**

- an EXPERIMENTAL INVESTIGATION

by

David Stuart Harrington

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of the requirements for the
Degree of Master of Engineering

**Department of Mechanical and Aerospace Engineering
Ottawa-Carleton Institute for Mechanical and Aerospace Engineering**

**Carleton University
Ottawa, Canada**

April, 1995

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**Fatigue Crack Coalescence and Shape Development
- an Experimental Investigation**

submitted by

David Stuart Harrington

in partial fulfilment of the requirements for
the degree of Master of Engineering.

Chair, Department of Mechanical and
Aerospace Engineering

Thesis Supervisor

Carleton University

April, 1995

ABSTRACT

This thesis presents an experimental investigation into the crack interaction, coalescence and shape development of multiple coplanar semi-elliptical fatigue cracks. To this end a series of nine fatigue tests were carried out on offshore grade flat plate steel specimens subjected to constant amplitude four-point bend loading.

A novel mobile probe arrangement was developed for monitoring the crack shape development during testing. This probe arrangement is based on the localized Direct Current Potential Drop (DCPD) method of crack measurement. Crack depth, surface length and profile calibrations for use with the mobile probe arrangement were obtained using a combination of experimental and three-dimensional Boundary Element Method (BEM) techniques. Details of the design, assembly and evaluation, including an accuracy assessment of this new probe arrangement have also been included.

The experimental results are compared with published data concerning the interaction and coalescence of multiple coplanar surface cracks. It has been observed in the present study that a small pre-coalescence crack interaction effect is present and was found to be in general agreement with published results obtained using numerical modelling. Growth rates in the coalescence region were also used to determine the magnitude of the stress intensity factors present in this rapid region of growth. These results were also found to show excellent agreement with several published numerical models.

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LIST of SYMBOLS

a	crack depth, [m]
N	number of applied stress cycles
N_i	number of cycles to crack initiation of the specimen
N_p	number of crack propagation cycles
N_t	total number of cycles to failure of the specimen
LEFM	Linear Elastic Fracture Mechanics
K_{IC} , K_{IC}	critical stress intensity factor and material fracture toughness
σ_x , σ_y	normal stresses in the x and y directions, [MPa]
τ_{xy} , τ_{xz} , τ_{yz}	shear stress components, [MPa]
K_I , K_{II} , K_{III}	stress intensity factors for modes I, II and III loading
r , θ	polar co-ordinates at the crack tip
r_y	crack tip plastic zone size, [m]
σ_{ys}	yield strength of material, [MPa]
SIF	stress intensity factor, [MPa $\sqrt{m}$]
FEM	finite element method
BEM	boundary element method
S_t	remote uniform tension stress, [MPa]
S_b	remote bending stress on outer fibre, [MPa]
H	boundary correction factor for bending

List of Symbols (cont.)

Q	shape factor for elliptical crack
F	stress intensity boundary correction factor
t, W, w	test plate thickness, [m]
c	half surface length of crack, [m]
B, b	half width of test plate, [m]
ϕ	parametric angle of the semi-elliptical crack, [deg]
$da/dN, dc/dN$	crack growth rates in depth and surface directions, [m/cycle]
ΔK	stress intensity factor range, [MPa $\sqrt{m}$]
K_{max}, K_{min}	maximum and minimum applied stress intensity factors, [MPa $\sqrt{m}$]
$\sigma_{min}, \sigma_{max}$	minimum and maximum applied stress in outer fibre, [MPa]
$\Delta\sigma$	stress range ($\sigma_{max} - \sigma_{min}$), [MPa]
R	stress ratio, ($\sigma_{min}/\sigma_{max}$)
C	crack growth law coefficient
C_d, C_s	crack growth law coefficients in depth and surface directions
m	crack growth law exponent
ΔK_{th}	threshold stress intensity factor range, [MPa $\sqrt{m}$]
ΔK_{app}	applied stress intensity factor range, [MPa $\sqrt{m}$]
ΔK_{eff}	effective stress intensity factor range, [MPa $\sqrt{m}$]
A, A'	designation for inner crack tips for adjacent cracks
A''	designation for depth point at coalescence location
B, B'	designation for depth points at centres of adjacent cracks

List of Symbols (cont.)

C, C'	designation for outer crack tips for adjacent cracks
t_c	crack tip separation distance, [m]
ACPD	Alternating Current Potential Drop
DCPD	Direct Current Potential Drop
τ	"skin" thickness of electric field in test specimen
μ_r, μ_o	relative and free space permeability of test material
σ	conductivity of the specimen material
f	frequency of applied electric field
V	the voltage measured across the crack
V_o	the initial voltage measured across the crack at start of test
V_r	reference probe voltage
V_{ro}	the initial reference probe voltage at the start of the test
PD	potential drop (voltage)
NPD	Normalized Potential Drop
NPD_{corr}	corrected NPD using reference probe readings
$S+, S-$	designation for PD measurement probes
$P+, P-$	designation for excitation current probes
SEN	single edge notched specimen
CT	compact tension specimen
u	the electrical potential at any point in a conducting medium
f	potential probe spacing from crack plane, [m]

List of Symbols (cont.)

d	current probe spacing from crack plane, [m]
κ	constant of integration
BIE	Boundary Integral Equation
n	the normal vector at any point in the BEM model
t	the potential gradient, (du/dn) , at any point in the BEM model
$a_{\max}$	maximum crack depth, [m]
$NPD_{\max}$	the maximum value of NPD occurring at the crack centre
ϕ	non-dimensional crack front position index
NPD_{coal}	NPD measured at the coalescence point
a_{coal}	crack depth at coalescence point, [m]
SS	machined starter notch spacing, [m]
a_{act}	measured crack depth, [m]
a_{est}	estimated crack depth, [m]
a_{error}	error in estimated crack depth, [m]
σ_{op}	applied stress required to open the crack, [MPa]
γ	crack interaction factor
k	coalescence coefficient

Chapter 1

Introduction

1.1 General Introduction

In engineering components and structures the condition frequently arises where the component is subject to loads that fluctuate between two or more levels. Examples of this type of loading include alternating stresses associated with a rotating shaft, pressurizing and depressurizing in an aircraft fuselage at takeoff and landing, and ocean wave loading of offshore oil platforms. Often, failure of these components has occurred under the action of these alternating stresses yet the most careful analysis revealed that the stresses were below the ultimate strength of the material, and quite frequently below the yield strength {1}. This process of repeated cyclic loading of a component is referred to as *fatigue* and is responsible for the majority of engineering structural failures {2}.

The fatigue process involves the cycle by cycle growth of a crack in a material. Once the crack reaches a critical size determined by the fracture toughness of the material an unstable fracture will occur. The fatigue crack generally initiates from a pre-existing flaw or discontinuity in the component such as a keyway in a shaft, change in section at the root of a turbine blade, or a welded joint in an offshore structure. Despite the most careful attention to detail during the design and manufacturing stages, flaws of this type are inevitable and thus the fatigue life of a component is an extremely important design consideration.

Some components contain crack-like flaws produced in the fabrication process. These types of defects are especially prevalent in welded components where imperfections in the weld serve as initiation sites for fatigue cracks. It is also quite common in welded structures, subjected to varying loads, such as pressure vessels and offshore oil platforms for multiple fatigue cracks to initiate along the weld. These small cracks grow and then join together in a process known as *coalescence* to form larger cracks. The shape change of the smaller cracks during the coalescence process is generally referred to as *shape development* or *recharacterization*. This coalescence and recharacterization process continues until the component or structure fails.

Although the coalescence process has been observed by many researchers, it is still not well understood. There are several relevant design codes {3,4} available to aid the engineer or designer when analyzing this process. It is generally accepted by many

researchers in this field that these codes handle coalescence in a very rudimentary way which leads to over-conservative and inefficient designs. In an effort to understand the coalescence process better, various researchers have developed numerical coalescence models which attempt to describe this process but there is comparatively little experimental data available to verify them.

It has been observed that coplanar surface cracks prior to the coalescence stage influence each other in what is termed an *interaction effect*. As the fatigue life of a component is greatly influenced by the growth pattern of these cracks, it is important to understand all aspects of the growth and coalescence process. It is only then that accurate models of fatigue crack interaction, coalescence and shape development may be constructed to predict the life of a component. With accurate crack growth models, components may be designed to be safer, more efficient and can be taken out of service or repaired before failure causing loss of life or capital may occur.

This thesis describes an experimental program that was carried out to study fatigue crack coalescence and shape development in offshore grade steel. To this end a series of fatigue tests were carried out on flat plate specimens subjected to constant amplitude four-point bend loading. The coalescence and shape development processes were monitored using a novel mobile direct current potential drop (DCPD) probe arrangement that was developed and calibrated for use in the current program.

This thesis is divided into seven chapters. A brief review of the relevant literature concerning fracture mechanics and the coalescence and shape development of fatigue cracks is presented in Chapter 2. The development of the mobile DCPD probe arrangement used for monitoring fatigue growth is described in Chapter 3. Chapter 4 presents details of the calibration of the mobile probe array using a combination of the boundary element method (BEM) and an experimental technique. The test specimens, loading apparatus and details of the experimental procedures used in the current program are presented in Chapter 5. The results of testing and their discussion relative to other published research are presented in Chapter 6. This thesis is concluded with several conclusions and recommendations for future work in Chapter 7.

1.2 Objectives of the Current Program

In summary, the objectives of this experimental study are :

- (1) development of a mobile DCPD probe array for surface crack measurements
- (2) calibration of the mobile probe arrangement using both the boundary element method and an experimental technique
- (3) investigate the crack shape development, crack interaction and coalescence processes for multiple coplanar semi-elliptical surface fatigue cracks

Chapter 2

Literature Review

This chapter presents a review of the background information and previous research that is relevant to the current experimental study. First, a general introduction to the topic of Linear Elastic Fracture Mechanics (LEFM) and its application to the study of experimental fatigue crack growth is given. Previous experimental research in the area of fatigue crack coalescence and shape development of surface cracks is then presented. Numerical and analytical research in this field has also been included to supplement the relatively small amount of available published experimental material.

2.1 General Introduction

The fatigue life of a component consists of three distinct stages (Figure 2.1) : crack initiation, crack propagation and final failure of the component.

Figure 2.1 Typical Fatigue Crack Growth Curve

It is generally accepted that fatigue crack initiation begins with the formation of micro-cracks at areas of highly localized plastic strain known as Persistent Slip Bands (PSB). Fatigue cracks then propagate from these micro-cracks through a multiple slip mechanism created by the repeated loading and unloading of the material. The size of the crack at the transition from the initiation to the propagation stage depends mainly upon the crack detection equipment available and the point of view of the researcher. Depending upon the size of the crack and the strain amplitudes, the majority of the component life may be spent either initiating or propagating the crack. Fracture mechanics is the science used to estimate the propagation life of a component containing an existing defect. Once the crack reaches a critical size determined by the fracture toughness (K_{IC}) of the material, a rapid, unstable failure of the component will occur.

2.2 Linear Elastic Fracture Mechanics

Linear Elastic Fracture Mechanics (LEFM) is the study of flaws in materials and the resulting fracture behaviour depending upon the flaw size, stress level and the material properties. In the 1920s Griffith {5}, performing experiments on glass, formulated the concept that a crack in a component will propagate if the total energy of the system is lowered with crack propagation. In the 1940s Irwin {6} extended Griffith's theory to include ductile materials through consideration of the energy associated with plastic deformation. Although useful from an academic point of view, the energy concepts used by Griffith and Irwin were difficult to apply practically.

In addition to using energy methods, the fracture process may also be analyzed using stress analysis based on the concepts of elastic theory. A crack in a component may be stressed in one of the following three different modes (Figure 2.2) :

mode I : opening or tensile mode, where the crack surfaces move directly apart

mode II : sliding or in-plane shear mode, where the crack surfaces slide over one other in a direction perpendicular to the leading edge of the crack

mode III : tearing or anti-plane shear mode, where the crack surfaces move relative to one another and parallel to the leading edge of the crack

or in any combination of the above three modes. The crack opening mode (mode I) is the most common as it tends to promote the fastest growth through opening of the fracture faces directly.

Figure 2.2 The Three Crack Opening Modes

The elastic stresses in the vicinity of the crack tip (Figure 2.3) for mode I loading are given by Irwin and Westergaard {7} as follows :

$$\begin{aligned}\sigma_y &= \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left(1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) \\ \sigma_x &= \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left(1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) \\ \tau_{xy} &= \frac{K_I}{\sqrt{2\pi r}} \left(\sin \frac{\theta}{2} \cos \frac{\theta}{2} \cos \frac{3\theta}{2} \right)\end{aligned}\tag{2.1}$$

where the notation is as indicated in Figure 2.3.

Figure 2.3 Local Stresses in the Vicinity of a Crack Tip

Note that there is a $1/\sqrt{r}$ singularity in the previous equations (2.1) indicating a rapid rise in the stress level as r tends to zero at the crack tip. This creates a zone of localized plasticity at the crack tip that is constrained by the surrounding elastic material. The size of this *plastic zone* under monotonic loading is given by

$$r_y = \frac{1}{2\pi} \left(\frac{K_I}{\sigma_{ys}} \right)^2 \quad \text{for plane stress} \quad (2.2a)$$

and

$$r_y = \frac{1}{6\pi} \left(\frac{K_I}{\sigma_{ys}} \right)^2 \quad \text{for plane strain} \quad (2.2b)$$

where σ_{ys} is the yield strength of the material.

Under fatigue loading the reversed or cyclic plastic zone size is reduced by four times over the comparable monotonic value. This is a result of the surrounding elastic material forcing the plastic zone into compression as the tensile stress is reduced during each loading cycle.

The parameter K_I in the previous expressions (2.1,2.2) is referred to as the stress intensity factor (SIF) for mode I loading and is used to characterize the crack tip stress field.

2.2.1 The Stress Intensity Factor, K_I

From the stress field equations given in (2.1) it is clear that in order to use LEFM practically one must be able to evaluate the stress intensity factor K_I . The parameter K_I relates the crack tip stress field to such quantities as the applied stress level, the crack size and the component geometry. For relatively simple geometries, such as through thickness cracks, there are classical solutions available in several handbooks {8,9,10}. These solutions are generally obtained by mathematical means and are exact for the geometry considered. However, for the more complex case of surface cracks in arbitrary shaped bodies, exact solutions are not easily obtained. In these cases stress intensity factors have been obtained using analytical methods {11}, experimental methods such as photoelasticity {12} and fatigue crack growth rate testing {13}. In addition to these methods, the recent availability of inexpensive computing power has made numerical methods very attractive as they offer fast, accurate, cost effective

solutions for practically any geometry. The most common numerical methods used are the finite element method (FEM), boundary element method (BEM) and the weight function method.

SIF solutions for single semi-elliptical surface cracks in flat plates have been published by several authors {14-18}. Scott and Thorpe {19} reviewed several of the available solutions and evaluated them based on their ability to accurately predict fatigue crack shape development. They concluded that the Raju and Newman solution {14} and the solution by Koterazawa and Minamisaka {15} are the most accurate SIF calibrations available for semi-elliptical surface cracks in specimens subjected to tension and bending respectively.

For the current experimental program, the SIF solution by Raju and Newman {14} was used to calculate the crack tip stress intensity factors. This FEM solution for numerous geometries of semi-elliptical surface cracks in a finite width plate subjected to tension and/or bending loads has found widespread acceptance. Using a series of curve fits to their FEM results, the following closed form solution was produced :

$$K_I = (S_t + HS_b) \sqrt{\pi \frac{a}{Q}} F\left(\frac{a}{t}, \frac{a}{c}, \frac{c}{b}, \phi\right) \quad (2.3)$$

for $0 < a/c \leq 1.0$; $0.0 \leq a/t < 1.0$; $c/b < 0.5$; $0 \leq \phi \leq \pi$.

where

- K_I mode I stress-intensity factor, [MPa $\sqrt{m}$]
- S_t remote uniform tension stress, [MPa]

S_b	remote bending stress on outer fibre, [MPa]
H	boundary correction factor for bending
a	depth of surface crack, [m]
b	half-width of cracked plate, [m]
c	half-length of surface crack, [m]
Q	shape factor for elliptical crack
t	plate thickness, [m]
ϕ	parametric angle of the ellipse, [deg]
F	stress-intensity boundary-correction factor

2.3 Fatigue Crack Growth

Of particular interest in studying the growth of fatigue cracks is the rate at which they propagate. With accurate knowledge of how fast a crack will propagate in a given material, with certain geometry and loading conditions, an estimate of the life of the component may be obtained. This knowledge can be used to determine fatigue design lives or set up inspection intervals to look for sub-critical cracks and therefore remove the component or structure from service before failure occurs.

The cyclic loading of a material containing a crack causes the value of the SIF at the crack tip to vary with time. It is therefore reasonable to assume that the growth rate of a fatigue crack (da/dN) may be related to the crack tip SIF in the form of an equation

$$\frac{da}{dN} = f(\Delta K) \quad (2.4)$$

where ΔK is the SIF range ($K_{\max} - K_{\min}$).

The above relationship (eq.(2.4)) has been determined experimentally to follow a sigmoidal shape, when plotted in log-log form (Figure 2.4), that may be divided into three regions.

Figure 2.4 Three Stages of Fatigue Crack Growth
 where ΔK_{th} is the threshold SIF range and K_{IC} is the critical SIF (fracture toughness) of the material

Stage I occurs at low stress intensities and is associated with threshold effects. Below the threshold SIF range (ΔK_{th}) fatigue crack growth does not occur or occurs too slowly to be measured. The value of ΔK_{th} has been found to be dependent on the stress ratio, R ($R = \sigma_{min}/\sigma_{max}$), frequency of loading and environmental effects. Component

design for fatigue below this threshold is certainly attractive due to the low probability of fatigue failure, but this is unrealistic in most cases due to unattainably small defect sizes or stress levels too low for practical application.

The third stage of the curve, referred to as the final failure region, features rapidly increasing growth rates until an unstable failure occurs when the peak SIF reaches the value of the fracture toughness of the material. Generally this stage of growth is ignored when considering the life of a component as the portion of life consumed is so small. For safety and economic reasons it is highly desirable for components to be removed from service before any cracks reach this stage of growth.

The linear middle region of this curve (stage II) is of most interest as it is the region where the majority of a fatigue crack's life is spent. Several researchers have developed equations to describe this central region of interest. The simplest and possibly the most widely used is the Paris-Erdogan Law{20} which may be written as

$$\frac{da}{dN} = C(\Delta K)^m \quad (2.5)$$

where C and m are empirically determined material constants.

The Paris Law has been found to describe the growth rates of fatigue cracks in the stage II growth region quite well. However there are a few instances where the Paris Law does not accurately predict crack growth rates :

- (i) Growth rates of cracks that are short in relation to the size of their plastic zones. Known as the "short" crack anomaly, this behaviour is believed to be related to decreased closure effects, Hertzberg {2}
- (ii) For long cracks, the Paris Law tends to underestimate growth rates as the cracks approach their critical size (stage III).
- (iii) The Paris Law does not consider the effects of the stress ratio, R , on growth rates. Several researchers {21,22,23} have studied the effects of R on growth rates which are primarily attributed to variations in the effective stress intensity factor, K_{eff} , due to closure effects. Different values of R generally produce a family of parallel lines when plotted as da/dN vs ΔK .

To account for the above limitations of the Paris-Erdogan Law (eq.(2.5)) several variations have been proposed during the last 30 years.

One of the commonly used growth laws to account for effect of stress ratio and the increased growth rates associated with stage III was proposed by Forman et al {24} as

$$\frac{da}{dN} = \frac{C\Delta K^m}{(1-R)K_{IC} - \Delta K} \quad (2.6)$$

Klesnil and Lukas {25} took into consideration the threshold SIF (K_{th}) below which crack growth would not occur

$$\frac{da}{dN} = C(\Delta K - \Delta K_{th})^m \quad (2.7)$$

This expression was then extended by Shutz{26} to incorporate the effect of stress ratio by modifying the Forman expression (eq.(2.6))

$$\frac{da}{dN} = \frac{C(\Delta K^m - \Delta K_{th}^m)}{(1-R)K_{IC} - K_{max}} \quad (2.8)$$

Some of the previous expressions require the use of a threshold SIF for the material which would require additional time consuming and expensive testing. It should be noted also that the values of the empirical constants C and m used in the previous relations are in general not interchangeable in the various equations. These values are generally obtained through crack growth rate testing on standard specimens for which accurate SIF calibrations are known. The values of C and m are obtained from experimental data using a specific growth relation and are in general only valid for use with that particular equation, Broek{27}.

Accurate predictions of fatigue life may be made if appropriate values of C and m , an accurate SIF calibration and the correct growth relation are available. With this information any of the above growth laws may be integrated between two crack

lengths to obtain an estimate of propagation life. In general, as the SIF calibration is not a simple function of crack length, this integration is performed numerically.

2.3.1 Limitations of LEFM

LEFM is based on the application of the theory of elasticity to bodies containing cracks or defects. Therefore the general assumptions used in the theory of elasticity, such as small displacements and general linearity between stress and strain are also applicable to LEFM.

As the name implies, LEFM does not consider the effects of plasticity. If the plastic zone size is small relative to the length of the crack then the assumptions are valid and LEFM may be applied with confidence. In those situations where the general assumptions of LEFM are violated other analysis techniques such as Elastic-Plastic Fracture Mechanics must be used.

2.4 Coalescence of Fatigue Cracks

Crack coalescence is the process in which two or more surface cracks join together to form a single dominant crack. This process is common in welded structures where numerous cracks are often initiated from the multiple defects that are present in the weld and surrounding material {28}. The coalescence process has been studied by many researchers {29-32} and is still not completely understood. The crack shape

development of two surface cracks undergoing coalescence may be broken down into the several stages depicted in Figure 2.5 and explained below.

Figure 2.5 Phases of Fatigue Crack Coalescence

Prior to the coalescence phase when the inner crack tips are still separated by a distance, t , (Figure 2.5a), the adjacent cracks influence each other in what is termed an *interaction effect*.

Using a numerical technique, Murakami and Nemat-Nasser {33} obtained stress intensity factors for interacting semi-elliptical surface flaws under tension, bending and combined tension-bending loading. They concluded that when two cracks are spaced such that the adjacent inner crack tips are separated by a distance exceeding the smaller cracks largest axis the interaction effect may be neglected.

Heath and Grandt {34} studied the effects of crack interaction on stress intensity factors for two symmetric coplanar corner flaws located along a hole bore. Using the finite element-alternating method (FEAM) they found that crack interaction does not occur until the separation distance is equal to or less than half of the crack length c .

Morgan {35} performed four-point-bend tests on specimens containing multiple surface defects and concluded that crack interaction is only significant when the crack tips are nearly touching. In addition, he found that shape development can be predicted accurately using fracture mechanics techniques.

It has been experimentally observed that the interaction between coalescing cracks causes the adjacent crack tips to deviate away from one another (Figure 2.5b). Instead of growing towards one another as one would intuitively expect, the crack tips avoid

each other and will often grow past each other on separate planes. This crack tip deviation has been observed by several researchers {31,35}.

It should be noted that the fatigue crack interaction and coalescence processes are not limited to metallic materials. McComb et al {36} conducted an experimental study of fatigue crack coalescence in polycarbonate test specimens. They noted similar deviations in the crack tips, due to interaction, which even grew past each other leading to an overlap of the crack fronts before coalescence eventually occurred.

Melin {37} studied the stability of the straight crack path (i.e. tip to tip coalescence) and showed that it was energetically unfavorable for any two adjacent crack tips to extend without these deviations.

The crack tip deviations result in the formation of a *cusp* region between two coalescing cracks as growth through the specimen thickness occurs on two separate planes. Otegui et al {31}, performing fatigue tests on welded T-plate specimens, observed the initiation and coalescence of multiple cracks along the welds. Similar deviations as noted previously were observed and it was found that the cusp depth was related in a linear fashion to the crack plane mismatch (i.e. deviation distance).

Growth at the coalescence point then proceeds very rapidly as the crack tries to assume the preferred semi-elliptical shape (Figure 2.5c,d). The stress intensity factor in this cusp region and the associated growth rates have been an area of interest for many

researchers {34,38,39}. Use of analytical and numerical techniques to obtain SIFs in the coalescence region is complicated by the out-of-plane crack tip deviations and the unusual shape development that occur in this region. Obtaining these quantities experimentally is also relatively difficult due to the lack of accurate methods to continuously monitor crack shape development in this rapid growth region. Currently, beachmarking is the only technique that provides indisputable crack profile information in this region.

Soboyejo et al {39} studied the coalescence process between coplanar semi-elliptical cracks in pure bending using both an experimental technique and the classical finite element method. Using FEM they obtained stress intensity factors in the cusp region. They found that the SIF peaked during the early stage of coalescence where the SIF at the point of contact (A") was approximately twice that at the free surface (C,C') or the maximum depth points (B,B'). Their experimental results showed that the cracks grew almost independently until the crack tips came into contact showing a minimal interaction effect.

As the coalescence phase consumes a portion of the specimen fatigue life it is important to understand this behaviour in order to develop design rules. There are existing design codes that provide guidance to engineers and designers when considering this

region of crack growth such as the ASME Section XI Code {3} and the BSI PD6493 Code {4}.

In the ASME code several assumptions are used to simplify the analysis of multiple fatigue crack growth. Surface cracks are assumed to be either semi-circular or semi-elliptical. Cracks are assumed to grow at a constant aspect ratio (a/c). Adjacent cracks are recharacterized into a single coalesced crack when the distance between the inside defect tips is less than or equal to twice the depth of the deeper defect.

In the BSI document, the cracks are assumed to be recharacterized into a straight-fronted crack if the bending component exceeds 20% of the total stress. Adjacent defects are replaced by a single crack when the distance between the inside tips is less than twice the smaller surface length crack.

For both the previous approaches, the coalesced crack size has a surface length equal to the sum of the two individual cracks plus the separation distance. The final depth is equal to the depth of the deeper of the two individual cracks. The recharacterization guidelines are very similar for both codes and greatly simplify the fracture mechanics analysis of multiple defects.

However, both codes feature an instantaneous recharacterization which implies an enormous crack interaction effect and does not allow for stable crack growth during

coalescence. This effect has not been observed experimentally in any of the available published research.

2.5 Crack Shape Development

In recent years the subject of crack shape development of semi-elliptical surface cracks has been of great interest for many researchers {40-44}. Crack shape development describes the shape change of a surface crack as it grows from some small flaw or defect size to a final failure crack size. The shape of a semi-elliptical surface crack is generally defined by its maximum depth, a , and its surface length, $2c$ (Figure 2.6 inset). It is generally more convenient to non-dimensionalize these parameters in the form of a crack aspect ratio, a/c , and a non-dimensional crack depth, a/t , where t is the specimen thickness.

Crack shape development is influenced by several factors including the applied stress field (tension, bending, etc.), other cracks creating interaction effects, coalescence with other cracks and environmental effects. Corn {40} observed the existence of a Preferred Propagation Path (PPP) for surface cracks in axial and flexural fatigued plates. Cracks initiating from notches that were not initially of the preferred shape (aspect ratio) would tend to grow towards the PPP. Fatigue surface cracks in specimens subjected to tension loads will adopt a nearly semi-circular shape. They are then observed to elongate a little as they grow towards the back surface of the

Figure 2.6 Typical Crack Shape Development Curves
Single and double crack growth curves generated using the Iida and Kawahara [45] "natural" crack shape development model

specimen. Under bending, the stress gradient through the specimen thickness causes the cracks to grow with a decreasing aspect ratio as the stress level decreases at the deepest point. The enhanced surface growth in the high stress region generally causes the cracks to reach the specimen edges and become straight-fronted. The accurate prediction of crack shape development in fatigue is an invaluable tool in the creation of crack growth models for estimation of fatigue life.

The experimental measurement of crack shape development has traditionally involved the insertion of beachmarks on the fracture surface to mark the shape of the crack front at several points during a test. Beachmarks are usually generated by decreasing the applied stress range by a factor of two and then cycling for an appropriate number of cycles to leave a clear marking on the fracture surface. Upon completion of the test, the specimen is opened and measurements of crack depth and surface length are taken. More recently, the use of potential drop techniques has found its way into the measurement of crack shape development. The continuous monitoring of crack shape that is made possible with these techniques allows a more complete profile of how cracks develop to be obtained. A more detailed discussion of these and other crack monitoring techniques is presented in Chapter 3.

The majority of available research concerning crack shape development is applicable to the growth of single surface cracks. When considering the coalescence of multiple surface cracks there is a rapid drop in the crack aspect ratio as the surface length increases without a significant change in crack depth (Figure 2.6).

Performing coalescence experiments with multiple crack arrays, Iida and Kawahara {45} observed that interaction between adjacent cracks was not apparent and the crack shape development was quite different from that described in the ASME and BSI design codes. They reported empirical formulas to describe the shape development of

multiple semi-elliptical surface cracks. For a pair of surface cracks, the predicted shape development using their model is given in Figure 2.6.

The numerical results of Soboyejo et al, Murakami and Nemat-Nasser, Heath and Grandt and Iida and Kawahara concerning crack coalescence are further discussed in Chapter 6 in comparison with the results of the current experimental program.

The next chapter presents details of the development of the mobile DCPD probe arrangement used to study the crack coalescence and shape development processes in the current program.

Chapter 3

Development of a Mobile DCPD Probe Arrangement

In the field of experimental fracture mechanics there are several commonly used techniques for the measurement of crack depth and shape. This chapter describes briefly some of the more common methods used and presents the development of the mobile DCPD probe arrangement used in the current test program.

3.1 Crack Measurement Techniques

The more commonly used methods used for experimental crack shape measurement are :

- (i) dye penetrants, DP
- (ii) beachmarking, BM
- (iii) ultrasonic testing, UT
- (iv) potential drop, PD

Dye penetrant techniques involve the insertion of a colored dye into the crack to mark the fracture surface. Otegui et al {31} used this method for indicating the initiation and crack shape development of multiple short cracks ($a < 0.5\text{mm}$) which would otherwise be difficult using any of the other techniques. Various stages of crack growth were marked using a series of successive ink stainings which used progressively lighter inks to ensure the visibility of previous markings. This technique can be rather messy and is not suitable for automated continuous testing as it requires an operator to be present to insert the dye at the desired crack growth intervals.

Beachmarking is similar to DP techniques in that it involves marking the fracture surface at various stages of crack growth. A beachmark is usually generated by decreasing the cyclic stress range and increasing the cycling frequency for a period long enough to mark the fracture surface. The decrease in stress range generally causes a period of crack arrest followed by cracking at a decreased growth rate. This is visible on the fracture surface as dark outlines of the crack shape caused by the change in surface texture. Beachmarking is often used in conjunction with potential drop techniques as an independent method to verify or update the calibration relating the crack depth to the potential drop measured across the crack.

Ultrasonic testing methods involve the input of a high frequency acoustic signal into the test specimen. This signal will reflect off of any internal surface such as a crack or void creating an "echo" which is recorded. The results obtained using this technique

are often difficult to interpret and thus a high degree of operator skill is usually required. They are usually qualitative in nature and are generally used to ascertain whether a crack is or is not present. These qualities and the relative portability of the equipment make this technique more useful as an in situ method for field testing of components.

Potential drop methods involve the set-up of an electric field in the vicinity of a crack in a test specimen through the input of a constant excitation current (Figure 3.1). The

Figure 3.1 Potential Drop monitoring of a surface crack in a flat plate specimen

displacement of the electric field by the crack causes an increase in the resistance to current flow which results in an increase in the potential drop (voltage) measured across the crack plane. Using an appropriate calibration, this change in voltage may then be related to the crack depth. These techniques are used quite commonly because

of their ease of automation, with the use of computer control, allowing continuous testing. The various PD methods used are described in the next section.

3.2 Potential Drop Techniques

The two main categories of PD methods are:

- (i) alternating current potential drop (ACPD)
- (ii) direct current potential drop (DCPD)

As the names imply, the major difference between these two methods is the frequency of the electric field set-up in the test specimen. Each of these techniques has its advantages and disadvantages which are presented in the following sections.

3.2.1 ACPD

In the ACPD method, an alternating current is input into the test specimen. The electric field that develops is present only in a thin layer near the specimen surface and therefore is sometimes referred to as a "skin effect". This "skin effect" is the result of an exponentially decreasing current density through the specimen material thickness due to the interaction of the electric and magnetic fields produced by the alternating current {46}. The thickness of this "skin", τ , is related to the frequency of the applied field and is given by :

$$\tau = \frac{1}{\sqrt{\mu_r \mu_0 \pi \sigma f}} \quad (3.1)$$

where μ_r , μ_0 are the relative specimen and free space permeability respectively, σ is the conductivity of the specimen material, and f is the frequency of the applied field.

A crack introduced in the path of this electric field will cause a disruption which is detected by measuring the change in electrical potential across the crack. Using a suitable calibration technique, {47,48,49}, the measured potential may be related to the crack depth thus yielding an effective method of crack measurement.

The ACPD method has been used successfully by several researchers {29,50,51} for the detection and measurement of surface cracks. Watt {52} made a comparison of AC and DC based PD measurement systems. The advantages and disadvantages of the two techniques as presented by Watt are listed in Table 3.1.

3.2.2 DCPD

3.2.2.1 Global DCPD Method

The traditional or "global" DCPD method differs from the ACPD method by only the frequency of the input current used. Using eq.(3.1), it is apparent that a current input at DC frequency will produce an electric field of "infinite" thickness within the test specimen. This may be interpreted as the field being distributed throughout the entire volume of material between the current input locations. With the field distributed over the whole specimen thickness at the crack plane, the percentage of the field disturbed by a shallow crack is quite small when compared to the "skin effect"

Table 3.1 A Comparison of a.c and d.c. Potential Methods for Crack Monitoring
(taken from {52})

	ADVANTAGES	DISADVANTAGES
DCPD	<ol style="list-style-type: none"> 1. Simple technique does not rely on advanced electronics 2. Well established technique for certain specimen sizes and geometries 	<ol style="list-style-type: none"> 1. Complex relationship between PD and crack length 2. Thermal emf effects 3. Technique sensitive to specimen size and geometry
ACPD	<ol style="list-style-type: none"> 1. Ease of calibration for differing specimen geometries 2. Inherently linear response 3. Lack of size dependence of method 4. Ease of amplification of input signal 5. Multiple P.D. probe systems can be used 	<ol style="list-style-type: none"> 1. Reliance on advanced electronics 2. Lead interaction 3. Requirement for high stability in electronics

produced by the ACPD method. This property leads to reduced sensitivity and the requirement to use large input current levels in order to obtain an easily measurable incremental change in voltage for a corresponding change in crack depth.

Wei and Brazill {46} compared two crack measurement systems; one based on the ACPD method and the other using the DCPD technique. For an equivalent crack length resolution of approximately 0.01 mm for both systems, the DCPD system required an excitation current level of 10 A while the ACPD one required only 0.75 A.

However, for monitoring the growth of deeper cracks, as in the current program, the DCPD method is generally preferred as the ACPD technique tends to lose sensitivity due to the "skin effect" {46}.

It is common to express the potential measured across the crack in the form of a normalized potential drop, NPD, given by

$$\text{NPD} = \frac{V}{V_o} \quad (3.2)$$

where V is the potential difference measured across the crack and V_o is the initial potential difference for an uncracked ($a = 0$) specimen. By expressing the voltages in this form they become independent of the input current level and the conductivity of the specimen material. Calibrations are generally expressed in terms of the NPD; making them a function of the specimen geometry only.

To compensate for changes in temperature during testing, which affect the specimen resistivity, a reference probe set is often used. The reference PD sensing probes are attached to an area of the specimen that will not be affected by crack growth. The voltages measured by the reference probe set will be affected by any temperature and/or current level fluctuations in the same manner as the probes spanning the crack plane. The NPD may then be corrected using

$$\text{NPD}_{\text{corr}} = \frac{V}{V_o} \left(\frac{V_{ro}}{V_r} \right) \quad (3.3)$$

where V_r is the reference probe voltage and V_{r0} is the initial reference probe voltage measured at the start of testing ($a = 0$).

The sensitivity of a potential drop crack measurement system may be expressed in terms of the NPD. For a given increase in crack length, the percent change in the value of the NPD indicates the sensitivity of the system. Increases in sensitivity may be obtained by placing the PD sensing probes closer to the plane of the crack due to the higher potential gradients located in this area. However, with the probes placed very close to the crack plane, the relationship between the measured NPD and crack depth becomes extremely sensitive to the sensing probe locations and small positioning errors can lead to large variations in the estimated crack length. Ritchie et al {53} used an analog method to find the optimum locations for attachment of the current leads and PD sensing probes to give the best trade-off between sensitivity to crack depth and current/sensing probe positional errors.

In addition to the large excitation currents required, the relationship between the crack length and the NPD across the crack plane for the DCPD method is in general non-linear and for complex specimen geometries theoretical solutions are not available{54}. Therefore, other techniques such as numerical, analog or experimental methods must be implemented to obtain the calibration relations. The various techniques used for calibrating the DCPD method of crack measurement are presented in Chapter 4.

3.2.2.2 Localized DCPD Method

Recently the "global" DCPD method has been improved upon by the development of the "localized" DCPD method. This revised PD technique places the excitation current input locations much closer to the crack plane (Figure 3.2) thus significantly decreasing the volume of material through which the electric field is distributed. With the smaller field produced, the excitation current level requirements for this method are reduced substantially over the "global" DCPD technique. In the present work, an input current level of approximately 2 A is used. This may be contrasted with a level of the order of 50 A to achieve a similar sensitivity using the traditional method.

Figure 3.2 Global and Localized DCPD monitoring of a surface crack in a flat plate specimen

However, this revised method does present one disadvantage. The localized current field produced is, like the ACPD method, non-uniform through the specimen thickness. In order to be useful as a crack measurement technique, there must be a calibration relating the NPD to the crack depth. The presence of this non-uniform field, even with simple specimen geometries, makes obtaining an effective calibration a difficult task. Details of how this point was addressed for the current program are presented in Chapter 4.

3.3 Mobile DCPD Probe Array

The main objective of this experimental program is to obtain information about the crack shape development and coalescence of multiple semi-elliptical fatigue cracks. However, using a single localized DCPD probe set, it is only possible to obtain information regarding the crack depth in the plane of the probes. Therefore, in order to obtain information about crack surface length and profile, it is necessary to place multiple probe sets along the crack path (Figure 3.3). Each probe set may be hooked into a separate channel of a data acquisition system with a switching unit used to apply the excitation current to the

Figure 3.3 Multiple fixed probe configuration
(8 probe sets in the standard localized DCPD configuration)

appropriate probe set. Indeed, this is done quite often, with the usual approach being to spot-weld the probe sets to the specimen at various locations along the anticipated plane of crack growth. To obtain the detailed crack profile information needed for studying the coalescence process, one would require a substantial number of probe sets. This would lead to lengthy instrumentation sessions and the substantial likelihood of fatigue cracks initiating from the spot-welded probe locations.

3.3.1 Preliminary Testing

It was believed that the above problems could be addressed with the development of a probe arrangement that could be traversed along the plane of the crack by means of a movable carriage (Figure 3.4). This probe set could be stopped at discrete locations and PD measurements taken. This concept was developed during some preliminary testing carried out prior to the current program {55}. A prototype mobile probe array was constructed (Figure 3.5)

which traversed a single probe set by means of a movable carriage positioned by a stepper motor and lead screw assembly.

Figure 3.4 Mobile probe arrangement concept

Figure 3.5 Prototype mobile DCPD probe assembly

Tests using the prototype model were performed on flat steel plates with simulated cracks machined using a slitting saw. This preliminary testing allowed optimization of the probe type and spacing to be carried out such that good sensitivity to incremental crack growth could be obtained. Figure 3.6 shows a typical output of the NPD monitored using the prototype model for a series of three collinear saw cuts.

3.3.1.1 Modified Probe Arrangement

During the preliminary testing phase it was discovered that a significant increase in crack depth sensitivity could be obtained by altering the order of the four probes used in the mobile probe array. It was found that by reversing the positions of the negative excitation, P-, and PD sensing, S-, probes from the "standard" probe set-up to a new

Figure 3.6 NPD Output of Prototype DCPD Mobile Probe Arrangement
Output is for a series of three collinear saw cuts in a 31 mm thick steel plate.

“staggered” arrangement (Figure 3.7) a thirty percent increase in sensitivity could be obtained at the deepest point of an 5 mm deep saw cut (Figure 3.8). This change in sensitivity is attributed to the increase in the current density of the electric field around the crack tip as a result of moving one of the excitation probes closer to the plane of

Figure 3.7 “Staggered” and “Standard” DCPD Probe Arrangements

Figure 3.8 Comparison of Staggered and Standard Probe Arrangements
 ref{55}

the crack. This localized region of higher current density results in larger potential gradients and hence an increase in the measured value of the NPD. The increased sensitivity obtainable using the staggered probe arrangement should provide higher resolution crack depth and profile determination and was therefore selected as the probe arrangement to use for the current experimental program.

3.3.2 The Current Program

3.3.2.1 Traversing Carriage and Probe Arrangement

Based on the encouraging results obtained during the preliminary testing phase, a new mobile DCPD probe arrangement was designed and built for use in the current experimental program (Figure 3.9). A four probe localized DCPD array wired using

Figure 3.9 Mobile DCPD Probe Arrangement
(shown with bracket for attachment to test specimen)

the staggered probe arrangement is mounted in a plastic traversing carriage (Figure 3.10). To maintain a relatively constant probe pressure against the test specimen surface, spring loaded pogo® probes were selected for use in the probe array. The use of spring loaded probes was necessary to avoid the scratching of the specimen surface which a solid probe set would produce. The probes selected for use are 1 mm in diameter with a radius contact point. They are attached to a carrier using epoxy and

then screwed into the traversing carriage such that when the entire assembly is mounted on the specimen they are partially compressed. This reduces the electrical contact resistance between the probes and the specimen and ensures that they remain in contact with the specimen surface despite small variations in surface roughness. It is important to minimize the contact resistance between the probes and the specimen surface

Figure 3.10 Close-up of probe traversing carriage

as this forms a portion of the potential drop measured across the crack plane. The smaller the portion of the total potential difference measured due to the probe/surface interface resistance, the higher the sensitivity of the crack measurement system. To further reduce the contact resistance between the probes and the specimen, the surface of the specimen where the probes contact is ground smooth. This procedure is further discussed in Chapter 5.

3.3.2.2 Carriage Positioning Mechanism

The linear positioning of the carriage is accomplished using a stepper motor and lead screw assembly. This method was selected to provide the carriage motion because of the good positioning accuracy and the relative ease with which a personal computer can be used for stepper motor control. The stepper motor used was a Slo-Syn model SS25-1001 featuring 200 step/rev. resolution and a 20 oz-in. stall torque. A custom machined Teflon nut and a stainless steel 3/8"-16 UNC threaded rod form the positioning members. A measured, repeatable positioning inaccuracy of less than 0.2mm over a 151 mm traverse was found to be achievable with the above described assembly. Linear bearings in the positioning carriage ride on an upper support rail formed from 3/8" drill rod. The endplates are machined from non-conducting Bakelite to reduce electrical interference between the stepper motor and the probe set. The entire assembly attaches to the test specimen using a bracket which is screwed directly into the specimen. Care was taken during the design to allow easy mounting of the traversing rig on a test specimen while it is in position in a four point bend loading jig (Figure 3.11). Mounting holes are pre-tapped into the specimen such that they are under compressive loading during testing to prevent fatigue cracks from initiating from them.

Figure 3.11 Mobile DCPD test rig mounted on specimen placed in four-point-bending jig - outer loading points not shown

3.3.2.3 Combined Staggered and Standard Probe Arrangements

During the first three tests of the current program, it was noted that for deeper cracks, ($a > \approx 8$ mm), the sensitivity of the "staggered" probe arrangement began to decrease (Figure 3.12) making further increases in crack depth more difficult to detect. It is believed that this reduced sensitivity for increasing crack depth is a result of a redistribution of the current field creating smaller potential gradients across the crack

Figure 3.12 STAGGERED PROBE SENSITIVITY

Note the decrease in sensitivity with increasing crack depth. Data is for test 3 - specimen FPB6-3.

plane. This behavior was not observed during the preliminary testing phase due to the difficulty in cutting deep slots ($a > 5$ mm) with a slitting saw. As a result of this finding, it was decided to wire the four probe arrangement into two separate data acquisition channels (Figure 3.13) using a standard DB-9 connector. Using two channels it was possible to obtain potential drop data for both the "staggered" and the "standard" probe configurations. During post-test data processing, the data from both probe sets could be combined and used such that the best data was used over the entire crack depth range, {56}. Details of data acquisition, instrumentation and data post-processing are presented in Chapter 5.

Figure 3.13 DCPD probe wiring diagram for standard and staggered probe set-ups

Chapter 4

Calibration of the Mobile DCPD Probe Arrangement

To develop an effective crack measurement system based on the localized DCPD method, a calibration is required which relates the potential drop measured across the crack plane to the crack depth. In order to be useful in crack shape development studies, such as the current program, the calibration should also provide details of crack shape such as the surface length and profile. This chapter introduces some of the methods commonly used to obtain these calibration relations. The methods used in the current program to calibrate the mobile DCPD probe arrangement are then described in detail and the calibrations obtained are presented.

4.1 Methods of Calibration

There are several methods which are commonly used to obtain the calibration relations for the DCPD method of crack measurement. These techniques may be separated into the following four distinct groups :

- (i) experimental
- (ii) analog
- (iii) theoretical
- (iv) numerical

4.1.1 Experimental Techniques

This method involves taking a test specimen for which a calibration is desired and measuring the potential drop across the crack plane for a series of accurately known crack sizes. These "calibration" cracks are generally grown by fatigue loading and the incremental stages of crack growth are marked by changing the loading parameters to form beachmarks on the fracture surface. Prior to the insertion of each beachmark, the value of the potential drop is measured at one or more points along the crack plane. Upon conclusion of the fatigue test, the specimen is broken open and crack shape measurements (both depth and surface length) are made for each beachmark. The calibration relation is then obtained by relating these measurements to the corresponding values of potential drop. If possible, several specimens can be used to obtain the calibration and the results combined to assess the repeatability and accuracy of the relation obtained.

This technique in general provides the most accurate calibration as it uses real cracks in actual test specimens as opposed to the theoretical or numerical models which are often used. Several researchers {57,58,59} have used this technique successfully to obtain effective calibration relations for a variety of test specimens. In general, the accuracy was found to depend upon the consistency of the current and sensing probe locations. With fixed probe arrangements, templates can be used {60} to ensure consistent probe positioning. Unfortunately, the precise path of crack growth is not accurately known ahead of time and slight deviations in this path can introduce significant errors in the estimated depth if the calibration is sensitive to the position of the crack plane. This method has the disadvantage that it may require multiple test specimens and can be quite time consuming. If, as in the current program, knowledge of the crack shape is not required during actual testing, the calibration can be obtained upon completion of testing and no additional test specimens are required specifically for calibration purposes. However, if the experimental program requires knowledge of the crack length during testing, such as increasing or decreasing K_I -gradient testing, then extra specimens are required to obtain a calibration. This method also has the disadvantage that the calibration is very specific to the specimen geometry and probe configuration used and the relation cannot be easily modified for other geometries or probe configurations.

4.1.2 Analog Techniques

In this method, an analog model, generally electrical, of the test specimen is created. Typically, this analog consists of the construction of a two-dimensional geometrically similar rendering of the specimen out of electrically conducting (graphitized) paper or aluminum foil. A constant current is then injected into the paper model through the same points as the actual test specimen. The paper is then cut in small increments at the crack plane to simulate crack growth and the change in electrical potential is measured across the plane of the slit. Ritchie et al {53} used this technique to vary the current input and sensing probe points to find the optimum locations giving the best combination of good crack sensitivity and poor sensitivity to small variations in probe position. However, this method has the disadvantage that it is only applicable for two dimensional current fields and straight-fronted cracks such as those obtained in single-edge notch (SEN) and compact tension (CT) specimens.

Soboyejo et al {61} addressed this problem by creating a three-dimensional electrical analog using an electrolyte filled perspex tank to simulate a flat plate test specimen. Semi-elliptical surface cracks of varying lengths and depths were modeled by placing insulating disks with simulated crack shapes in the bath and measuring the drop in electrical potential across them. Comparison with experimental benchmark data from similar flat plate specimens yielded very good results for both the crack depth and surface length calibrations.

4.1.3 Theoretical Techniques

The electrical potential, u , at any location in a conducting medium may be described in three dimensions by Laplace's equation :

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = 0 \quad (4.1)$$

Theoretical methods involve the solution of the above equation in two or three dimensions subjected to the appropriate boundary conditions for the particular specimen geometry. For relatively simple specimen geometries and uniform current distributions, eq.(4.1) may be solved using conformal mapping techniques for the potential distribution as a function of crack depth. For the special case of a flat plate with a straight fronted crack and point current inputs, the theoretical solution in two-dimensions for eq.(4.1) by Gilbey and Pearson {62} was presented by Cooke and Robinson {63} in the following form :

$$a = \left(\frac{2w}{\pi} \right) \cos^{-1} \sqrt{\frac{(1-M_1^2)}{(M_2-M_1^2 M_3)}} \quad (4.2)$$

where

$$M_1 = \frac{e^{\left(\frac{V}{\kappa}\right)} - 1}{e^{\left(\frac{V}{\kappa}\right)} + 1} \quad M_2 = \operatorname{sech}^2 \left(\frac{\pi f}{2w} \right) \quad M_3 = \operatorname{sech}^2 \left(\frac{\pi d}{2w} \right)$$

and

a	crack depth
w	specimen thickness
f	potential probe spacing from crack plane
d	current probe spacing from crack plane
V	potential difference between signal probes
k	constant of integration

The above 2D theoretical solution is valid for straight-fronted cracks, however, it is not applicable for the present work concerning the coalescence of multiple semi-elliptical surface cracks. The difference in crack front shape causes a change in the current field distribution which is not described by the 2D solution. Costanza and Mohaupt {64} dealt with this by modifying the 2D Gilbey solution, eq.(4.2), with a correction factor, to make it applicable to single semi-elliptical surface cracks. This method was reported to give good results for the range of crack depths, a/w tested. The modified Gilbey solution as presented in {64} is discussed further in sections 4.2 and 4.3.3.1.

The advantage of theoretical techniques is that they present an exact solution that may be manipulated to permit optimization of sensing probe and current lead locations. However, exact theoretical solutions are generally only obtainable for relatively simple specimen geometries and boundary conditions. The author is not aware of any existing theoretical solutions for use with the localized DCPD method and semi-elliptical surface cracks.

4.1.4 Numerical Techniques

Where the specimen geometry or boundary conditions are such that a theoretical solution to eq.(4.1) is not readily available, numerical methods are often implemented to obtain the calibration relation. Various researchers have successfully used numerical techniques such as finite element methods, FEM {65}, and boundary element methods, BEM {68}, to obtain calibrations for the DCPD method.

The use of these numerical techniques involves modeling the specimen domain as an assemblage of discrete elements. The appropriate boundary conditions are then applied and the unknown boundary values of potential and potential gradient are solved for. The background theory of the BEM is discussed in section 4.3.1. For details on the formulation and applications of the FEM technique, the reader is referred to {66}.

4.2 The Current Program

The literature indicates that calibration methods discussed in the previous section provide very useful results when applied to the *global* DCPD method of crack measurement.

However, the *localized* DCPD technique of crack measurement is a relatively novel method and as such there is very little published research available regarding its calibration. Unlike the global DCPD method, which involves a fairly uniform current field throughout the specimen, the current field using the localized method is

non-uniform and is concentrated in the vicinity of the crack plane. With the absence of a uniform field, the development of a theoretical solution becomes very difficult. Mohaupt et al {64} found that by modifying the Gilbey solution (eq.(4.2)) with a correction factor, an effective calibration could be obtained for the localized DCPD method for cracks simulated using sawcuts. However, it was noted that for increasing a/w , the solution diverged. As the current program required measurements of significantly deeper cracks, this calibration method was not used. Also, the use of a three-dimensional analog was not considered due to the time and expense required for its construction.

For the current experimental program, it was decided to use a combination of the boundary element method and the experimental method to obtain a calibration. Two independent methods were chosen to give a comparison of accuracy and allow the choice of the calibration yielding the best results. These two particular techniques were chosen because they required relatively little time and expense to carry out. The following two sections discuss the details of the each of the two methods used.

4.3 BEM Calibration

The boundary element method, sometimes referred to as the boundary integral equation, BIE method, was used to obtain a calibration for the localized DCPD method using the standard probe arrangement. This particular numerical method was selected as it only requires discretization of the boundary rather than the entire domain as in the case of other numerical techniques. The QPOT3D software used for the analysis is for solution of three dimensional problems in potential theory. For further details on program input and output data formats, the reader is referred to {67}.

Due to the lack of symmetry present in the boundary conditions for the staggered probe arrangement, a separate sub-region would need to be created to model each side of the crack plane. Unfortunately, the software used does not allow the analysis of models consisting of multiple sub-regions to be performed. Therefore, only the case of the standard probe arrangement was considered in the analysis. The calibration for the staggered probe arrangement was obtained experimentally. This section presents the relevant BIE background theory, details of modeling, test cases and presents the results in the form of a calibration relation.

4.3.1 Background Theory

The following is a summary of the development of the BIE method taken from {68}.

Consider the problem of determining the potential function $u(x)$ in a domain R with boundary S , Figure 4.1, where u satisfies Laplace's equation (eq.(4.1)) and $i = 2$ or 3 in two-dimensions or in three-dimensions, respectively. On the boundary S , values of the potential, u , (the Dirichlet boundary condition) or the potential gradient, $t = \partial u / \partial n$, (the Neumann boundary condition) are prescribed, where n is the unit outward normal to S .

By employing the fundamental solution to eq.(4.1) and Green's theorem, and carrying out the usual limiting process, see, e.g.{69}, the boundary integral equation (BIE) corresponding to Laplace's equation may be obtained as follows :

$$C(P)u(P) + \int_S T(P, Q)u(Q)dS(Q) = \int_S U(P, Q)t(Q)dS(Q) \quad (4.3)$$

In eq.(4.3), P and Q are points on the boundary S , $U(P, Q)$ is the fundamental solution to eq.(4.1) and $T(P, Q) = \partial U / \partial n$. Also, the value of $C(P)$ depends on the local geometry

of S at P ; it is $1/2$ if P lies on a smooth plane. More specifically, for three-dimensions and using the indicial notation,

$$U(P, Q) = \frac{1}{4\pi r} \quad (4.4)$$

and

$$T(P, Q) = \frac{-1}{4\pi r^2} n_i r_{,i} \quad (4.5)$$

where $r = [(x_{iQ} - x_{iP})(x_{iQ} - x_{iP})]^{1/2}$ is the distance between P and Q , and n_i are the components of the unit outward normal at Q .

To solve eq.(4.3) numerically, the surface S of the domain is discretized into an assemblage of boundary elements. In the present work, eight-noded quadrilateral and six-noded triangular isoparametric elements are employed. Thus the representation of the geometry, the potential, u , and the potential gradient, t , over each of these elements may be expressed in terms of quadratic shape functions of intrinsic co-ordinates, $N^c(\zeta, \eta)$, and the respective nodal point values. Thus,

$$\begin{aligned} x_i(\zeta, \eta) &= N^c(\zeta, \eta) x_i^c \\ u(\zeta, \eta) &= N^c(\zeta, \eta) u^c \\ t(\zeta, \eta) &= N^c(\zeta, \eta) t^c \quad ; \quad -1 \leq \zeta, \eta \leq +1 \end{aligned} \quad (4.6)$$

where the subscript c has a range of 8 or 6 depending upon whether the element is a quadrilateral or a triangle.

Substitution of the previous parametric representations into eq.(4.3) results in the following :

$$\begin{aligned}
 & C(P^a)u(P^a) + \sum_{b=1}^M \sum_{c=1}^{8qr6} u(P^{d(b,c)}) \int \int_{S_b} T(P^a, Q) N^c(\zeta, \eta) d\zeta d\eta \\
 & = \sum_{b=1}^M \sum_{c=1}^{8qr6} t(P^{d(b,c)}) \int \int_{S_b} U(P^a, Q) N^c(\zeta, \eta) J(\zeta, \eta) d\zeta d\eta; \quad P^a = 1, q \quad (4.7)
 \end{aligned}$$

where M is the total number of boundary elements, q is the total number of distinct nodes disposed at the surface S , P^a is the a^{th} node, $P^{d(b,c)}$ is the c^{th} node of the b -th element, and $J(\zeta, \eta)$ is the Jacobian of transformation. Equation (4.7) represents a system of q linear algebraic equations to be solved for the unknown nodal values of u and t . The solution of these equations, which are in general fully populated with non-zero coefficients, may be obtained by direct Gaussian elimination, with perhaps a block solution algorithm for large values of q , see, e.g. {70}, as is employed in the present work.

4.3.2 Test Case

To verify the correct implementation of the BIE in the QPOT3D program, a test case with an exact analytical solution was modeled. The test case consists of a rectangular block (Figure 4.2) electrically insulated on two opposite sides, subjected to a uniform potential, U_1 , on three sides and a different uniform potential, U_2 , on the remaining side.

Figure 4.2 BEM Test Case

Original geometry and as modeled including boundary conditions.

The presence of the insulated sides reduces this to a two dimensional problem with a normalized potential distribution, U^* , given by {71}

$$U^* = \frac{U - U_1}{U_2 - U_1} = \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1} + 1}{n} \sin\left(\frac{n\pi x}{W}\right) \frac{\sinh(n\pi y/W)}{\sinh(n\pi H/W)} \quad (4.8)$$

The boundary element mesh used to model the block and the boundary conditions applied are shown in Figure 4.2. Two planes of symmetry were used to reduce the analysis to one quarter of the original domain.

The results of the analysis are presented as a plot (Figure 4.3) of the normalized potential along the vertical plane of the cube. The results of the analytical solution, eq.(4.8), have been

included on the plot for comparison. The excellent agreement between the two data sets shows the BIE formulation in the QPOT3D program to be correct.

Figure 4.3 BEM Test Case - results compared with exact solution

4.3.3 Modeling

The numerical analysis was carried out in two stages. A preliminary phase, using some two and simplified three-dimensional models, was carried out first to determine if a further, more detailed analysis would be worthwhile.

4.3.3.1 Preliminary Two-dimensional Modeling

For the 2D modeling, the program CPOT2D was used to perform the analysis. This program utilizes constant line elements for the solution of 2D problems in potential theory. A description of the program and the required input is presented in {72}.

The boundary element mesh used for modeling the test specimen is shown in Figure 4.4 with the appropriate boundary conditions applied. The domain size was reduced in half by taking advantage of a line of symmetry at the crack plane. Only the standard probe

arrangement could be modeled due to the non-symmetrical current input locations present in the staggered probe arrangement.

Figure 4.4 Two-dimensional boundary element mesh modeling localized DCPD method of crack measurement

Crack growth was simulated by varying the boundary conditions on the crack plane elements. The value of the potential at the PD sensing node was recorded for incremental crack depths from $0 \leq a/w \leq 0.5$.

The results of the 2D modeling are presented in Figure 4.5. As expected, there is good agreement with the two-dimensional Gilbey solution, but there is substantial deviation from the experimental and 3D BEM results. This is attributed to the fact that the 2D model simulates a straight fronted crack with a line input for the current when in

actuality the crack is semi-elliptical with a point current input which gives a varying distribution along the plane of the crack. This result indicates that a three-dimensional analysis is required to accurately model this method of crack measurement.

Figure 4.5 Results of preliminary BEM modeling

A second result obtained from the preliminary 2D analysis was the variation in potential as the crack plane is approached (Figure 4.6). The presence of the steep

potential gradient in the vicinity of the crack plane shows the relative sensitivity to sensing probe location that exists and the need for accurate probe placement for consistent results. Although this is a two-dimensional result, similar behavior would be expected in three dimensions.

Figure 4.6 Potential gradient in vicinity of crack plane for 2D BEM model

4.3.3.2 Preliminary Three-dimensional Modeling

Due to the computationally intensive nature of three-dimensional boundary element analysis, preliminary BEM modeling was carried out with a simplified mesh to optimize the size of the domain to be modeled. Three boundary element meshes (Figure 4.7) were constructed to model one half, two thirds and the full specimen width. The crack fronts modeled (Figure 4.8) were taken from the beachmark profiles

for an actual test specimen (FPB6-4) so comparisons with the experimentally measured potentials could be made. The domain modeled and the boundary conditions applied are shown in Figure 4.9. The details of the current input and PD sensing locations are also included. Each model

contained six of these current input/PD sensing mesh arrangements to simulate several positions of the mobile DCPD probe arrangement along the crack front. The value of the potential at the sensing node was obtained for a

Figure 4.7 Preliminary 3D boundary element meshes

Figure 4.8 Portion of BEM mesh showing modeling of several crack fronts

prescribed value of the potential gradient over the current input element.

The results of the initial 3D modeling using the three domain sizes is presented in Figure 4.10 .

It can be seen that there

Figure 4.9 Schematic of fatigue test specimen as modeled indicating boundary conditions

is excellent agreement

between the full and

two-thirds specimen models while the NPD obtained for the half specimen model

diverges as the centerline of the specimen is approached. This deviation is attributed to

the imposition of the Neumann boundary condition along the specimen end plane.

Although this corresponds to a geometric plane of symmetry, there is a lack of

symmetry in the boundary conditions due to the localized current input. Forcing the

potential gradient along this plane to be zero has an effect on the potentials as this

plane is approached, especially for the larger crack depths. This effect is not observed

in the two-thirds specimen model as the end plane is far enough removed from the

sensing locations. The current field distribution is shown qualitatively in Figure 4.11

Figure 4.10 Comparison of preliminary 3D BEM results for various models with experimental NPD values

Figure 4.11 Relative electric field distributions for 1/2 and 2/3 specimen BEM models

for both the half and two-thirds specimen models. Note the difference in the field distribution and hence the potentials obtained as the specimen mid-plane is approached. This result led to the choice of the two thirds specimen model with which to continue with a more in depth analysis.

The values of crack depth vs NPD for this preliminary analysis are presented on Figure 4.5 with some experimental data and the results of the 2D analysis for comparison. The agreement with the experimental data is excellent, hence indicating that the model is good and that a further more in depth analysis is worthwhile.

4.3.3.3 Detailed Three-dimensional Modeling

From the results of the initial 3D modeling (section 4.3.4.2), the use of a model of two thirds of the specimen domain was found to be the optimal choice. This mesh was further refined through the addition of more closely spaced current input and PD sensing locations (Figure 4.12). This refinement was carried out to allow a more detailed comparison with experimental results.

Figure 4.12 3D boundary element mesh refined for 21 measurement locations

The results of the detailed 3D modeling showing the effect of crack profile on the NPD are presented in Figure 4.13. To facilitate the presentation of the results, a non-dimensional parameter, ϕ , was chosen to indicate the measurement position along the crack front. Assuming symmetrical crack growth, the value of ϕ will vary from -1 at one crack tip to +1 at the other. The values of $a_{\max}$ and $\text{NPD}_{\max}$ correspond to the maximum values of the crack depth and NPD respectively obtained at the crack centerline ($\phi = 0$).

The effect of the crack profile on the NPD is evident from the increasing deviation between the two curves as the PD measurement location is shifted away from the

Figure 4.13 Results of 3D BEM analysis - crack profile effects

Solid lines represent second order least squares regressions through data points for cracks 4, 5 and 6.

This is attributed to

changes in the current field distribution around the crack front which varies with changes in current input/PD measurement locations. This current re-distribution

effect is described qualitatively in Figure 4.14 for two current input locations. It should be noted that the outlying data points in Figure 4.13, indicated by the squares, correspond to the results obtained at the starter notches. These discrepancies are a result of the large aspect ratio, a/c , difference between a scallop-shaped saw cut and a nearly semi-elliptical crack front. Similarly, the data points (triangles) for crack #1 fall outside the trend of the other results. This was expected as this crack has not yet started to grow in the surface direction (Figure 4.8) and therefore has not developed into the preferred shape typical of single semi-elliptical fatigue cracks {41}.

Figure 4.14 Electric field redistribution due to crack profile effects

The BEM results of Figure 4.13 were compiled into a DCPD crack profile calibration consisting of two relations. The first, an equation relating the maximum crack depth, $a_{\max}$, to the maximum value of the NPD, $\text{NPD}_{\max}$, is given by :

$$a_{\max} = A + B(\text{NPD}_{\max}) + C(\text{NPD}_{\max})^2 + D(e^{\text{NPD}_{\max}}) \quad (4.9)$$

where

$$A = 10.025$$

$$B = 7.841$$

$$C = -5.091$$

$$D = 2.962$$

Equation (4.9) was obtained through a series of curve fits and is presented graphically in Figure 4.15 .

Figure 4.15 Results of the BEM analysis
- maximum crack depth calibration - eq. (4.9)

The second relation, given by

$$\frac{a}{a_{\max}} = e^{\left(F + G \left[\frac{|\phi|}{\left(\frac{\text{NPD}}{\text{NPD}_{\max}} \right)} + H \left[\frac{|\phi|}{\left(\frac{\text{NPD}}{\text{NPD}_{\max}} \right)} \right]^2 \right) \right)} \quad (4.10)$$

where

$$F = 7.568 \times 10^{-3}$$

$$G = -4.744 \times 10^{-2}$$

$$H = -4.214 \times 10^{-1}$$

relates the crack depth ratio, $a/a_{\max}$, at any position, ϕ , along the crack front to the value of the NPD ratio, $\text{NPD}/\text{NPD}_{\max}$. Equation (4.10) was obtained using a curve fitting algorithm on the results of the BEM analysis and is presented graphically in Figure 4.16. Using eq.(4.9) and experimental data, the maximum crack depth, $a_{\max}$, may be calculated from the measured value of $\text{NPD}_{\max}$. With this information, the crack depth at any desired location, $|\phi|$, along the crack front, may be calculated from the measured value of NPD using eq.(4.10). The crack profiles obtained using this method and an accuracy assessment of this calibration are presented in Chapter 6.

Fig. 4.16 Results of the BEM analysis
- crack profile calibration - eq.(4.10)

4.3.4 Comments

During the BEM modeling it was decided to ignore the coalescence region and consider this area during the experimental calibration. This decision was made because the actual crack shape in the cusp region varies out of plane and differs widely from specimen to specimen. It was felt that because of these effects that an accurate modeling that was general in nature could not be performed. The coalescence region will be addressed in the following section concerning the experimental calibration.

4.4 Experimental Calibration

An experimental technique was used to obtain calibration relations for both the standard and staggered DCPD probe arrangements. As outlined in section 4.1.1, this method involves comparing the NPD values obtained during testing to crack depth and surface length measurements made from beachmarks. During the experimental calibration there were four areas of interest with regard to the current program :

- (i) crack depth, a
- (ii) crack surface length, $2c$
- (iii) crack profile
- (iv) location and depth details at the crack coalescence points

Having calibration relations for each of these areas is necessary to obtain information concerning crack shape development and coalescence of multiple surface cracks. These areas are each considered in detail in the following sections.

4.4.1 Crack Depth Calibration

The crack depth calibration was obtained through comparison of the NPD measured at each of the starter notch centers (deepest point of crack) with the actual depth taken from beachmark measurements at the same location. This procedure was carried out for both the standard and staggered probe arrangements.

The results of the depth calibration for all test specimens are presented in Figures 4.17a-b in the form of $a_{\max}$ versus NPD plots for both probe configurations. Note the significantly higher sensitivity of the staggered probe arrangement, especially for the shallower depths. For each data set, a best fit curve has been fitted to the data points and has been included on the figure for each specimen. Where applicable, the curve obtained from the BEM analysis (eq.(4.9)) has been included on the figures for comparison with the data obtained using the standard probe arrangement. Note that with the exception of the data from specimen FPB6-9 the BEM calibration fits the experimentally observed data for all tests conducted using the standard probe arrangement. At this time there is no explanation for the discrepancy observed between the BEM calibration and the experimental PD data obtained from specimen FPB6-9.

Figure 4.17a Experimental calibration results - crack depth
specimens FPB6-1 - FPB6-5

**PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT**

PRECISIONSM RESOLUTION TARGETS

Figure 4.17b Experimental calibration results - crack depth
specimens FPB6-6 - FPB6-9

Note, that for the staggered probe arrangement, a decrease in sensitivity occurs for increasing crack depth (especially for $a > \sim 5\text{mm}$). This has the implication that small fluctuations in the value of the measured NPD will generate large variations in the estimated crack depth. This is exacerbated by the fact that the scatter in the measured NPD values for the staggered probe arrangement tends to increase with crack depth. The observance of this behavior led to the choice of incorporation of the standard probe arrangement starting with test 4. The more consistent sensitivity and reduced scatter obtained using this method made it more suitable for use when estimating the larger crack depths.

The actual crack depth calibration used was carried out on a specimen by specimen basis. The probe arrangement yielding the least scatter in the crack depth data was selected to calculate the maximum crack depths for the entire test. Although this is not as convenient as having a single general calibration for all tests, it will provide the most accurate depth data.

4.4.2 Surface Point Calibration

In order to determine the surface length, $2c$, of a crack, it is necessary to obtain the locations where the crack tips break the surface. A calibration for determining these locations was obtained by noting the surface breaking points for each beachmark from several specimens and then going back over the NPD record to determine its value at this location. It was anticipated that a trend would develop which would allow

accurate determination of the surface breaking points. This would permit calculation of surface direction growth rate information and hence any crack to crack interaction effects that may occur.

The results of this portion of the calibration are presented in the form of a plot of NPD, for the staggered probe arrangement, at the surface breaking point versus the maximum depth of the crack (Figure 4.18). Note the relative independence of these two quantities once the crack profile reaches its preferred shape, ($a > \approx 5\text{mm}$). Prior to reaching this depth there is essentially no crack growth in the surface direction. For developed cracks, the average value of NPD of 1.5 seems reasonably consistent over a wide range of depths. This reduces the job of locating the surface breaking points to determining the location at which the value of NPD is 1.5.

The NPD for the staggered probe arrangement was chosen for use in this calibration for the significantly higher sensitivity available.

Figure 4.18 Experimental calibration - surface breaking points

This is shown in Figure 4.19 where the value of the NPD for both probe arrangements is shown in the region of the crack tip. This reduces the chance of falsely identifying surface breaking points due to point to point fluctuations in the measured NPD values as a result of positional variations in the probe/specimen surface contact resistance.

Figure 4.19 Experimental calibration - surface breaking points

The accuracy of this surface point calibration method based on comparison with benchmark measurements is presented in Chapter 6.

4.4.3 Crack Profile Calibration

Traditionally, with most surface crack growth models, the assumption of a semi-elliptical shape is generally used. Therefore the only required parameters to fully define the crack profile is the surface length, $2c$, and the maximum crack depth, $a_{\max}$. The calibrations regarding each of these two quantities were addressed in the previous two sections. In this section, an experimental crack profile calibration will be developed based on the same form as the 3D BEM calibration presented in section 4.3.3.3. It was felt that this additional calibration was justified to determine variations from the generally assumed semi-elliptical shape. In addition, with the value of NPD measured at every 1 mm along the specimen width, it seemed like sufficient use was not being put to the data by only obtaining the values of $a_{\max}$ and $2c$.

The results of this calibration are presented in Figures 4.20a-4.20d. The data is presented in the same form as the BEM calibration for both probe arrangements for all the test specimens. The calibration curve from the BEM analysis (eq.(4.10)) has been included on all plots for comparison. The agreement between the standard probe arrangement data and the BEM calibration is seen to be excellent. At the deeper crack portions ($a/a_{\max} > 0.6$), the agreement with the staggered probe arrangement is quite good. The increased sensitivity of this arrangement at the shallower crack depths causes an overestimation of the actual crack depth when compared with the BEM result.

The excellent agreement of the BEM calibration with the experimental results led to the choice of the calibration based on the relations presented in section 4.3.3.3 to determine the crack shape profiles when processing the NPD data from testing. Comparisons of crack profiles generated using this method with actual beachmarks is presented in Chapter 6.

Figure 4.20a Experimental calibration - crack profiles - specimens FPB6-2,3

Figure 4.20b Experimental calibration - crack profiles - specimens FPB6-4,5

Figure 4.20c Experimental calibration - crack profiles - specimens FPB6-6,7

Figure 4.20d Experimental calibration - crack profiles - specimens FPB6-8,9

4.4.4 Coalescence

Obtaining useful information from the NPD record in the coalescence region was the goal of this stage of calibration. It was desired to obtain the time and location at which adjacent crack tips touch as well as the depth at that point during the coalescence period. The NPD value at the time and point of crack tip contact was determined to try and evaluate a relatively accurate cycle count for the beginning of coalescence. A second part involved comparing the depth at the point of coalescence to the value of NPD measured at this location. With this information, values of the growth rates in this rapidly changing area could be determined in addition to obtaining the cycle count for the end of the coalescence phase.

The location of the coalescence point was determined through comparison of the NPD value at the mid distance between two adjacent crack tips with the separation distance, t_s , Figure 4.21. Extrapolation of this curve through the data to a separation distance of zero yields an NPD value of

Figure 4.21 Experimental calibration - coalescence point determination

approximately three for the staggered probe arrangement. The calibration thus consists of determining the cycle count and location at which the value of the NPD between two approaching crack tips would reach a value of three.

In a similar fashion as the crack depth calibration was obtained in section 4.4.1, the value of the NPD measured at the coalescence point is plotted against the beachmark depth measured at this location, Figure 4.22. Unfortunately the scatter in the points from specimen to specimen make a single general curve applicable to all coalescing surface cracks impossible. This is attributed to the crack plane mismatch of coalescing cracks. The variation in the ligament size and depth in the cusp region has a large effect on the path of the current field and hence the value of PD measured in this region. When the data for

all the specimens are plotted, there appears to be two distinct groups, tests 2-7 and tests 8-9. Other than the reasons previously mentioned, an explanation for the distinct differences between these two data sets

Figure 4.22 Experimental calibration - crack depth at coalescence point

is not known. The final coalescence depth calibration used consisted of two curves which apply to the two respective groups of test specimens. An evaluation of the accuracy of this calibration method is presented in Chapter 6.

Chapter 5

The Experimental Program

This chapter describes the fatigue testing apparatus and the experimental procedures used in the current testing program. Details of the fatigue test specimens and their preparation are also presented. In addition, details of the data acquisition system and the post-processing of the data have been included.

5.1 Test Specimens

5.1.1 Specimen Material

The test specimens were machined from 31 mm rolled steel plate manufactured to CSA G40.21 grade 350 WT specification. This material is a high strength low alloy (HSLA) steel with a chemical composition and mechanical properties as presented in Table 5.1.

Table 5.1 Chemical and Mechanical Properties of the Test Material

Element	Composition	Element	Composition
C	0.07	Cr	0.25
Mn	1.43	Mo	none
Si	0.29	Cu	none
S	0.01	V	0.08
P	0	Nb	0.02
Ni	0.25	Al	0.05
Yield Strength		374 MPa	
Ultimate Strength		479 MPa	
Elongation		63 %	

5.1.2 Specimen Preparation

A total of nine fatigue specimens were machined for use in the current testing program. The specimens are of a flat plate type configuration, (Figure 5.1) 31 mm thick, 152 mm in width, and 760 mm in length. Special attention was paid to the orientation of the plane for crack growth such that it coincided with the plate rolling direction. This was done to reduce potential crack growth or initiation problems due to material anisotropy. The specimens were bandsaw cut to rough dimensions and then milled accurately to size in the width direction. Screw holes were then tapped on either side of the specimen width, in the anticipated plane of crack growth, to allow

Figure 5.1 Fatigue test specimen geometry and starter notch details

mounting of the mobile DCPD test rig. The final stage of specimen machining involved the grinding of a ten centimetre wide strip across the centre of the specimen width to provide a good traversing and electrically conducting surface for the mobile probe arrangement.

5.2 Test Equipment

Fatigue testing was carried out on a load frame equipped with a 100 kN capacity MTS servo-hydraulic actuator (Figure 5.2). The actuator was controlled via MTS 406/436 control units interfaced to an IBM AT compatible computer. The interface card, an

Figure 5.2 Load frame equipped with servo-hydraulic actuator and associated control units

Figure 5.3 Schematic of instrumentation and servo-hydraulic control system

MDT Signal Generator/Data Acquisition Card, supplied the necessary control signals for actuator operation. A test equipment and instrumentation schematic showing the interconnection of all components is presented in Figure 5.3. Software control of the loading system was performed using a modified version of the MDTest1 software supplied by MDT Engineering.

Test specimens were loaded in a four-point-bending configuration to give a region of constant bending stress between the two central loading points. The loading jig (Figures 5.4, 5.5) used in a previous fatigue testing program {60}, formed the two central loading points. This jig features support points on rollers to minimize fretting between the specimen and the loading points during testing. The fixed, outer loading points, attached to the loading frame, are mounted on sliding platens (Figure 5.4) with screw-adjustable support points for specimen alignment purposes.

Figure 5.4 Four-point-bend loading jig

Figure 5.5 Four-point-bend loading jig

5.3 Test Procedure

The following sections outline the various stages of the test procedure used for each of the nine tests carried out in the current experimental program.

5.3.1 Specimen Surface Preparation

The central machine ground portion of the test specimen surface was further ground by hand with progressively finer papers from 240 to 600 grit using water as a lubricant. Strain gauges were then mounted on either side of the specimen width using standard procedures. Finally, a coating of WD40[®] spray lubricant was placed on the surface and left on for the duration of testing. This was required to prevent oxidation of the finely

ground surface which would have deleterious effects on the potential drops measured by the data acquisition system. Previous experience showed that the presence of such a lubricant on the specimen surface would have negligible effects on the PD readings.

5.3.2 Initial Potential Drop Readings

Prior to starting each fatigue test, a data acquisition sequence was initiated to obtain the initial PD readings, V_o , required to calculate the value of the NPD. This procedure, controlled by the modified MDTest1 software, involved traversing the mobile DCPD probe array across the surface of the specimen where it would take PD readings at 1 mm intervals over the entire specimen width. This data set would then be checked for any anomalous readings which would indicate a problem with the probe arrangement/data acquisition system or the specimen surface preparation. Further details concerning the motor control and data acquisition software are presented in section 5.4.3.2.

5.3.3 Starter Notch Machining

Starter notches were machined into the specimen along the centreline to provide initiation sites for fatigue cracks. In addition to greatly reducing the number of cycles required for crack initiation, the starter notches were also used to control the position of the plane of crack growth such that it would fall between the central two probes of the mobile probe arrangement.

Figure 5.6 Low speed slitting saw used for machining starter notches in test specimens

The starter notches were machined using a low speed slitting saw (Figure 5.6) designed and built for use in this testing program. The saw features a dial gauge for depth measurement and a manual positioning screw for blade depth control to allow accurate cutting. The slitting saw blades used were 44.5 mm in diameter and 0.15 mm in thickness. These particular blades were chosen specifically for their ability to produce very thin (sharp) scallop shaped cuts which would reduce the number of loading cycles required for crack initiation.

While the notch aspect ratio, a/c , was kept essentially constant, ($a/c \approx 0.23$), for all test specimens, the number and placement of the starter notches was varied. The general

notch geometry is indicated in Figure 5.1, while a summary of the notch and other testing parameters for each specimen is presented in Table 5.2.

Table 5.2 Test specimen starter notch geometry and loading parameters

Test	Specimen	# of notches	notch depth a [mm]	notch length 2c [mm]	notch spacing SS ₁ [mm]	notch spacing SS ₂ [mm]	stress range $\Delta\sigma$ [MPa]
1	FPB6-1	1	2.7	27.4	n/a	n/a	250
2	FPB6-2	2	2.1	18.5	42.4	n/a	250
3	FPB6-3	2	2.1	18.5	46.3	n/a	250
4	FPB6-4	2	2.1	18.6	44.8	n/a	200
5	FPB6-5	2	2.1	18.7	42.4	n/a	175
6	FPB6-6	2	2.1	18.6	42.1	n/a	175
7	FPB6-7	2	2.2	18.7	43.9	n/a	200
8	FPB6-8	3	2.1	18.8	34.1	n/a	150
9	FPB6-9	3	2.1	18.2	33.6	n/a	150

5.3.4 Specimen Alignment

After the machining of the starter notches, the test specimen was placed in the loading frame and the strain gauges balanced under a "no-load" condition. A "small" load of approximately 3 kN was then applied to remove any slack in the load train and permit an alignment to be carried out. Specimen alignment involved squaring up the specimen with the load frame. This procedure ensures uniform loading across the

specimen width and reduces lateral movement of the specimen during testing which could damage the DCPD test rig. The first stage involved a preliminary visual alignment of the specimen and loading fixture using a metre stick and spirit level. Loading was then increased in 5 kN increments from 5 to 40 kN and the readings for both strain gauges compared at each load level. If the differential strain reading was more than 20 μ -strain at any load level, the load would be removed and the specimen position adjusted. This procedure was repeated until the alignment was considered satisfactory. The mobile DCPD test rig would then be attached to the test specimen and the probes reversed to the reference starting position.

5.3.5 Software Set-up

The next step in the test procedure involved the calculation of the loads required to achieve the desired stress ranges and the programming of the MDTest1 software with the loading parameters. Two types of loading sequences were used. The first, normal cycling at a frequency of 2.5 Hz at the desired stress range (Table 5.2) and a stress ratio, R ($R = \sigma_{\min}/\sigma_{\max}$), of 0.05; the second, beachmark cycling, where the frequency is raised to 5 Hz and the stress range is halved while keeping the same mean stress level. The cycling frequencies were selected from experience as the maximum values that could be used while still achieving the desired load limits. Other quantities required by the test control software included data acquisition parameters such as the number of channels, cycle count for data acquisition sequences and the load level at which data

acquisition is to occur. Typically, data acquisition sequences would be performed every 10 kilocycles at the beginning of a test and then changed to every 5 kilocycles as the crack coalescence stage approached. In order to eliminate any short circuiting of the DCPD field due to crack closure, data acquisition sequences were performed at 80 - 85 % of the maximum cyclic load. Other parameters required by the MDTest1 software are detailed in the software manual {73}.

5.3.6 Fatigue Testing

Upon completion of programming the control software, a second data acquisition sequence would be initiated to record the PD data for the starter notches and also verify that the entire system was working correctly. Following this data acquisition sequence, the block loading sequencing program was initiated. At this stage, the system, both loading and data acquisition, is completely automated and was allowed to run continuously. Periodically (once a day), checks were made on the progress of crack growth and general system status. If visual inspection revealed the onset of crack coalescence, the number of beachmarking sequences would be increased to mark the fracture surface at several points during this interesting period of growth. Individual fatigue tests would be terminated automatically by the control software once the extent of crack growth had caused enough loss in specimen stiffness that the load actuator would hit the upper stroke limit trying to maintain the programmed loading levels.

This would typically occur when the crack had progressed approximately seventy percent through the specimen thickness.

Upon failure, the specimen would be removed from the loading frame and the fracture surfaces cleaned with acetone and coated with a polyurethane clear coat to prevent oxidation. The sections of specimen containing the fracture surfaces were then trimmed to a more manageable size using a bandsaw. Photographs of the specimen and beachmark profile measurements using a Nikon profile projector (model 6C) were then performed to complete the experimental test record.

5.4 Instrumentation

The instrumentation used in the experimental program consisted of an MDT data acquisition system, an MTS digital display and a pair of strain gauges. Details of each of these pieces of equipment are presented in the following sections.

5.4.1 Strain Gauges

Prior to beginning a new test, two strain gauges were used for specimen alignment purposes. The locations of these gauges are indicated on Figure 5.7. The strain gauges used were of the electrical resistance foil type with an 8 mm gauge length. A quarter bridge arrangement was used with a Vishay switch and balance unit (model SB-1) to

Figure 5.7 Fatigue test specimen with strain gauge locations indicated

obtain the strain readings in μ -strain on a Vishay portable strain indicator (model P-350A). In addition to the alignment procedure already mentioned, the strain gauges were also used as an independent check of load cell accuracy. Using simple beam formula and the strain readings, the calculated load comparisons were found to be within three percent for static loads.

5.4.2 MTS Digital Display

An MTS Digital Display (model 464) was used to monitor the output of the load cell during testing. This display unit has several modes of operation and can be used to monitor the peak maximum and minimum loads that the specimen is subjected to during any time period. This feature was extremely useful in checking for possible

over/underloads exerted on the specimen during unattended periods of operation.

Details of the operation of this display unit may be found in the operation manual {74}.

5.4.3 Data Acquisition and Control System

The computer controlled data acquisition and actuator control system (MDTEST) used in the current testing program consisted of both a hardware and a software component. Details of each of these are presented in the following sections.

5.4.3.1 Hardware

Excitation for the localized DCPD technique and PD measurement was performed using an MDT model M100 data acquisition system. This system consists of a data acquisition unit and a computer interface card for use in an IBM compatible computer. The system has several modes of operation including : PD, strain, analog voltage and temperature measurement. In the PD mode, this multi-purpose system, supplies an excitation current (typically 2.5 A) to the designated probe set and following a software controlled settling time, samples the respective potential probes. To reduce or eliminate time dependent amplifier drift as well as thermocouple effects, the system uses a solid state switched excitation current and zero current to full current potential drop differencing technique. Full technical details on this system may be found in the

operating manual {75}. Only two of the 128 available channels were required to implement the staggered and standard probe arrangements, as discussed in section 3.3.2.3. A schematic of the data acquisition system and other instrumentation is shown in Figure 5.3.

The MDT computer interface card and software provided by MDT Engineering was used for control of both the MTS servo-hydraulic actuator and the MDT M100 data acquisition system.

5.4.3.2 Software

Software control of the testing equipment and data acquisition system was carried out using the MDTest1 software provided with the MDTEST system. This menu driven software is easy to use and can accommodate a wide range of testing requirements. Complete details concerning program operation may be found in the operating manual {73}.

The MDTest1 software was modified for use in the current testing program to provide stepper motor control for the mobile DCPD probe arrangement. Subroutines added to the data acquisition program module generated the required TTL control signals at the computers parallel port. Parameters such as the specimen width and the PD measurement spacing may be changed for different specimens or test requirements through minor modifications to the source code.

5.4.4 Data Post-Processing

The data files output by the modified MDTest1 software consisted of potential drop values for both the staggered and standard probe arrangements measured at 1 mm intervals across the 152 mm specimen width. Data reduction of the large amount of data produced during each fatigue test was facilitated by the use of two QuickBASIC programs, FATDATA and POST, written for use in the current program. Details of each of these two programs are presented in the following sections.

5.4.4.1 FATDATA

The FATDATA program performs a series of data reduction manipulations on the raw potential drop data files. The individual steps, in order, that the program performs are summarized in point form below. For a more complete description of program operation please refer to the software documentation {76}.

- Inputs raw data files containing cycle count and PD data.
- Calculates values of the NPD based on an average value of V_0 obtained during the initial data acquisition sequence.
- Corrects any effects due to temperature variations (appear as an offset in PD data) by applying a correction factor. The requirement is to obtain an NPD value of unity over uncracked portions of the specimen.
- Calculates the value of the NPD at the notch centres based on a second order regression using 7 points. These values of NPD are output to a separate file which is used by POST to calculate the crack depths.

- Performs a "smoothing" of the NPD data using a series of overlapping second order regression curves across the specimen width. Each regression curve uses 12 data points and overlaps adjacent curves by four points. This "smoothing" operation is performed to reduce some of the point to point fluctuations in the NPD values that occur due to small probe positioning errors and variations in the probe/surface electrical contact resistance.
- Using interpolation, values of the NPD are calculated at the same positions where post test beachmark profile measurements were made. This provides for easy comparison of crack depths and NPD values for calibration purposes.

5.4.4.2 POST

The POST program takes the modified NPD values produced by FATDATA as input and performs the following data reduction steps :

- Determines locations of the crack surface breaking points by interpolation between the measured NPD positions (based on the calibration in section 4.4.2).
- Calculates the half surface crack length, c , based on the surface breaking points.
- Calculates the value of the crack growth rate in the surface direction, dc/dN , for each crack tip based on the seven-point incremental polynomial method outlined in the appendix of ASTM3412 E647 {77}.
- Calculates the maximum crack depth, a_{max} , based on the individual specimen experimental calibrations presented in section 4.4.1.
- Determines the coalescence location and depth based on the experimental calibrations presented in section 4.4.4.

-
- Calculates the crack profile based on the BEM calibration presented in section 4.3.3.3.
 - Obtains the stress intensity factor range, ΔK_I , at the maximum depth and surface points based on the relations of Raju and Newman {14}.
 - Calculates the crack growth rate, da/dN , at the notch centres and the coalescence points using the ASTM seven point incremental polynomial method {77}.

Chapter 6

Results and Discussion

This chapter presents the results obtained from the nine specimens tested in the current program. Each test specimen is described and details of the fracture surface are given. The results obtained using the mobile DCPD probe arrangement, described in Chapter 3, are compared with beachmark data to assess accuracy and hence evaluate its usefulness as a crack measurement device. For brevity, only typical examples of some of the intermediate results obtained are presented. The crack interaction, coalescence and shape development results observed are then discussed in detail. Wherever possible, crack growth and coalescence models presented in the literature are included with the experimental results for comparison.

6.1 Results of Testing

The following sections detail the experimental results for all the tests carried out in the current program. Specimen test results are divided into three groups differentiated by the number of machined starter notches used. Test specimens had either one, two or three starter notches. Photographs of all fracture surfaces and beachmark profiles are given. Details of unexpected occurrences during testing are also presented where required.

6.1.1 Stress-Life Results

For the current program, the following definitions with respect to specimen fatigue life have been used :

initiation life, N_i : the number of cycles required for 0.5mm of crack growth in the depth, a , direction from the machined starter notch. This value has been selected as it is the smallest detectable change in crack depth that may be reliably measured using the mobile DCPD probe arrangement. This criterion for the initiation life is also used by researchers in the Canadian Offshore Steel Research Program {78}.

total life, N_t : the number of cycles required for the crack to grow to a size that results in the loading actuator hitting its upper stroke limit due to excessive deflections caused by loss of specimen compliance. This would typically occur when the crack had propagated through approximately seventy percent of the specimen thickness.

propagation life, N_p : the number of cycles required for the crack to grow from the initiation size to the final crack size, ($N_p = N_t - N_i$).

A stress-life (S-N) summary of all the tests is presented in Table 6.1 below and graphically in Figure 6.1.

Table 6.1 Stress - Life Summary

test #	specimen	# of starter notches	stress range $\Delta\sigma$ [MPa]	FATIGUE LIFE		
				initiation N_i x 10^3 cycles	total N_t x 10^3 cycles	propagation N_p x 10^3 cycles
1	FPB6-1	1	250	40	301	261
2	FPB6-2	2	250	40	287	247
3	FPB6-3	2	250	35	253	218
4	FPB6-4	2	200	90	502	412
5	FPB6-5	2	175	105	718	613
6	FPB6-6	2	175	105	738	633
7	FPB6-7	2	200	60	550	490
8	FPB6-8	3	150	180	1376	1196
9	FPB6-9	3	150	170	1377	1207

The number of cycles required for the cracks to grow to the initiation size is seen to decrease for tests carried out at higher stress ranges. This behaviour is expected given the Paris relation (eq.(2.1)) between crack growth rates and the applied stress intensity factor (SIF) range. The extremely linear nature and the relatively small amount of scatter that exists in the fatigue life data for tests carried out at the same applied stress levels is attributed to the careful monitoring and adjustment of the loading levels during testing.

Figure 6.1 Stress - Life Summary

The solid line is a linear regression through data points for double-notched specimens tested in the current program ($r^2 = 0.988$). Dotted lines represent 95% confidence intervals.

Intuitively, one would expect the total life of a specimen with three starter notches to be less than that for a double-notched specimen tested at the same applied stress range. Examining Figure 6.1 it is seen that the data points for the triple-notched specimens lie to the right of the regression line for the double-notched specimens. This unexpected behaviour is attributed to the relatively low stress range, which approaches the endurance limit of the material, that these tests were carried out at. Currently, as no tests were carried out on double-notched specimens at this stress range, this point cannot be verified.

6.1.2 Single-Notched Specimens

Only one test (FPB6-1) was performed using a specimen with a single starter notch.

Fracture surface details and the results of beachmark profile measurements are presented in Figures 6.2 and 6.3 respectively. This first test was primarily intended to test the operation of the mobile DCPD probe arrangement on an actual specimen undergoing fatigue. The high stress range used ($\Delta\sigma = 250$ MPa) and the relative inexperience in carrying out fatigue tests of this nature resulted in fewer beachmarks than desired to show crack shape development and aid in the calibration of the mobile DCPD test rig.

Figure 6.2 Fracture Surface of Specimen FPB6-1
scale units are in cm.

Figure 6.3 Beachmark Profile Details for Specimen FPB6-1
scale units are in mm

6.1.3 Double-Notched Specimens

A total of six tests (FPB6-2 - FPB6-7) were carried out using specimens with twin starter notches. Care was taken during the notch machining stage to get the notch depth, a_i , and notch spacing, SS , as similar as possible between test specimens to reduce any possible effects on total life or the coalescence process that variations in notch shape and positioning would produce. A variety of stress ranges ($\Delta\sigma = 175 - 250$ MPa) were also used to generate a good range of S-N and da/dN vs ΔK data.

The testing of double-notched specimens was performed to study the coalescence process between two coplanar semi-elliptical surface cracks. To aid in this, the number of beachmark sequences was increased when the onset of coalescence was detected through visual inspection. Fracture surface photographs and beachmark profiles for each of the six tests are presented in Figures 6.4 to 6.27. Macro photographs of the coalescence region between the two starter notches have also been included. Details of the fractography in this region are discussed in the coalescence section (section 6.3.3).

One exception to note to the above comment is the lack of beachmarks detailing the coalescence region for the fifth test (FPB6-5), Figure 6.18. This was a result of a "bug" in the MDTEST1 software which was resolved for future tests.

Figure 6.4 Fracture Surface of Specimen FPB6-2
scale units are in cm

Figure 6.5 Beachmark Profiles for Specimen FPB6-2
scale units are in mm

Figure 6.6 Coalescence Region for Specimen FPB6-2
scale units are in cm

Figure 6.7 Beachmark Profile Details for Specimen FPB6-2
scale units are in mm

Figure 6.8 Fracture Surface of Specimen FPB6-3
scale units are in cm

Figure 6.9 Beachmark Profiles for Specimen FPB6-3
scale units are in mm

Figure 6.10 Coalescence Region for Specimen FPB6-3
scale units are in cm

Figure 6.11 Benchmark Profile Details for Specimen FPB6-3
scale units are in mm

Figure 6.12 Fracture Surface of Specimen FPB6-4

scale units are in cm

Figure 6.13 Beachmark Profiles for Specimen FPB6-4

scale units are in mm

Figure 6.14 Coalescence Region for Specimen FPB6-4
scale units are in cm

Figure 6.15 Beachmark Profile Details for Specimen FPB6-4
scale units are in mm

Figure 6.16 Fracture Surface of Specimen FPB6-5

scale units are in cm

Figure 6.17 Beachmark Profiles for Specimen FPB6-5

scale units are in mm

Figure 6.18 Coalescence Region for Specimen FPB6-5
scale units are in cm

Figure 6.19 Benchmark Profile Details for Specimen FPB6-5
scale units are in mm

Figure 6.20 Fracture Surface of Specimen FPB6-6
scale units are in cm

Figure 6.21 Beachmark Profiles for Specimen FPB6-6
scale units are in mm

Figure 6.22 Coalescence Region for Specimen FPB6-6
scale units are in cm

Figure 6.23 Beachmark Profile Details for Specimen FPB6-6
scale units are in mm

Figure 6.24 Fracture Surface of Specimen FPB6-7
scale units are in cm

Figure 6.25 Beachmark Profiles for Specimen FPB6-7
scale units are in mm

Figure 6.26 Coalescence Region for Specimen FPB6-7
scale units are in cm

Figure 6.27 Beachmark Profile Details for Specimen FPB6-7
scale units are in mm

6.1.4 Triple-Notched Specimens

Two tests (FPB6-8,9) were carried out with specimens containing three starter notches at an applied stress range of 150 MPa. The spacing of the starter notches was set up such that two of the cracks would coalesce into a dominant crack which would then coalesce with the third smaller crack. This procedure was successful for Test 8 as can be seen from the fracture surface details presented in Figures 6.28 to 6.35.

The staining of the fracture surfaces is a result of the WD-40[®] spray lubricant placed on the specimen surface to reduce oxidation. As this staining is not present on the other test specimen fracture surfaces, it is believed that the increased length of these two tests as a result of the low applied stress range was the major contributing factor.

Figure 6.28 Fracture Surface of Specimen FPB6-8
scale units are in cm

Figure 6.29 Beachmark Profiles for Specimen FPB6-8
scale units are in mm

Figure 6.30 Coalescence Region for Specimen FPB6-8
scale units are in cm

Figure 6.31 Beachmark Profile Details for Specimen FPB6-8
scale units are in mm

Figure 6.32 Fracture Surface of Specimen FPB6-9
scale units are in cm

Figure 6.33 Beachmark Profiles for Specimen FPB6-9
scale units are in mm

Figure 6.34 Coalescence Region for Specimen FPB6-9
scale units are in cm

Figure 6.35 Beachmark Profile Details for Specimen FPB6-9
scale units are in mm

6.2 Mobile DCPD Probe Arrangement

This section presents the crack depth and surface length results obtained from the use of the mobile DCPD probe arrangement. The estimations of crack depth and length are based on the calibrations presented in Chapter 4. An assessment of the accuracy of the mobile probe arrangement and suggested modifications to improve the accuracy for future testing have also been included.

6.2.1 Crack Depth Measurements

As described in Chapter 4, it was found that the sensitivity of the mobile probe arrangement tended to decrease with increasing crack depth. This occurrence is illustrated for specimen FPB6-6, Figure 6.36, where the crack depth estimations at the notch centre measurement position are compared with the actual depths taken from beachmark profile measurements. The agreement between the two data sets is

Figure 6.36 Specimen FPB6-6 : a vs N

Estimated and actual crack depths measured at notch centres. Every second estimated crack depth shown for clarity

satisfactory ($a_{\text{error}} < 1 \text{ mm}$) up to a crack depth of approximately 6 mm. For greater depths there are variations in the estimated crack depths of greater than 2 mm which is considered unacceptable for use in any experimental crack growth study. A quantitative assessment of the crack depth accuracy and explanations are presented in section 6.2.4.1.

6.2.2 Crack Surface Position Measurement

In contrast to the relatively poor results obtained for the crack depth estimations, the accuracy of the crack surface breaking point measurements was better than anticipated. A typical example of the estimated and actual crack tip surface positions obtained during the course of a test is presented in Figure 6.37 for specimen FPB6-8.

Figure 6.37 Crack Tip Surface Locations (specimen FPB6-8)

Both estimated and actual locations are indicated. For clarity only every third estimated data point is shown.

The lack of data between 800 and 1000 kilocycles was a result of a temporary problem with the data acquisition system.

The excellent surface breaking point results obtained with the mobile probe arrangement are ideal for the monitoring of any crack-to-crack interaction effects and the determination of the time and location where two adjacent crack tips touch. Previously, the interaction effect and coalescence details have been difficult to obtain due to the limited amount of accurate surface point data available using traditional (fixed probe) potential drop techniques {60}.

6.2.3 Crack Profile Measurements

Using the calibrations presented in Chapter 4, estimated crack profiles were generated. Due to the inaccuracy of the crack depth estimations, as described in section 6.2.1, the accuracy of the profiles are somewhat less than hoped. A typical example of the profile estimations compared with beachmark profile measurements is shown in Figure 6.38.

Figure 6.38 Crack Profile Measurements

Estimated and actual crack profile measurements for specimen FPB6-8

Currently there is no estimated profile data for the period during and after the coalescence stage. This is primarily due to the lack of an adequate calibration that relates the NPD to the crack shape in the coalescence region. Variations in crack plane mismatch and short circuiting across the unbroken ligament in the cusp region make anything other than a specimen specific calibration unlikely at this time.

6.2.4 Accuracy Assessment

6.2.4.1 Crack Depth Accuracy

An estimate of the crack depth accuracy based on comparison with actual depth measurements is presented in Figure 6.39. The estimated crack depth accuracy is assessed based on the magnitude of the crack depth error, $|a_{\text{error}}|$, given by

$$|a_{\text{error}}| = |a_{\text{act}} - a_{\text{est}}| \quad (6.1)$$

where a_{est} and a_{act} are the estimated and actual crack depths respectively.

Due to the lack of published results for localized DCPD monitoring of surface cracks, fixed or mobile probes, a relative assessment of the current implementation cannot be made.

Data scatter and the magnitude of the crack depth error are both seen to increase substantially with increasing crack depth. This rise in the data scatter is associated

Figure 6.39 Accuracy Assessment - Crack Depth Estimation
Compares estimated crack depths with actual for all specimens

with both the reduced PD sensitivity to crack depth noted in Chapter 4 and the increase in the potential gradients in the vicinity of the crack plane that occurs with increasing crack depths. Small changes in the positioning of the probe set relative to the crack plane during testing result in an increased scatter in the estimated crack depth due to these larger potential gradients.

As crack growth rate calculations are relatively sensitive to scatter present in crack depth data, it is felt that the current depth accuracy is not sufficient for use in these

calculations. However, it is believed that the reasons for the inaccuracies are well understood and that several design modifications are possible which will significantly increase the resolution of the mobile probe arrangement. These are detailed in section 6.2.5.

6.2.4.2 Crack Surface Length Accuracy

The accuracy of locating the crack surface breaking points is assessed in Figure 6.40 based on a comparison with the actual measured surface breaking points.

Figure 6.40 Surface Point Accuracy Assessment

Graph indicates deviation of estimated surface breaking point from actual point as a function of the number of data acquisition sequences performed.

In the previous figure, the error has been plotted against the number of data acquisition sequences performed to try and determine if there is any contribution due to cumulative errors in positioning.

The average error of 0.83 mm (Table 6.3), which is less than the 1 mm measurement spacing, is relatively small when compared to that obtainable with the generally widely spaced fixed probe arrangements. It is believed that a large percentage of the error is a result of errors in probe positioning during the tests which appear as an offset in the estimated surface point data. This effect is shown in Figure 6.41. This point is further addressed in section 6.2.5.

Figure 6.41 Crack Tip Surface Locations (specimen FPB6-9)

Both estimated and actual locations are indicated. For clarity only every third estimated data point is shown. Note how the estimated surface position becomes increasingly offset from the actual as the test progresses due to suspected wear of the positioning nut

6.2.4.3 Crack Profile Accuracy

As the estimated crack profiles from the calibration in Chapter 4 are based upon the predicted values of surface length and depth, any inaccuracies in these quantities will propagate into the crack profile calculation. Therefore the suggested improvements discussed in the next section will provide better results for the estimated crack profiles.

6.2.5 Areas for Improvement

There are several areas where refinements to the mobile DCPD test rig and data acquisition techniques will result in improvements to the accuracy of the crack depth and surface point measurements.

It is believed that the largest contribution to the scatter in the crack depth estimations is the increase in the potential gradients in the vicinity of the crack plane that occur with increasing crack depth. The larger gradients in this region result in an extremely high sensitivity of the crack depth calibration to small changes in the probe positioning relative to the crack plane. This error is compounded by the fact that the fatigue crack tends to grow out of the central plane of the probes as a test progresses. It is felt that the only way to compensate for this source of error is to increase the PD sensing and excitation probe spacing sufficiently such that they are in a region of reduced potential gradients. Although this will reduce the overall sensitivity to increases in crack depth, the expected increase in accuracy possible will be worthwhile.

It is suspected that a portion of the crack depth error is a result of time varying temperature effects. The electrical resistivity variation of the specimen material with ambient temperature changes during the course of a test creates a fluctuation of the voltages measured with time. This is illustrated in the a_{err} vs N curves measured at the three notch centres for specimen FPB6-9, Figure 6.42. It is believed that this effect can be compensated for through implementation of a fixed four probe reference array as was mentioned in section 3.3.1.1. Prior to taking a set of data readings with the mobile probe arrangement, the reference probe set could be sampled and the voltages used to correct the NPD values. This refinement will be implemented for future tests.

Cumulative probe positioning errors (discussed in section 6.2.4.2) are believed to be related to wear of the Teflon nut used in the positioning carriage. Upon conclusion of the final test of the current program it was noted that the position of the probe array was over a millimetre further back from its initial reference starting position. This gives the impression that the cracks are shifted by an offset distance as illustrated in Figure 6.41. This effect will be corrected through the use of a brass nut in a redesigned DCPD rig to be used in future testing.

A relatively minor source of error in the potential drop estimations is a result of the variation in contact resistance that occurs at the probe/specimen surface interface. The build-up over time of oxide and dirt result in an increase in the potential drop

measured due to greater contact resistance. Currently this is reduced as much as possible by keeping the specimen surface coated in WD40.

Figure 6.42 Areas for Improvement - a vs N

Estimated and actual (a vs N) data measured at each of the notch centres for specimen FPB6-9. Note the similar fluctuations in the estimated data that occur for all three notches. This is attributed to temperature effects.

Finally, the use of a higher current level input would provide increased sensitivity for the overall system. Although one of the primary benefits of the localized DCPD method is the reduced current input required, it is felt that a mere doubling of the excitation current to approximately five amperes would result in a significant increase in the sensitivity of the system. As the current source used in this experimental program is integrated into the MDT data acquisition system, an external one would be required to interface with the MDT unit for current pulsing timing purposes. Modifications of this type would be expensive and this final recommendation would have to be thoroughly considered. In addition, it should be noted that to take advantage of any increased sensitivity due to a larger input current, the previously mentioned sources of error would have to be significantly reduced through the suggested modifications.

6.3 Discussion of Results

6.3.1 Crack Growth Rates, SIFs and the Paris Law Constants

Crack growth rates in the depth direction, da/dN , and the surface direction, dc/dN , were calculated from the a vs N and c vs N data respectively using the secant method. The crack depth, a , and half surface length, c , values were taken from beachmark profile measurements. The estimated crack profile parameters from the DCPD probe arrangement were not used in this calculation due to the previously mentioned inaccuracies discussed in Section 6.2.4. The secant method was chosen over the seven point incremental polynomial method suggested in ASTM E647 {77} because of the loss of six data points (initial 3 and final 3) that occurs when using this method. With relatively few beachmarks available, the number of growth rate data points generated would be too few to be useful.

The stress intensity factor (SIF) ranges, ΔK , were calculated using the equations of Newman and Raju {14}. This SIF solution is based on a series of curvefits to SIF results obtained from an in-depth series of three-dimensional finite element analyses of semi-elliptical cracks in finite elastic plates subjected to tension and bending.

6.3.1.1 Depth Direction.

Growth rate and SIF results in the depth direction for all specimens have been plotted as $\log da/dN$ vs $\log \Delta K_a$ in Figure 6.43. The values of the Paris constants C and m obtained from a least squares linear regression through the data are :

$$C_a = 2.51 \times 10^{-11} \quad \text{for } \Delta K_a \text{ in [MPa}\sqrt{\text{m}}]$$

$$m = 3.96 \quad \text{and } da/dN \text{ in [m/cycle]}$$

Figure 6.43 da/dN vs ΔK_a

Data is for all test specimens. Crack growth rate, da/dN calculated using the secant method and crack depth measurements taken from beachmarks. ΔK_a values obtained using the relations of Newman and Raju [14]. Each symbol denotes individual specimen test results.

It is clear that in order to predict crack growth rates and hence the life of a component undergoing fatigue accurately, values of these growth rate constants for the material of interest must be available.

The values of C and m obtained by various researchers for a similar steel as was used in the current program are presented in Table 6.4 below.

Table 6.4 Paris Law Growth Constants

values of C and m are for ΔK in $\text{MPa}\sqrt{\text{m}}$ and da/dN in m/cycle

Reference	Specimen and Loading	R	C	m
current study	surface crack - four point bend	0.05	2.5×10^{-13}	4
Lambert and Bell {80}	edge crack - four point bend	0.1	2.4×10^{-13}	4
		0.5	6×10^{-12}	3
Morgan and Thorpe {81}	SEN	-1 - 0.85	3.26×10^{-12}	3.27
McFadyen et al {51}	surface crack - four point bend	0.02 - 0.1	8.36×10^{-12}	2.5
McFadyen {82}	surface crack - four point bend		2.9×10^{-12}	3
Morgan {35}	surface crack - four point bend	0.1	2.2×10^{-13}	3.96

From the above Table, the results from the current program are in excellent agreement with those of Lambert and Bell{80} and Morgan{35} for a similar steel and stress ratio. The relatively wide range of values obtained for the Paris growth constants for the same material indicates the dependence of growth rates on other parameters besides the applied SIF range as in the case of the Paris Law (eq. (2.5)). As discussed in Chapter 2, experimental data exists that indicates the relationship that the stress ratio, R ($R = \sigma_{\min}/\sigma_{\max}$), has on the crack growth rates and hence the values of C and m .

Lambert and Bell {80} noted distinctly different values for the growth rate constants for tests carried out at two different stress ratios. Using tensile fatigue results for a 6063-T6 alloy, Srivastava and Garg {21} found that for a given value of ΔK the value of ΔK_{eff} increased with R , where ΔK_{eff} is the effective stress intensity factor range given by :

$$\Delta K_{\text{eff}} = \frac{1 - (\frac{\sigma_{\text{op}}}{\sigma_{\text{max}}})}{1 - R} \Delta K_{\text{app}} \quad (6.2)$$

and σ_{op} is the stress required to open the crack, σ_{max} is the maximum applied stress and ΔK_{app} is the applied SIF range.

Shih and Wei {23} determined that a partial effect of the stress ratio on the growth rates was due to closure effects. However they noted that no closure occurred in their specimens for R ratios greater than 0.3 even though there was still a noticeable although diminished effect of stress ratio for tests carried out above this level.

The above results indicate that for accurately predicting fatigue life using the Paris Law, growth rate constants should be sought out for both the appropriate material and stress ratio the specimen or component is subjected to.

6.3.1.2 Surface Direction

Values of the crack growth rate constants in the surface direction were calculated in a similar fashion from the $\log dc/dN$ vs $\log \Delta K_c$ graph of Figure 6.44 to be :

$$C_c = 4.77 \times 10^{-13} \quad \text{for } \Delta K_c \text{ in [MPa}\sqrt{\text{m}}]$$

$$m = 3.76 \quad \text{and } dc/dN \text{ in [m/cycle]}$$

Figure 6.44 dc/dN vs ΔK_c

Data is for all test specimens. Crack growth rate, dc/dN calculated using the secant method and crack surface length measurements taken from beachmarks. ΔK_c values obtained using the relations of Newman and Raju [14]. Each symbol denotes individual specimen test results.

The slight reduction in the surface direction growth rate exponent, m , relative to that obtained in the depth direction is attributed to the change in stress state from plane strain to plane stress that occurs at the surface breaking point. This change in stress state results in slightly reduced surface growth rates causing the crack front to "bow" near the surface. This effect is observable in any of the fracture surface photographs presented in the results section.

Generally, because of the difficulty in calculating growth rates in the surface direction due to the problem in determining the surface points, values of C_c and m are not widely available. Newman and Raju {14} recommended the formula

$$C_c = 0.9^m C_a \quad (6.3)$$

for calculating the growth rate constant in the surface direction. The above equation is used to compensate for the fact that small cracks tend to remain semi-circular under tension and bending loads despite the fact that the SIF at the surface point is approximately ten percent higher than at the deepest point. Although this indicates a value of the growth rate constant to be lower in the case of the surface, the values fit the experimental data well. When using the above formula, the value of the growth rate exponent is generally assumed to be equal for both the surface and depth directions.

6.3.2 Crack Interaction Effects

Prior to the crack coalescence phase, an interaction effect is said to exist between adjacent crack tips for two coplanar cracks. As described in Chapter 2, the ASME section XI {3} and BSI PD 6493 {4} design codes place a very heavy interaction effect between two adjacent cracks that results in the recharacterization into a single crack when the approaching crack tips are still a considerable distance apart.

In the current program the interaction effect was studied by comparing the crack growth rates of the two approaching inner crack tips with those of the outer tips. The crack growth rates were obtained by fitting polynomial curves to the beachmark surface point (c vs N) data and then explicitly differentiating. Values of the growth rate vs the crack tip separation distance, t , are shown in Figure 6.45 for tests performed at various stress ranges.

Note that there is an observable increase in the growth rate that occurs between the two approaching crack tips compared with the outer tips as the separation distance decreases.

On an individual specimen basis, polynomial curves were fit to the growth rate data to further quantify the interaction effect, Figure 6.46.

Figure 6.45 Crack Interaction Effects - Tip Growth Rates

Data is for inner and outer crack tips of coalescing cracks in specimens tested at a variety of stress ranges. Growth rates were calculated using the secant method

Figure 6.46 Crack Interaction Effects - Surface Crack Growth Rates

Curves obtained through polynomial curve fits to c vs N data. Data is for specimen FPB6-6

Using values of growth rates determined at discrete points along the fitted region, values of the SIF at the crack tips were calculated using the previously determined values of C and m (section 6.3.1.2) and the Paris growth law. These values of ΔK were then normalized by using values of SIF for a single crack of the same aspect ratio (a/c) based on the relations of Newman and Raju {14} to obtain an interaction factor, γ , where

$$\gamma = \frac{\text{SIF for an interacting crack}}{\text{SIF for a single crack}} \quad (6.4)$$

Values of this interaction factor for several specimens are presented in Figure 6.47.

Using the body force method, Murakami and Nemat-Nasser {33} studied the interaction between two dissimilar semi-elliptical surface flaws under tension and bending. They presented results for various configurations and shapes and concluded that if the distance between the centres of the cracks exceeds $3c$, ($t/c = 1$), the interaction effect may be neglected. Their results for the case of twin semi-elliptical cracks is in general agreement with the results obtained in the current program, Figure 6.47.

The alternating finite element method has been used by several researchers {34,83} to obtain SIF solutions for interacting coplanar semi-elliptical cracks. The SIF solutions obtained by Heath and Grandt {34} for twin interacting corner cracks along a hole

bore in a plate have been included on Figure 6.47 for comparison with the results from the current program.

Although it is clearly evident that there is an interaction effect present, the increase in SIF determined in the current program is only approximately 10% when the crack tips

Figure 6.47 Interacting Cracks - Interaction factors

are $1/8$ the surface length of the cracks apart. This is clearly not the huge effect built into the design codes.

Another observed indication of the interaction effect is the deviation of two approaching crack tips, Figures 6.48,49, that was observed in all tests prior to the

Figure 6.48 Crack tip deviation of two coalescing cracks specimen FPB6-8

Figure 6.49 Cusp region formed at point of crack tip deviation specimen FPB6-8

coalescence phase. Similar behaviour has been observed by several other researchers studying the growth of multiple surface cracks {39,31,37}.

Melin {37} performed a theoretical analysis of a periodic array of approximately collinear but slightly curved cracks. He showed that the straight crack path is unstable, i.e. that tip to tip coalescence will not take place. It was also assumed that this result holds also for non-periodic arrays such as two originally collinear cracks.

The observed crack tip deviations and their relation to the coalescence process are further discussed in the next section.

6.3.3 Crack Coalescence

For the current program the following conventions have been used to define the beginning and ending stages of the coalescence process :

start of coalescence : the cycle count at which the tips of two adjacent cracks touch a common plane perpendicular to the plane of crack growth

end of coalescence : the cycle count at which the depth at the coalescence point between two coalescing cracks is equal to or greater than the maximum depth of either of the two individual cracks.

A summary of the percentage of total and propagation life consumed during the coalescence process is presented in Table 6.5.

Table 6.5 Coalescence Summary

test #	specimen	coalescing crack #'s	COALESCENCE				
			start x 10 ³ cycles	end x 10 ³ cycles	total x 10 ³ cycles	% of propagation life	% of total life
1	FPB6-1	single notched specimen					
2	FPB6-2	1↔2	240	260	20	8.1	7
3	FPB6-3	1↔2	210	221	11	5	4.3
4	FPB6-4	1↔2	414	464	50	12.1	10
5	FPB6-5	data not available					
6	FPB6-6	1↔2	590	656	66	10.4	8.9
7	FPB6-7	1↔2	475	525	50	10.2	9.1
8	FPB6-8	1↔2	1155	1310	155	13	11.3
		2↔3	1320	1360	40	3.3	2.9
9	FPB6-9	1↔2	1140	1337	197	16.3	14.3
		2↔3	1290	1342	52	4.3	3.8

The average percentage of the total life consumed by the coalescence process is approximately ten percent. The second coalescence phase for the specimens containing three starter notches was observed to consume a considerably smaller (3 - 4 %) percentage of the total specimen life. This behaviour is attributed to the fact that the SIF at the coalescence point is significantly higher due to the presence of a larger crack during the second coalescence phase.

Performing four-point bend fatigue tests on notched specimens of a similar material, Frise {60} reported coalescence periods consuming between thirty and eighty-seven

percent of the total specimen fatigue life. The significantly longer coalescence periods observed by Frise compared with the current program are partially attributed to the substantially smaller starter notch spacing (15 - 31 mm) he used versus the constant 42 mm spacing used in the current program. The shorter starter notch spacing results in the coalescence of relatively smaller cracks. The smaller SIFs associated with these cracks results in decreased growth rates and hence a longer period of time to complete the coalescence process.

Although there exists a large difference in the two sets of experimental results, they both suggest a significantly larger portion of the fatigue life is consumed by the interaction and coalescence processes compared with the instantaneous recharacterization used in the ASME {3} and BSI {4} design codes.

As was mentioned in the previous section, the coalescence process is preceded by an interaction between the approaching crack tips which causes a deviation. It was observed in the current program and by several other researchers {39,31,37} that the cracks will often grow past each other. This results in the formation of a "cusp" region being formed as the crack growth continues on two different planes, Figure 6.49. At a deeper point the cracks join and form into one dominant crack. The remaining ligament in the cusp region would generally fail by ductile tearing caused by increased crack opening displacement. The depth of this cusp region was observed to vary

considerably from less than 5 mm for specimen FPB6-3, Figure 6.10, to greater than 18 mm for specimen FPB6-4, Figure 6.14.

Several researchers have related this crack tip deviation or crack plane mismatch to such parameters as the number of cycles required to complete the coalescence process, Soboyejo et al {39}, or the final coalescence depth, Otegui et al {31}. A plot of the data from the current experimental program, Figure 6.50, reveals no clear relationship

Figure 6.50 Crack Coalescence - Tip Deviation and Cusp Depth

The percent of propagation life refers to that amount consumed by the coalescence process

between the cusp depth and crack tip deviation or the number of cycles consumed during coalescence and the crack tip deviation. It should be noted that the other experimental work mentioned previously contained a significantly wider range of data, especially in the smaller crack region, than was obtained in the current program. Difficulties in accurately measuring crack tip deviations on specimens whose fracture surfaces had already been separated may have also contributed to the lack of any correlation in the data.

The SIFs and related crack growth rates in this cusp region have brought about considerable interest among researchers. The growth rate in the surface direction at the coalescence point was observed to come to a complete halt as the cracks passed each other due to a "shielding" effect. This is observable as a rapid crack profile change in the cusp region, (see Figure 6.26 for example). Contrastingly, the growth in the depth direction at the coalescence point is greatly accelerated. This is evidenced by observing the distance between beachmarks at the coalescence point relative to the same cycle increment at the notch centre, (Figure 6.22). There have been several SIF solutions published for interacting cracks, {33,34,38}, but no easily reusable SIF solution for coalescing coplanar semi-elliptical cracks, Soboyejo et al{39}.

The growth rate at the coalescence point was evaluated by fitting a curve to the beachmark (a_{coal} vs N) data, shown in Figure 6.51 for FPB6-6, and then differentiating in a similar procedure as was performed for the crack tip interaction growth rates.

Figure 6.51 Coalescence (a vs N)

Comparison of growth in depth direction for notch centres and coalescence point for specimen FPB6-6.

A typical growth rate plot comparing the crack depth and surface direction growth rates during the course of a test is presented in Figure 6.52 for specimen FPB6-6.

Note the significant increase in crack growth rate in the cusp region that occurs at the beginning of the coalescence process. It should be noted that no extrapolation of the data was performed outside the available experimental coalescence depth information due to the uncertainty involved.

Figure 6.52 Crack Growth Rates Before, During and After the Coalescence Phase
Data is for specimen FPB6-6

Values of the SIF in the coalescence region were calculated from the growth rate information using the experimentally determined values of C and m (section 6.3.1.1) and the Paris growth law. Typical values of the SIF for the coalescence region and the notch centre point depth are compared in Figure 6.53 for specimen FPB6-6.

Figure 6.53 SIFs at the Coalescence Point

comparison of SIF values at the notch centre and coalescence point as a function of the coalescence depth. Data is for specimen FPB6-6

Note the significant increase in SIF ($\approx 2x$) that occurs at the beginning of the coalescence process. The SIF at the coalescence point then decreases rapidly, as the coalescence process continues, until it matches the SIF at the notch centre at which point the crack becomes nearly straight-fronted.

These values of SIF at the coalescence point were normalized using the SIFs for single cracks to obtain interaction factors, γ , for coalescing cracks where

$$\gamma = \frac{\text{SIF coalescence point}}{\text{SIF single crack at surface point}} \quad (6.5)$$

Soboyejo et al {39} modelled the coalescence region using FEM and determined values of γ for various a/c ratios. These have been included with results for several test specimens for both the interaction and coalescence regions on Figure 6.54. There is general agreement between the data despite the differences in the crack aspect ratios and the fact that the numerical models coalesce tip to tip (ie. do not consider crack plane mismatch).

Figure 6.54 Interaction factors for interacting and coalescing cracks

6.3.4 Crack Shape Development

Typical crack shape development data for double and triple-notched specimens are presented in Figures 6.55 and 6.56 respectively. As discussed in Chapter 2, cracks that are not initially of the preferred or equilibrium shape will tend to grow towards it. This was observed in the current program during the initial stages of crack growth from the starter notch. The low initial aspect ratio of the notch ($a/c \approx 0.22$) resulted in a substantial amount of crack growth in the depth direction before any was noted in the surface direction. A typical example of this behaviour is apparent from the

Figure 6.55 Crack Shape Development for Double-Notched Specimen
Data is for specimen FPB6-7

beachmarked fracture surface of specimen FPB6-6, Figure 6.21. Upon reaching the preferred shape, the aspect ratio then remained approximately constant (0.55-0.58) until the adjacent flaws coalesced causing a sudden drop in aspect ratio due to the increase in surface length. The aspect ratio then remained essentially constant until specimen failure occurred. Similar behaviour was noted for the triple-notched specimens except there were two drops in aspect ratio due to the two separate coalescence phases.

Figure 6.56 Crack Shape Development for Triple-Notched Specimen
Data is for specimen FPB6-9

Some of the experimental crack shape development results from the current program were used by Zhang {84} to aid in the development of several fatigue crack growth models. The interaction, kSC1 and kSC2 models developed by Zhang incorporate the coalescence process as a stable portion of crack growth and not the instantaneous recharacterization used in the Iida model {45} or prescribed in the ASME and BSI design codes. Several crack shape development models are presented in Figures 6.57 and 6.58 with the experimental results of specimen FPB6-6 for comparison.

Figure 6.57 Crack Shape Development Models

Figure 6.58 Crack Shape Development Models

Both the Iida SC1 “natural” crack growth model and the SC2 constant aspect ratio model show excellent agreement with the observed experimental results. The SC1 models the changes in aspect ratio more accurately however the coalescence depth predicted using this model is shallower than that predicted by the SC2 model or observed during testing.

The interaction and kSC1 models exhibit very similar characteristics and both are observed to show excellent agreement with the experimental results, Figure 6.58. The deeper observed coalescence depth is more accurately predicted by these models than either of the two Iida models. This is attributed to the fact that coalescence is treated as a stable crack growth process which allows for further crack growth in the depth direction to occur before the coalescence process is complete.

The previous discussion reinforces the fact that experimental studies of this type are required to aid in the development, refinement and verification of fatigue crack growth models. It is only with accurate predictive models are we able to better understand the process of fatigue and its impact on the safe design life of engineering structures.

Chapter 7

Conclusions and Recommendations

7.1 Conclusions

Based on the objectives outlined in Section 1.2 and the results of the current program discussed in the previous chapter, the following conclusions can be made :

1. A mobile DCPD probe arrangement has been developed which has the capability of providing the detailed crack profile information necessary for crack shape development and coalescence studies. The high accuracy achievable for locating the crack surface breaking points with this novel arrangement offers the ability to study surface crack growth rates and interaction effects. Previously the use of widely spaced fixed probe arrangements could not provide data of this type. It should be noted however that several refinements to the design of this crack sizing system are necessary to fully realize the potential of this piece of equipment.

2. The three-dimensional boundary element method was found to be an effective technique for providing crack profile calibration information for the localized DCPD method of crack measurement. The NPD results obtained using this technique were in excellent agreement with those obtained experimentally for the *standard* probe arrangement. An experimental technique was used successfully to determine the surface breaking point and crack profile calibrations for values of NPD obtained using the *staggered* probe arrangement.
3. An experimental fatigue crack coalescence study was carried out using nine flat plate specimens subjected to constant amplitude four-point-bend loading for a variety of applied stress ranges. The coalescence period was observed to consume approximately ten percent of the total life of the specimen for the starter notch geometry and spacing used. This may be contrasted with the extremely conservative recharacterization guidelines set forth in the ASME {3} and BSI {4} design codes.
4. A small interaction effect between approaching crack tips was observed as an increase in the growth rate just prior to the start of the coalescence process. This was quantified to correspond to an approximately fifteen percent increase in the stress intensity factor, over that of a single crack, for a tip spacing to surface half-length ratio (t_s/c) of 0.1.

5. Stress intensity factors at the coalescence point were determined from growth rate information extracted from crack depth data in the cusp region. The peak SIF at a cusp depth of 2 mm was found to be approximately twice that of the deepest point of the two coalescing cracks. This value was seen to decrease quickly with increasing cusp depth until the coalescence process was complete. The experimental data obtained was found to be in general agreement with the numerical results of several other researchers {33,34,39}
6. The observed crack shape development was found to correspond with the expected preferred propagation path described by several crack growth models. In particular the Iida {45} model using natural crack growth was found to show excellent agreement with the experimental data both before and after the coalescence process.

7.2 Recommendations for Future Work

The following recommendations are made with respect to future work carried out in this area :

1. To take full advantage of the capabilities of the mobile DCPD probe arrangement, the recommendations laid out in Chapter 6 (section 6.2.5) should be implemented for use in future work. It is felt that these design modifications will significantly

improve the accuracy of the crack shape development information obtainable with this equipment.

2. The three-dimensional boundary element software, used for the calibration of the standard probe arrangement, should be modified to handle sub-regions. With this capability, the boundary conditions for the *staggered* probe arrangement could be modelled and a calibration obtained.
3. The calibration for the mobile probe arrangement could be advanced to include full crack profile development in the coalescence region. This calibration could take the form of a combined numerical/experimental method as was used in the current program.

With the increased knowledge of the coalescence and shape development process generated from research such as in the current program, more accurate modelling of fatigue crack growth can be performed. The improved modelling made possible by research of this type will allow for the safer, more efficient design of structural components.

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