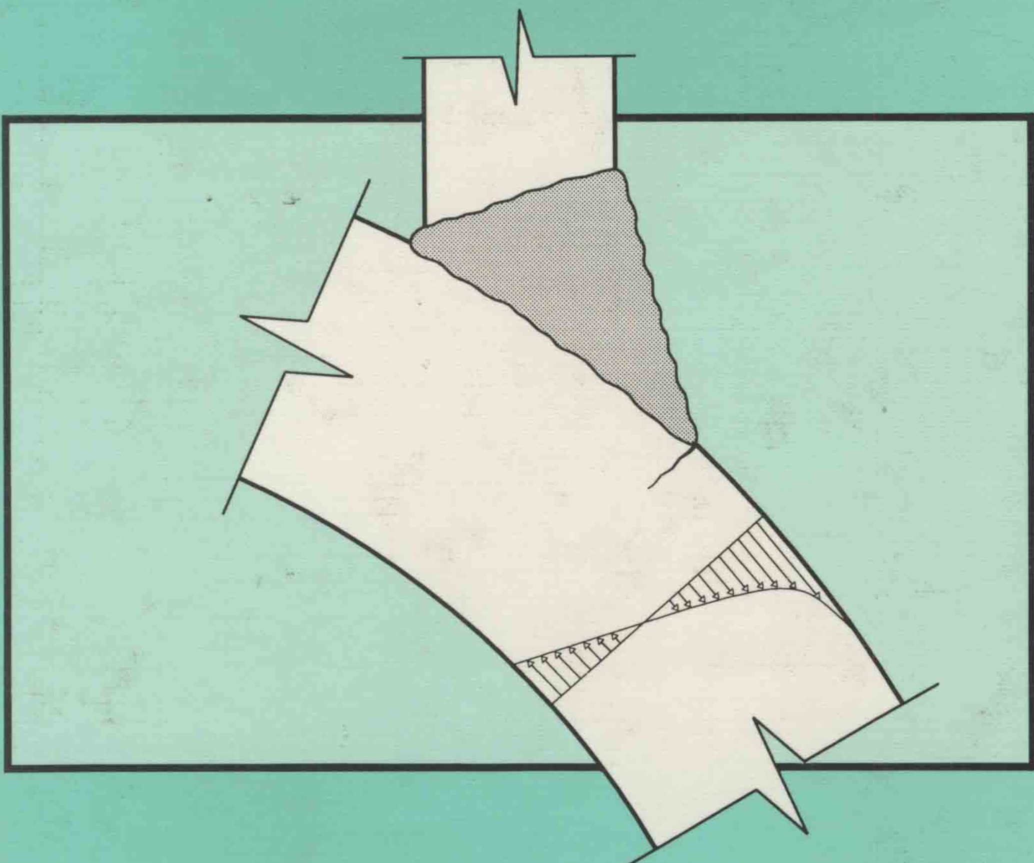
Early Fatigue Crack Growth at Welds

C.C. Monahan



Computational Mechanics Publications
Southampton UK and Boston USA

Series Editors
C.A. Brebbia and J.J. Connor

Author
C.C. Monahan
NDE Centre
Department of Mechanical Engineering
University College London
UK

Published by

Computational Mechanics Publications
Ashurst Lodge, Ashurst, Southampton, SO40 7AA, UK
Tel: 44 (0)1703 293223 Fax: 44 (0)1703 292853
Email: CMI@uk.ac.rl.ib
Intl Email: CMI@ib.rl.ac.uk

For USA, Canada and Mexico

Computational Mechanics Inc
25 Bridge Street, Billerica, MA 01821, USA
Tel: 508 667 5841 Fax: 508 667 7582

British Library Cataloguing-in-Publication Data

A Catalogue record for this book is available
from the British Library

ISBN 1-85312-364-1 Computational Mechanics Publications, Southampton
ISBN 1-56252-288-4 Computational Mechanics Publications, Boston
ISSN 0952-5300 Series

Library of Congress Catalog Card Number 95-67469

Printed in Great Britain by Antony Rowe Ltd, Chippenham

PREFACE

This book addresses the problems associated with monitoring and predicting the early stages of fatigue crack growth in welded steel components. It comprises postgraduate level research that should be of great practical value to engineers and material scientists working in the fields of fracture mechanics and/or non-destructive testing. Novel approaches for overcoming experimental and theoretical difficulties are described in detail. Although the emphasis is on early fatigue crack growth in welded tubular joints, the same principles and theory may be applied to a variety of component geometries.

The term "early fatigue crack growth" has been adopted to represent the first 15-20% of fatigue crack propagation through the wall thickness of a welded component. Fabrication defects such as undercuts and slag inclusions are thought to abolish the presence of a crack initiation stage in welded steel joints. It is for this reason that factors influencing fatigue crack initiation have largely been ignored.

Each chapter begins with a brief overview of the subject matter to help the reader conceptualise the objectives. Headings and subheadings are used throughout the text to divide the material into logical parts and to emphasise the major elements and considerations. The text is also supported by more than a hundred original tables and figures, many of which took several hours to produce.

I would like to express sincere thanks to Professor W.D. Dover for providing me with the unique opportunity to undertake this study, to Mr. Keith Blenkinsopp for fabricating many of the fatigue test frames and other important pieces of equipment used in the investigation, and to my wife, Jill, for her patience and support while this book was being written.

CONTENTS

CHAPTER ONE

INTRODUCTION

1.1 Overview

Small fabrication defects (e.g. under-cuts and slag intrusions) are known to be present in welded joints. In-service loading conditions may favour the growth of these initial flaws into semi-elliptical surface fatigue cracks. Once a surface fatigue crack is present, it can grow until complete separation of the joint has occurred. In practice, this problem is controlled with the aid of sophisticated crack detection and sizing equipment. Planned periodic inspections of critically stressed joints are carried out to prevent catastrophic failures from occurring and ensure that the integrity of the component is maintained throughout its useful lifetime. The time interval between inspections depends on the ability of non-destructive testing (NDT) technologies to reliably detect and size small surface breaking fatigue cracks, and on the accuracy with which their subsequent growth can be predicted. As progress is made in each of these areas, inspection intervals can be increased and considerable savings realised by those responsible for the safe operation of welded structures.

The need for dependable information on defect size and location has prompted the initiation of several important studies aimed at quantifying the reliability of different NDT techniques for the detection and sizing of surface breaking fatigue cracks. Many of the research projects conducted by the NDE Centre at University College London are concerned with providing industry with information on the probability of detection (POD) and probability of sizing (POS) for different types of NDT equipment. The generation of POD and POS curves for welded joints requires that a large number of fatigue cracked samples be made available for inspection trials. Welded specimens (especially large scale tubular joints) are expensive to manufacture and difficult to test. In the process of generating these samples, it is often possible to collect detailed fatigue crack growth information with little additional effort. The only disadvantages are that the experiment must be stopped when the crack reaches a pre-determined size, and destructive sectioning to verify the final defect size is not always done. These restrictions apply to many of the fatigue cracks analysed in this study.

The fatigue crack growth problem in welded structures is a difficult topic for laboratory research, offering unique inter-disciplinary challenges to engineers, material scientists, computer scientists, electrochemists and mathematicians alike. No single study could be expected to provide all the answers necessary for a complete understanding of the fatigue crack growth process. This book is primarily concerned with the early stages of fatigue crack growth in welded offshore structures, for the case of constant amplitude loading in air. Once this case is understood, it may be possible (in future studies) to evaluate the modifying influences of other important variables such as corrosion, cathodic protection and variable amplitude loading.

Previous studies concerned with the fatigue behaviour of welded structures have tended to concentrate on the behaviour of relatively large (>3mm deep) fatigue cracks. The initial stages of crack growth were often neglected in these early studies because of experimental difficulties associated with the detection and sizing of small (<3mm deep) surface fatigue cracks. Recent advances in NDT have now made it possible to detect and size small surface fatigue cracks much more accurately. In this study, a special effort has been made to obtain detailed experimental data for the purpose of improving our current understanding of the early fatigue crack growth problem in welded joints.

This chapter begins with an introduction to linear elastic and elastic plastic fracture mechanics concepts, with particular attention being paid to small fatigue cracks. The important mechanical variables thought to influence the early fatigue crack growth behaviour of welded joints are identified and discussed. The NDT techniques used in this study for small fatigue crack detection and sizing are also described, and the advantages and disadvantages associated with each method are pointed out. The objectives and scope of the present study are then given.

1.2 Linear Elastic Fracture Mechanics

In the analysis of stresses near the tip of a sharp crack (where a stress singularity is presumed to exist) the concept of using elastic stress concentration factors breaks down. Linear elastic fracture mechanics (LEFM) manages to overcome this problem by analysing the stress field surrounding the crack tip, rather than the infinite stress in this region. Cracked components may be stressed in one or more of the following modes:

Mode I	- tension, normal to the crack faces (opening mode)
Mode II	- shear, normal to the crack front (edge sliding mode)
Mode III	- shear, parallel to the crack front (tearing mode)

Mode I is the predominant stress situation in most practical cases. Modes II and III tend to be less significant and their contributions to fatigue crack growth can often be ignored.

The parameter which has been adopted to describe the elastic stress field in a cracked structure is called the crack tip stress intensity factor K. The value of K depends on the applied stress field, the size and shape of the crack, and the geometry of the cracked component. For the case of mode I loading, it is typically expressed in the form

$$K_I = Y \, \sigma_{n_o} \sqrt{\pi a} \tag{1.1}$$

where σ_{n_o} is the nominal surface stress, a is the crack depth and Y accounts for the effects of crack shape and component geometry.

Provided K is the same for two different cracks, the stress fields near both crack tips will be identical and both cracks should behave similarly. It is for this reason that K can be used to describe the residual strength of a cracked body. When the load is increased on a cracked component, the level of stress intensity at which the crack begins to propagate is called the fracture toughness of the material. For relatively thick materials in which conditions of plane strain develop, this critical value of K is considered to be a material property and is designated K_{I_c}. For thinner materials, where toughness depends on thickness and developed plasticity, it is denoted as K_c. An important limitation of LEFM is that it can only be used to characterise crack growth under conditions of small scale yielding. If the theory is to remain valid, plastic deformation must be confined to a region in front of the advancing crack tip, called the crack tip plastic zone. The size of the crack tip plastic zone should remain small in relation to the dimensions of the crack and the uncracked ligament.

In the analysis of fatigue crack growth, where stresses are cyclic in nature, it becomes necessary to define a linear elastic crack tip stress intensity factor range,

$$\Delta K = K_{max} - K_{min} \tag{1.2}$$

where K_{max} and K_{min} are the maximum and minimum mode I stress intensity factors in the cycle. Equation (1.1) then takes the form

$$\Delta K = Y \, \Delta\sigma_{n_o} \sqrt{\pi a} \tag{1.3}$$

where $\Delta\sigma_{n_o} = \sigma_{no}^{max} - \sigma_{no}^{min}$ is the nominal surface stress range. Note that the mode I subscript has been dropped from these expressions. This is done for convenience. In cases where the subscript is missing, it is always assumed that mode I is being considered.

When crack growth rate (da/dN) data from a fatigue experiment are plotted against ΔK on a log-log scale, the curve exhibits a sigmoidal shape with three distinct regions (see figure 1.1). In region one, the crack growth rate goes asymptotically to zero as ΔK approaches a threshold value (ΔK_{th}). This means that for stress intensities below ΔK_{th} there is no crack growth, i.e. there is a fatigue limit. The threshold effect is believed to be caused by a number of different processes which lead to crack blocking for small stress intensities. In region two, the log of da/dN tends to vary linearly with respect to the log of ΔK. The crack growth rate (da/dN) during this portion of the propagation stage has been successfully related to ΔK by the Paris-Erdogan [1.1] equation

$$\frac{da}{dN} = C \cdot \Delta K^{m} \tag{1.4}$$

where a is crack depth, N is the number of cycles, and C and m are material and environment dependant constants that must be determined empirically. In welded offshore structures, the early stages of fatigue crack growth are most likely to occur in regions one and two. During the transition from region two to region three, the crack growth rate accelerates dramatically as K_{max} approaches K_{I_c}.

1.3 The Anomalous Behaviour of Short Fatigue Cracks

Over the past two decades, ΔK has been used to correlate long fatigue crack propagation data in a variety of engineering materials and structural geometries. Despite its success in applications that concern long cracks, the suitability of LEFM for predicting the early stages of fatigue crack growth in notched components such as welded joints remains questionable. A major complication associated with modelling small fatigue cracks in welded joints is the likelihood of plasticity occurring in the blunt notch of the weld toe. The size of the notch plastic zone will depend on the geometry of the welded joint and the degree of in-service loading to which the structure is subjected. When the crack is short and its tip is contained within the notch plastic zone (see figure 1.2), the small scale yielding requirement of LEFM becomes violated. Fatigue cracks that propagate under conditions of gross plastic deformation generally grow at rates faster than LEFM would predict. As these cracks extend beyond the field of plastic deformation and into the elastic domain of the structure, their growth rates eventually merge with LEFM predictions [1.2].

Some investigators have tried to rationalise the anomalous growth behaviour of short fatigue cracks in plastic strain fields by providing plasticity corrections to ΔK, while others have resorted to elastic plastic fracture mechanics (EPFM) concepts. Before proceeding to discuss each of these approaches in detail, it is appropriate to identify the factors which contribute to the anomalous behaviour of short fatigue cracks and single out those which apply to welded components. It is also necessary to establish a clear distinction between short and long fatigue cracks. This is best done by introducing a set of definitions that are based on local stress and strain considerations as well as physical crack size.

A fatigue crack is considered to be "microstructurally short" when its depth is comparable to some microstructural dimension such as the grain size. Cracks of this size exhibit what has been referred to as a "free surface" effect [1.3]. Material at the surface is less constrained than material below the surface and tends to flow more freely. This results in vastly different fatigue behaviour for a crack growing from a free surface than for a crack growing within the bulk. Microstructurally short fatigue cracks can, for example, propagate below the threshold intensity range established for long cracks [1.4]. Interactions with microstructural barriers such as grain boundaries can also influence fatigue behaviour when the crack is on the order of the grain size [1.5]. The growth rates of microstructurally short fatigue cracks are initially high and decelerate to a minimum as ΔK increases [1.6]. Depending on the applied stress field and crack tip-grain boundary interactions, their growth may stop completely (curve A of figure 1.3), or accelerate to match that of long cracks growing at the same ΔK (curve B of figure 1.3). Free surface and grain boundary effects are thought to die out once the crack extends through a few grains of the material [1.3]. For fine-grained structural steels, this typically corresponds to a crack depth of about 0.1mm.

Once beyond the influence of the free surface, short fatigue cracks may continue to exhibit anomalous behaviour if the applied stress and component geometry are such that the crack tip plastic zone is contained within a larger region of plasticity caused, for example, by the presence of a notch. Fatigue cracks that fall into this category are said to be "physically short." The occurrence of large scale plastic strains leads to growth rates that are significantly faster than LEFM would predict based on stress field considerations alone (curves C & D of figure 1.3). A transition to long fatigue crack growth behaviour (curve E of figure 1.3) occurs once the tip of the crack extends beyond the plastic zone of the notch [1.7]. The depth of the crack at this stage will depend on the severity of the stress concentration caused by the notch, material properties, and the level of remote stress applied to the component. The growth rate trends for physically short cracks also appear to be sensitive to notch geometry [1.8]. Cracks initiating from sharp notches generally exhibit a decelerating, then accelerating pattern similar to that observed for short cracks growing from smooth surfaces, except the trend can occur at much higher levels of ΔK (curve C of figure 1.3). Cracks which grow from blunt notches tend to display a steadily increasing growth rate trend (curve D of figure 1.3).

Since welded components are known to contain sharp fabrication defects with depths on the order of the free surface effect [1.9], the growth behaviour of microstructurally short fatigue cracks is of little importance in studies concerning the fatigue behaviour of welded structures. Crack growth will most often begin in the physically short regime, and the fatigue life will depend on the time it takes to propagate a physically short crack to a critical size.

1.4 Elastic-plastic Fracture Mechanics for Short Fatigue Cracks

1.4.1 Crack Tip Plastic Strain Range

An ability to characterise strain-controlled fatigue crack growth is inherent to the plastic shear decohesion model proposed by Tomkins [1.10] to describe fatigue crack propagation in regions of low or high stress. Tomkins considered crack extension to take place when a new crack surface formed as a consequence of irreversible plastic flow (decohesion) along the inner edges of two narrow shear bands of length D, positioned on ±45° planes immediately in front of the crack tip (see figure 1.4). He suggested that the crack growth rate is given by

$$\frac{da}{dN} = \Delta\varepsilon_p \cdot D \tag{1.5}$$

where $\Delta\varepsilon_p$ is the plastic strain range in the vicinity of the crack tip and D is a measure of the plastic zone size (which is crack depth dependant). The analysis requires a method for calculating $\Delta\varepsilon_p$ that takes into account the cyclic stress-strain behaviour of the material. Shin *et al* [1.11] assume that $\Delta\varepsilon_p$ is approximately given by half the plastic strain range at the crack tip position and use the finite element method to estimate this quantity.

1.4.2 Total Shear Deformation Parameter

Hammouda *et al* [1.12] consider fatigue crack growth to be controlled by the total shear deformation ($\emptyset_t$) occurring near the crack tip. When the crack tip is embedded in the plastic field of a notch, $\emptyset_t$ is made up of shear deformation due to notch plasticity ($\emptyset_p$) and shear deformation due to crack tip plasticity ($\emptyset_e$). As the fatigue crack propagates through the notch plastic zone, $\emptyset_p$ decreases while $\emptyset_e$ increases. Once the crack tip passes the elastic-plastic boundary of the notch stress-strain field, $\emptyset_p$ is zero and the fatigue process is under crack tip plasticity control ($\emptyset_t = \emptyset_e$). It is suggested that a linear elastic fracture mechanics analysis of the crack tip opening displacement can be used to determine $\emptyset_e$, while $\emptyset_p$ can be obtained by summing the shear deformation between the crack tip position and the boundary of the notch plastic zone for an uncracked specimen.

1.4.3 Modified Stress Intensity Factor

In order to account for the influence of large scale plasticity on fatigue crack growth behaviour in notched steel plates, Gowda and Topper [1.13] defined a modified stress intensity factor range,

$$\Delta K' = \Delta K \sqrt{1 + \frac{\Delta e_p^N}{\Delta e_e^N}} \tag{1.6}$$

where ΔK is the range of the linear elastic stress intensity factor, and Δe_e^N and Δe_p^N are the net section elastic and plastic strain ranges, respectively, obtained from a cyclic stress-strain curve for the material of interest. The derivation of this expression is founded on Neuber's hypothesis that an approximate relation, similar to the one he proposed between stress and strain concentration factors in notches, exists between the stress and strain intensities at a crack tip [1.14, 1.15].

1.4.4 Strain Based Intensity Factor

El Haddad *et al* [1.16,1.17] recommend that the growth rates of physically short surface fatigue cracks be correlated using a strain based intensity factor of the form

$$\Delta K_\varepsilon = E\,\Delta\varepsilon \sqrt{\pi(a + a_c)} \tag{1.7}$$

where E is the modulus of elasticity, $\Delta\varepsilon$ is the local strain range near the crack tip, a is the crack depth, and a_c is an empirical crack length correction factor introduced to compensate for the "free surface effect" discussed in section 1.2. It is suggested that estimates of $\Delta\varepsilon$ corresponding to different ranges of applied nominal stress may be obtained from elastic-plastic finite element models, or from Neuber's rule [1.15] combined with cyclic stress-strain data for the material of interest.

1.4.5 Cyclic J Integral

The J integral (J) was first introduced by Rice [1.18] to provide a means of determining energy release rates for cracks contained in non-linear elastic solids. In the planar case (see figure 1.5), J is defined as

$$J = \int_{\Gamma} \left(W\, dy - \underline{T} \frac{\partial \underline{u}}{\partial x}\, ds \right) \tag{1.8}$$

where Γ is a closed contour surrounding the crack tip, W is the strain energy density per unit volume, $\underline{T}$ is a traction vector, $\underline{u}$ is a displacement vector, and ds is an increment along Γ. When J is applied around a crack tip, from one crack surface to the other, the value obtained is independent of the path which is taken. This path independence allows J to be calculated along a contour remote from the crack tip, for which the loads and displacements may be known.

Rice [1.18] managed to show that J, as defined above, can be interpreted as the change in potential energy per unit crack extension. That is,

$$J = -\frac{1}{t}\left(\frac{dE_p}{da}\right) \tag{1.9}$$

where E_p is the stored mechanical energy of a component under load containing a crack of length a, and t is the plate thickness. The physical interpretation of J as an energy release rate makes it possible to determine J from load-deflection curves for a number of specimens containing cracks of different lengths [1.19]. For example, if two specimens of similar geometry containing cracks of slightly different length are loaded to the same displacement (δ_l), the area between their load-deflection curves will correspond to their difference in stored energy, E_p (see figure 1.6). If the difference in crack length is known, calculation of J is straightforward. For certain specimen configurations (deeply notched compact tension and bend bar specimens), an approximation is available which allows J to be determined from a single load versus displacement curve [1.20]. For more complicated specimen geometries and actual components, it is generally necessary to use equation (1.8) in a finite element model in order to obtain estimates of J.

For elastic-plastic materials such as steel, the quantity E_p does not represent stored potential energy. Instead, it is a measure of the total amount of work (elastic and plastic) that is needed to deflect the specimen. Since the plastic work energy is unrecoverable, J loses its physical interpretation as an energy release rate. However, it has been suggested that J retains physical significance as a measure of the intensity of the crack tip strain field up to the beginning of crack extension, and it is this interpretation which accounts for its success as a geometry independent static fracture toughness criterion for metals subjected to elastic-plastic conditions [1.21].

Physical justification for the application of J to fatigue loading is more difficult to give. The path-independence of J only holds for non-linear elastic behaviour, where the stress-strain response for unloading is the same as for loading. Since, during each complete fatigue cycle, the material at the crack tip experiences reverse plastic deformation, one of the key assumptions surrounding the mathematical derivation of the *J* integral is clearly violated. Despite this limitation, several investigators [1.22-1.28] have attempted to correlate fatigue crack growth rates using a cyclic J integral (ΔJ) and have met with considerable success. Paris [1.29] has suggested the reason for the apparent success of ΔJ may be that material deformations which occur during unloading are insignificant compared to those which occur during loading. The implication is that *J* defines the stress-strain field near the crack tip during the rising portion of the cycle, despite intermittent unloading. Leis and Zahoor [1.30] disagree with this view. These researchers are of the opinion that many of these preliminary test results represent select experimental conditions where the influence of history dependent residual stresses and transient material response on *J* determination have not needed consideration. They conclude that additional analytical and experimental studies are required to evaluate the uniqueness and utility of ΔJ as a characterising parameter for fatigue crack growth in real structures.

1.4.6 Change in Crack Tip Opening Displacement

The presence of a stress singularity near the tip of a sharp crack means that plastic deformation occurs in the crack tip region immediately upon application of a tensile load. The crack opening displacement at a location close to the crack tip provides a unique measure of this localised plastic strain. Use of the crack tip opening displacement (*CTOD*) as an elastic-plastic fracture criterion for engineering materials subjected to monotonic loading was first proposed by Wells [1.31]. Wells suggested that fracture occurs once the crack tip plastic strain, and hence the *CTOD*, exceeds a critical value that is characteristic of the material containing the crack.

Using the Dugdale strip yield model [1.32] for the crack tip plastic zone, Burdekin and Stone [1.33] developed an expression for the *CTOD* in an infinite centre cracked plate subjected to a uniform tensile stress, σ. The result is

$$CTOD = \frac{8\sigma_y a}{\pi E} \ln \sec\left(\frac{\pi\sigma}{2\sigma_y}\right) \tag{1.10}$$

where a is half the crack length, σ_y is the yield stress and E is the modulus of elasticity. Implicit to the derivation of this expression, were the assumptions of a state of plane stress and elastic-perfectly plastic material behaviour.

If LEFM conditions prevail (i.e. if $\sigma \ll \sigma_y$), the *ln sec* expression in equation (1.10) can be expanded as a series to give

$$CTOD = \frac{8\sigma_y a}{\pi E}\left(\frac{1}{2}\left(\frac{\pi\sigma}{2\sigma_y}\right)^2 + \frac{1}{12}\left(\frac{\pi\sigma}{2\sigma_y}\right)^4 + \frac{1}{45}\left(\frac{\pi\sigma}{2\sigma_y}\right)^6 + \dots\right). \tag{1.11}$$

If all terms in the series beyond the first are neglected, the above expression reduces to

$$CTOD = \frac{\pi\sigma^2 a}{E\sigma_y} . \tag{1.12}$$

Since an assumption of linear elastic behaviour has been invoked, the terms $\pi\sigma^2 a$ in equation (1.12) may be replaced by K^2 to arrive at

$$CTOD = \frac{K^2}{E\sigma_y} . \tag{1.13}$$

Thus, under conditions of small scale yielding, there is a direct relationship between the crack tip opening displacement *CTOD* and the crack tip stress intensity factor *K*.

If the material is in a state of plane strain, equation (1.13) needs to be modified to include Poisson's ratio (ν) and a plastic constraint factor (C_p) such that

$$CTOD = \frac{K^2(1-\nu^2)}{C_p E\sigma_y} . \tag{1.14}$$

The value of C_p in the above expression is most often taken to be 2 [1.34], but will vary depending on component geometry.

Additional modifications to equation (1.14) are necessary if it is to be applied to a fatigue crack: *K* needs to be replaced by ΔK, and σ_y by $2\sigma_{yc}$, where σ_{yc} is the cyclic yield stress (refer to section 1.5.3 for an explanation of cyclic stress-strain behaviour). Multiplying the cyclic yield stress by a factor of two accounts for the influence of the residual compressive stress field that surrounds the crack tip each time the component is unloaded [1.35]. The resulting expression is

$$\Delta CTOD = \frac{\Delta K^2(1-\nu^2)}{2 C_p E\,\sigma_{yc}} . \tag{1.15}$$

Equation (1.15) demonstrates that for elastic material behaviour, a $\Delta CTOD$ approach to fatigue crack growth is compatible with LEFM. However, the $\Delta CTOD$ approach is not limited to elastic conditions since the occurrence of plastic strain is inherent to it. If the small scale yielding requirement of LEFM becomes violated, equation (1.15) will not remain valid, but $\Delta CTOD$ should continue to provide a characteristic measure of the crack tip plastic strain range.

Unfortunately, equation (1.10) only applies to an infinite centre cracked plate and similar expressions are difficult to derive for practical component geometries. This is probably the biggest disadvantage associated with using $\Delta CTOD$ as a correlating parameter for fatigue crack growth rate data. Accurate estimates of $\Delta CTOD$ in engineering structures may, however, be obtained from finite element based methods if the material behaviour is modelled properly.

A second problem arises with respect to the definition of *CTOD*. In finite element models, the crack normally does not advance, but simply becomes blunted as the load is applied. In such cases, it is conventional to define *CTOD* as the opening displacement between the intersections of two 45° lines (extending from the crack tip) with the crack flanks (see figure 1.7) [1.36]. In real situations, the crack extends as it blunts and it is sometimes difficult to decide on a location for measuring *CTOD*. If the increment in crack length is known, the opening displacement at the original crack tip position can be used to define *CTOD* (see figure 1.8) [1.37]. Alternatively, *CTOD* can be measured at the position where the linear part of the crack profile changes slope [1.38] or at the point nearest the crack tip where the crack faces are relatively undeformed [1.39]. For each convention, the measured values of *CTOD* may differ slightly and it is important to bear this in mind if the results are later used to make crack growth predictions.

In an early attempt to relate $\Delta CTOD$ to the amount of crack extension that occurs during each fatigue cycle, Tomkins [1.40] relied on direct observation of the fatigue striations left behind on the crack flanks as a result of the crack tip deformation process. Although a unique relationship between da/dN and $\Delta CTOD$ could not be established, several important insights were gained. It was learned that the space between striations does not always represent the amount of new crack surface that is produced during a fatigue cycle. At low crack growth rates a single fine striation can be the result of several fatigue cycles, whereas at high crack growth rates several fine striations can be produced during one fatigue cycle. Coarse striations may also form on the fatigue fracture surfaces. The fine striation spacing reflects the distance between shear planes and is material dependant. Under certain conditions, the coarse striation spacing can approach $\Delta CTOD/2$. *CTOD* is achieved by decohesion over a number of different shear planes near the crack tip, but only a fraction of the deformation that occurs in the crack tip region may actually contribute to the production of new crack surface area. A portion of the total *CTOD* can occur as a consequence of slip along previously deformed shear bands adjacent to the crack tip and not contribute to crack extension. In such cases, the crack growth increment will be less than $\Delta CTOD/2$.

Others [1.37,1.38,1.41,1.42] have used $\Delta CTOD$ in a general Paris-type power law expression of the form

$$\frac{da}{dN} = A \cdot \Delta CTOD^{\,b} \tag{1.16}$$

where A and b are empirically determined constants. The most encouraging results come from the work of Dover and Charlesworth [1.42]. These researchers have shown that it is possible to correlate fatigue crack growth rates under conditions of both small and large scale yielding by inserting the plastic component of $\Delta CTOD$ into equation (1.16). The material investigated was Q1N, a low alloy medium strength structural steel. Fatigue crack growth rate data were obtained from load controlled and clip gauge (displacement) controlled experiments and ranged over four decades in magnitude.

1.4.7 Concluding Remarks

Welded joints contain blunt notches that may be capable of generating large inelastic strains under typical in-service loading conditions. When fatigue cracks propagate within such regions of local plasticity they are said to be "physically short" because their growth behaviour is not in tune with linear elastic fracture mechanics theory. The presence of notch plasticity results in crack growth rates which are faster than the LEFM similitude parameter ΔK would predict.

Accurate modelling of physically short fatigue crack growth behaviour will require a fracture mechanics parameter that is capable of correlating fatigue crack growth rates under conditions of high cyclic strain. Several different elastic-plastic fracture mechanics parameters for dealing with high strain fatigue crack growth problems have been introduced. Choosing from this list of options is not an easy task. In the literature, the J integral (J) and the crack tip opening displacement (*CTOD*) seem to have received more attention than the others, although their use has been restricted mainly to the prediction of crack initiation in fracture toughness specimens. When used to characterise fracture toughness, each of these parameters has a separate appeal. J gives an indication of the intensity of the critical crack tip strain field, whereas *CTOD* provides some insight into the mechanism of crack extension. However, when it comes to describing elastic-plastic fatigue crack growth in welded components, $\Delta CTOD$ appears to be the better choice. First off, J was developed mainly as a fracture criterion for materials used in the nuclear power industry where no significant variations are expected between laboratory samples and real components. The *CTOD* concept, on the other hand, has been directed more towards the design of welded structures in which material properties can vary substantially in the region of interest. Secondly, the presence of cyclic plasticity near the tip of a growing fatigue crack invalidates one of the key assumptions upon which the derivation of J is based. As such, there is no theoretical justification for applying ΔJ to the study of fatigue crack growth. In contrast with this, there exists an obvious physical connection between $\Delta CTOD$ and the extent of reversed plastic deformation which occurs ahead of a fatigue crack tip. $\Delta CTOD$ also possesses a natural ability to account for residual stress effects (e.g. plasticity-induced crack closure and over-load retardation), that are a direct consequence of the inelastic flow process in the crack tip plastic zone. Based on this rational, it is the author's opinion that $\Delta CTOD$ is the most suitable parameter for tracking the growth of physically short fatigue cracks in welded components.

1.5 Other Factors Important to Early Fatigue Crack Growth

In addition to notch plasticity, other factors that might affect early fatigue crack growth behaviour include the effects of crack closure, mean stress, and cyclic strain hardening and softening. It is important to understand not only how each of these parameters can influence the fatigue crack growth process in general terms, but also how the magnitude of their effect can change with crack size. Each of these variables will now be reviewed and,