Reliable Operation of Drillstring Threaded Connections

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Submitted for the Degree of Doctor of Philosophy

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February 2002
Abstract

This thesis presents an investigation into the two common failure modes of rotary shouldered connections of the type used in the drillstring in hydrocarbon exploration. The threaded connection is a critical component of the drillstring, which is highly susceptible to fatigue damage, due to the inherent stress concentrations around the thread form. Fatigue crack growth can either lead to a catastrophic failure of the connection, known as a twist-off, or can be a non-critical failure, known as a wash-out. The design philosophy of Controlled Failure Design, which accepts that not all failures can be avoided and is concerned with managing the manner in which the failure may occur, has been used in order to promote a “friendly” failure in the connection, i.e. a wash-out before twist-off.

The significance of fatigue crack location, shape and size has been investigated analytically and experimentally, using structural integrity design codes, finite element stress analysis, and full scale experimentation. A custom-built fatigue test rig was designed and constructed for the full scale testing of NC-26 drill collar connections. Through a novel design in the test rig and the use of the ACFM inspection technique, crack growth data was collected during testing, which has led to a better understanding of the fatigue mechanism in drill collar threaded connections.

The influence of compressive residual stresses and its effect on improved fatigue performance has been experimentally investigated through the development of thread root cold rolling equipment. The technique of cold rolling has been studied in order to maximise the fatigue life of the connection. Through the control of the cold rolling process, it has been demonstrated that fatigue crack growth can be controlled to produce a localised, non-critical wash-out failure, which leads to a more reliable operation of drillstring threaded connections.
Acknowledgements

I wish to acknowledge the advice and guidance of my supervisors, Dr. Feargal Brennan and Professor Bill Dover, whose faultless supervision and unbounded enthusiasm has helped bring out the best of this work.

I would like to thank all my colleagues in the NDE Centre, especially Mr. Bijan Talei-Faz and Mr. Farid Uddin who have been a great support throughout my time at UCL. I am grateful for the assistance from the technical staff of Department of Mechanical Engineering workshop, in particular Mr. Neil Collings whose help was invaluable in the test rig set-up and cold rolling equipment design and manufacture.

I would also like to thank the following people and companies for their assistance and advice;

- Mr. Colin Griffiths, Offshore Rentals, Great Yarmouth.
- Mr Neil Young and Mr. Gary Baker, Tube Care Inspection Ltd., Great Yarmouth.
- Mr Francois Kessler, Grant Prideco, Candresse, France.
- TSC Inspection Systems, Milton Keynes.
- The Design Unit, University of Newcastle-upon-Tyne, Newcastle.
- Mr Thibault Baradat-Bujoli.
- Mr Owen Pearson.

The financial support for this work, provided by Shell International Exploration and Production B.V., Statoil ASA and Norsk Hydro, is greatly acknowledged.

I would finally like to thank Natacha, who has shown great patience and understanding throughout the many late nights and weekends spent on this project.
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Glossary

ACFM : Alternating Current Field Measurement.

ACPD : Alternating Current Potential Drop.

ACSM : Alternating Current Stress Measurement.

API : American Petroleum Institute. The leading standardising organisation for the oil and gas industry.

BBB : Bore Back Box.

BHA : Bottom Hole Assembly. An assembly of thick-walled pipes used to provide weight on the drill bit.

Blow out : an uncontrolled flow of formation fluids into the atmosphere.

Box : the female threaded connection

Break-out : to unscrew one section of pipe from another.

Build rate : the rate at which the wellbore is being deviated from vertical.

CTOD : Crack Tip Opening Displacement.

COF : co-efficient of friction

Drill bit : the cutting element at the bottom of the drillstring used for boring through rock.

Dogleg : a bend in the wellbore

Dope : a greasy lubricant for oilfield threaded connections.

Driller : the employee of the drilling contractor who is in charge of the drilling rig and crew. His main duties are to operate the drilling equipment and direct rig floor activities.
Fishing: the process by which broken or lost equipment is recovered from the wellbore.

LEFM: Linear Elastic Fracture Mechanics.

LET: Last Engaged Thread.

Make-up: to assemble and join thread connections.

MPI: Magnetic Particle Inspection.

Mud: the common term for drilling fluid. The fluid is circulated through the drillstring to the drill bit and back up the wellbore annulus.

NDT: Non-Destructive Testing.

NC: Numbered Connection.

Pin: the male threaded connection.

POD: Probability Of Detection.

RSC: Rotary Shouldered Connection. Threaded connection machined onto the ends of drill collars.

SCC: Stress Corrosion Cracking.

SCF: Stress Concentration Factor.

SIF: Stress Intensity Factor

SRGP: Stress Relief Groove Pin.

SST: Super Strength Thread.

SRT: Stress Relief Thread.

Side track: to drill around a permanent obstruction in the wellbore.

Slimhole: small diameter BHA components.

Tongs: large wrenches used to connect and disconnect sections threaded of pipe.
Trip : to pull out or run in the drillstring in the wellbore.

Twist-off : separation of the drillstring downhole, catastrophic failure.

Wash-out : a leak in the drillstring, partial failure.

Wellbore : a general term to describe the hole.

WOB : Weight On Bit. The load put on the drill bit by the drill collars.
## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>crack depth.</td>
</tr>
<tr>
<td>B</td>
<td>magnetic flux density.</td>
</tr>
<tr>
<td>c</td>
<td>crack $\frac{1}{2}$ length.</td>
</tr>
<tr>
<td>E</td>
<td>modulus of elasticity.</td>
</tr>
<tr>
<td>I</td>
<td>second moment of area.</td>
</tr>
<tr>
<td>K</td>
<td>stress intensity factor.</td>
</tr>
<tr>
<td>$K_I$</td>
<td>mode I stress intensity factor.</td>
</tr>
<tr>
<td>$K_{IC}$</td>
<td>fracture toughness.</td>
</tr>
<tr>
<td>$K_r$</td>
<td>stress intensity ratio.</td>
</tr>
<tr>
<td>$K_T$</td>
<td>theoretical stress concentration factor.</td>
</tr>
<tr>
<td>L</td>
<td>plate length.</td>
</tr>
<tr>
<td>$L_r$</td>
<td>load ratio.</td>
</tr>
<tr>
<td>N</td>
<td>number of cycles to failure.</td>
</tr>
<tr>
<td>$R_e$</td>
<td>external radius.</td>
</tr>
<tr>
<td>$R_i$</td>
<td>internal radius.</td>
</tr>
<tr>
<td>S</td>
<td>nominal stress.</td>
</tr>
<tr>
<td>$S_r$</td>
<td>stress ratio.</td>
</tr>
<tr>
<td>T</td>
<td>section thickness.</td>
</tr>
<tr>
<td>y</td>
<td>distance to the neutral axis.</td>
</tr>
<tr>
<td>$\delta$</td>
<td>CTOD.</td>
</tr>
<tr>
<td>$\delta_r$</td>
<td>fracture ratio using CTOD parameters.</td>
</tr>
<tr>
<td>$\sigma_{flow}$</td>
<td>flow stress.</td>
</tr>
<tr>
<td>$\sigma_{max}$</td>
<td>maximum local stress.</td>
</tr>
<tr>
<td>$\sigma_{nom}$</td>
<td>nominal stress.</td>
</tr>
<tr>
<td>$\sigma_{net}$</td>
<td>net section stress.</td>
</tr>
<tr>
<td>$\sigma_{UTS}$</td>
<td>ultimate tensile strength.</td>
</tr>
<tr>
<td>$\sigma_{YIELD}$</td>
<td>yield stress.</td>
</tr>
<tr>
<td>$\theta$</td>
<td>crack angle.</td>
</tr>
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</table>
# Table of Conversion Factors

<table>
<thead>
<tr>
<th>Category</th>
<th>Unit</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>1 inch</td>
<td>= 25.4 mm</td>
</tr>
<tr>
<td></td>
<td>1 foot</td>
<td>= 0.3048 m</td>
</tr>
<tr>
<td><strong>Torque</strong></td>
<td>1 ft-lb</td>
<td>= 1.35582 N.m</td>
</tr>
<tr>
<td><strong>Pressure</strong></td>
<td>1 psi</td>
<td>= 0.06894757 bar</td>
</tr>
<tr>
<td><strong>Flow</strong></td>
<td>1 gallon/min</td>
<td>= 4.546092 lit/min</td>
</tr>
</tbody>
</table>
Chapter 1

1.0 Introduction & Background

1.1 Introduction

Under today's economic pressures the oil and gas industry has made considerable technological advance in exploring new frontiers and in extending the life of present reserves. A part of that technology, which is now seen as common practise in exploiting these new discoveries, and in improving oil recovery rates of the existing reservoirs, is that of extended reach drilling, horizontal well bores and multilateral completions.

These new drilling techniques have placed even more demands on the drillstring, which has basically remained of the same design throughout the history of the industry. Downhole failure of the drillstem is a costly and not uncommon occurrence. Indeed, a recent drillstring failure in a deepwater development in the Gulf of Mexico reportedly cost one operator US$1 million [1.1].

The majority of drillstring failures are recognised and attributed to metal fatigue. The vast majority of failures occur in the threaded connections, which join together the lengths of drillstring. Considerable effort has been made to reduce these downhole failures. Numerous studies have been conducted based upon improved threaded connection design [1.2, 1.3], revised operating practices [1.4, 1.5], damage detection [1.6, 1.7]. More recent investigations have introduced new philosophies such as Fail-Safe and Controlled Failure Design [1.8]. Indeed, it is these new methodologies that will be investigated in this study.
Controlled Failure Design is based upon the fact that statistically, irrespective of quality and maintenance procedures, some failures will inevitably occur. It is an acceptance that not all failures can be avoided, and is aimed at controlling the manner in which a structure or component may fail. In terms of downhole drillstring fatigue it is represented by a failure which can be detected from the surface, and so enabling remedial action to be taken in order to avoid the situation becoming catastrophic.

Drillstring fatigue failures can be categorised into two groups, known to the industry as twist-off and wash-out. A twist-off failure is catastrophic, and results in the total separation of the drillstring downhole. A washout failure on the other hand, is a partial failure, and is detectable from the surface operations via a pressure drop in the circulating cutting fluid, and so allowing recovery of the damaged string. The average cost of a twist-off is 10 times that of a wash-out [1.9]. It is therefore apparent which type of failure is preferable.

Drillstem failures are often accepted as “part of the business”, however, with the recent initiatives to reduce costs, this may no longer be considered as acceptable. In today’s economic climate, drillstem failure can contribute significantly to the cost of drilling a well. These costs grow exponentially when the failure is a twist-off and the drillstem separates downhole. The resulting recovery operation, known as fishing, can lead to well control problems, the possibility of side tracking the well and in extreme cases, total well abandonment. Therefore, by using a Controlled Failure Design approach and encouraging the failure to be non-critical, wash-out before twist-off has clear and distinct advantages.

1.2 The Drillstring & Drilling Operations

The drillstring, as illustrated in Figure 1.1, refers to all the components from the kelly, which is connected to the swivel and suspended from the travelling block on the derrick, down to the drill bit. It includes drill pipe, drill collars, and auxiliary tools, such as jars, stabilisers, reamers, and bit subs.
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The purpose of the drillstring is to transmit rotary torque and to put weight on the drill bit, via the drill pipe and drill collars. Weight on bit (WOB) and rotation are the principal requirements in cutting through the rock and making a hole. The drillstring also provides a conduit for circulating drilling fluid, mud, to the drill bit. The drilling fluid's main function is to clean the hole of cuttings made by the bit, and to control the wellbore pressure. Any uncontrolled flow of formation fluids (oil, gas, or water) into the wellbore may result in a blow-out of the well. The circulating fluid also has a secondary function, it acts as a medium for detecting leaks in the drillstring. Mud is pumped downhole at pressures of between 3000 - 5000 psi (200 – 340 bar), and it is a drop in this pressure, which indicates a damaged drillstring [1.7]. Leakage in the circulation system is detectable from the surface standpipe pressure gauge instrumentation, as shown in Fig. 1.2. This allows the driller to react before the drillstring catastrophically fails.

Drill pipe is the major component of the drillstring. It is a seamless pipe with threaded connectors at either end, known as tools joints. These tool joints are short cylindrical pieces with either an external or internal thread and are normally friction welded to the drill pipe. The external threaded end is known as the pin and the internally threaded end is described as the box. Drill pipe is normally supplied in approximately 30 ft (9.1 m) lengths and is specified in different grades according to its mechanical properties, [1.11].

The drillstring is assembled by threading together individual lengths of drill pipe in a pin down configuration and then stabbing the assembly into the hole. The threaded connections are greased with a thread compound, known as dope, then screwed together (made-up) to a high torque using hydraulically powered tongs, prior to stabbing.

Between the drill pipe and the drill bit is an assembly of components called the Bottom Hole Assembly (BHA), of which drill collars are the majority. Drill collars are thick walled pipes used to provide WOB and to keep the drill pipe in tension. The drill pipe has a relatively low stiffness and is susceptible to buckling under
compression. This is eliminated by keeping it in tension with the heavier BHA components. Drill collars are normally supplied in 31 ft (9.4 m) lengths, and are generally manufactured from chromium-molybdenum alloy steels, which are heat treated over their entire length to improve the mechanical properties [1.12]. Due to their heavy wall thickness, drill collars do not have tool joints welded onto them, instead the threaded connections are machined from the pipe body, as shown in Figures 1.3 and 1.4.

The drill collar threaded connection, Fig. 1.5, or more appropriately rotary shouldered connection, (RSC), is a tapered thread that forces the drill collar shoulders together to form a metal seal when correctly made-up. Threaded connections have complex geometries, which inherently cause stress concentrations, which in turn act as initiation sites for fatigue damage to occur. Indeed, in the drillstring, it is the RSC that is particularly susceptible to fatigue damage. An investigation by a leading North Sea operator into its drillstring failures, identified fatigue as the root cause of failure in the majority of its 110 BHA failures [1.9].

Auxiliary tools such as drilling jars, stabilisers and reamers are also configured into the BHA above the bit. These aid and improve the hole cutting process, or specify the direction when drilling a directional well.

Wellbores are seldom straight, all vertical wells contain varying degrees of deviation from the vertical, which is known as a dogleg, as shown in Figs. 1.6 and 1.7. Since the advent of Extended Reach Drilling (ERD), deviated wells are now a standard application in reservoir exploitation. With the growth in these and directional/ERD wells, the rate of inclination, or build rate, has increased significantly from 2°/100ft up to very high curvatures of 60°/100ft. Figure 1.7 illustrates a typical modern well path [1.13]. These doglegs and highly deviated sections in the wellbore introduce large cyclic bending stresses in the drillstring when it is rotated, which are well understood to result in fatigue damage [1.4, 1.8, 1.14].
1.2.1 Drillstring Materials

In view of the severe downhole conditions in which drillstrings operate, high strength low alloy steels have been developed and adopted for use in the oilfield. The majority of steel conforms to AISI designations 4137H, 4140H, 4142H and 4145H, all of which have a fine grained quenched and tempered microstructure. Tables 1.1 and 1.2 show the chemical composition and mechanical properties of the most commonly used material, 4145H (0.45% carbon content). The heat treatment (H) gives rise to the high yield and UTS values, [1.15].

Specific downhole tasks, such as directional surveys, require magnetic transparency for the correct operation of the tool. To satisfy these requirements high strength austenitic steels have been developed. Traditionally, these have been chromium-nickel alloys. However, the mechanical properties of such non-magnetic alloys are poor, and they are expensive due to their high alloy content. Recent metallurgical developments have led to the substitution of nickel by manganese and the addition of nitrogen (Fe-Cr-Mn-N). This alloy steel reportedly has improved strength, hardness and corrosion resistance compared to the traditional austenitic steels [1.16].

As Horbeek et al [1.9] mention in the development of the drillstring quality procurement procedure [1.17], the need for good material properties is most basic and essential, of which some could benefit from enhancement. This led to one North Sea operator making significant gains in failure reduction, by influencing the drillstring material property requirements during the purchase of new drillstring components.

1.3 Drill Collar Threaded Connections

The Rotary Shouldered Connection (RSC) has been the subject of numerous research studies [1.18, 1.19, 1.20], as it is well recognised as the weakest item in terms of reliability of drillstring components. The pin / box arrangement was first used in oilwell drilling in 1909 [1.21]. The simple rugged design has seen little change, except in thread form and style, as basically there has been no better design
since. The thread form and style have evolved over the years, with manufacturers keen to demonstrate improved operating performance. Each time a new style was introduced, every effort was made to keep it interchangeable with the old.

In 1968 the American Petroleum Institute (API), the guardians of oilfield standards, rationalised the amount of thread styles, and introduced 17 numbered connections (NCs). These NCs ranged from NC-23 through to NC-77 and replaced the old and obsolete RSC connection styles. Figure 1.9 illustrates the many thread styles and forms, present and outdated, that have been used on RSCs. The NC number signifies the pitch diameter of the connection at a point 5/8 in. from the shoulder, called the gauge point. Therefore, for example, an NC-50 has a gauge point diameter of 5.0417 inches [1.11], Fig. 1.10.

However, the API regular (Reg.) thread style is still common in BHA components even though they are inferior to the NC's. The sharper root radii (Fig. 1.9) raises the stress concentration and so the probability of fatigue crack initiation. The reason for their popularity is probably habit, and the belief that changing to NCs would cost more than it is worth [1.22].

1.3.1 Special RSC Features

Newly machined drill collar connections are coated in a chemical solution, usually iron-manganese-phosphate, which acts as an anti-gall, and gives them their darkened appearance, Figs. 1.3 and 1.4. Galling can occur where there is excessive friction between high spots of two mating parts resulting in the localised welding of the two contacting surfaces. In RSCs this may occur on the thread flanks and the make-up shoulder of newly cut connections. However, the chances of galling are reduced by the hot-dip chemical coating. The anti-gall coating also assists in holding in the thread compound (dope) when the connection is made-up [1.21].

A feature that is still considered optional in the industry’s specification [1.11], is that of thread root cold rolling. Cold working a region of stress concentration is a
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well established technique, that has been demonstrated to improve a component's fatigue performance [1.23]. Thread root cold rolling generally involves forcing a hardened roller of the same geometry as the thread root radius into the thread root, and traversing the roller along the thread helix. This results in a layer of compressive residual stress being set up in the region of the stress concentration, as shown in Fig. 1.11. Most drillstring manufactures have adopted the cold rolling of drill collar thread roots. It is not uncommon for the operating companies, who are often ultimately responsible for the drillstring, to insist that it be performed as part of any procurement contract on new BHA elements [1.9, 1.17]. However, where specifications are made to cold roll, there is very little explanation of the procedure and quantification of the parameters [1.17 1.21]. It is very much left up the manufacture's discretion.

Another optional feature [1.11], which may improve the fatigue life of the connection, is that of stress relief features, such as stress relief groove pin (SRGP) and bore back box (BBB), Fig. 1.12. Material is removed from the pin and box components to reduce the stress concentration effect of the unengaged thread roots. This provides a more flexible connection and reduces the possibility of fatigue damage in this region, as the joint bends in areas of the smooth relief surfaces. The benefits of adding stress relief features to a connection were illustrated by Tafreshi & Dover [1.24]. Using the finite element method to model a popular drill collar connection, it was reported that the maximum stress concentration factor could be reduced by as much as 23% in a connector with stress relief features over that of a standard connector. SRGP and BBB are almost universal on drill collars of outer diameters greater than 5 in. [1.25]. However, the smaller connections have insufficient material to accommodate these features and are manufactured as standard [1.11]. The disadvantage of these features is that more material must be removed when the connection is cut, thus adding to the expense of the connection.

1.3.2 Make-Up Torque

Drillstring threaded connections are made-up using hydraulically powered tongs. This established drilling practise to further tighten the threaded connections after
assembly acts to pre-load the connection. The purpose of pre-loading the connection is to remove any slack in the connection, and to ensure that the shoulders do not separate in service. However, pre-load also has the benefit of relieving the thread of a proportion of any subsequent applied load, which is particularly relevant when considering fatigue loading.

The application of pre-load forces the pin and box shoulders together, resulting in the elongation of the pin and compression of the box shoulder, as shown in Fig. 1.13. This behaviour can be represented on a bolted joint bolt diagram, Figure. 1.14, which combines the force-deflection characteristics of bolts and bolted members [1.26]. Referring to Figure 1.1.4, the line $k_p$ represents the stiffness of the pin, with $k_j$ representing the stiffness of the joint. Typically, the stiffness of the bolt (pin) is only one-third to one-fifth the stiffness of the joint. When the connection is tightened, the pin extends by $\Delta P$ and the joint reduces by $\Delta J$. The tension in the pin is opposed by an equal and opposite force in the joint, and the connection is said to be pre-loaded, $F_p$. When an external tension load is applied, the pin elongates further to $\Delta P'$, and the joint compression is reduced to $\Delta J'$. As the bolt and joint have different stiffnesses, equal changes in deformation results in an unequal change in force (following their elastic curve). The net result is that the load in the pin only increases by a proportion ($\Delta F_p$) of the external load ($P$). The remainder is a reduction in the compression (pre-load) force ($\Delta F_j$) of the joint. This maybe of particular service when considering fatigue loading, in that pre-load can reduce the amplitude of the applied load. However, it presents a compromise situation between reduced cyclic load amplitudes, and a high static load. Nevertheless, the effect of pre-load can be seen as beneficial in both reducing the magnitude of the applied load and in providing a good sealing force on the connection shoulder.

The level of pre-load in a drillstring threaded connection is developed from the applied make-up torque. Traditionally, the level of make-up torque was based upon field experience [1.27]. For many years, drillers followed the rule of thumb that effective connection make-up torque was based upon one wrap of the tong line on the
rotating drum of the draw works (cathead) for each nominal inch of the connection size. Thus, a 3-1/2 in. connection required three wraps on the cathead, a 4-1/2 in. required 4 wraps, and so on. Figure 1.15 illustrates the traditional oilfield method of torquing drillstring connections. Despite the unexpected effectiveness of this rule of thumb, a more accurate method, based upon a combination of theory and empirical measurements, was developed [1.27]. Known as the Farr equation (1.1), an expression to define the torque requirements of rotary shouldered connections was developed. Derived from the power screw equation and full-scale laboratory fatigue tests, the expression was soon adopted by the API as the recommended definition of make-up torque [1.28].

\[
T_{	ext{mu}} = \frac{\sigma A}{12} \left( \frac{p}{2\pi} + \frac{R_t f}{\cos \theta} + R_s f \right)
\]  

(1.1)

where :
- \(T_{	ext{mu}}\) = make-up torque, ft-lbf
- \(\sigma\) = recommended make-up stress-level*, psi
- \(A\) = cross-sectional area of pin ¾ inch from the shoulder, in
- \(p\) = thread pitch, in.
- \(R_t\) = mean thread radius, in.
- \(R_s\) = mean shoulder radius, in.
- \(f\) = friction coefficient
- \(\theta\) = ½ included angle of thread in degrees

* obtained from Table 14 in API 7G [1.28].

1.4 Failure of the Connection

The BHA threaded connection has been identified as one of the most fatigue prone elements of the drillstring [1.9, 1.14, 1.29]. The inherent stress concentrations of the thread geometry act as likely fatigue crack initiation sites. Fatigue begins as
microscopic changes in the crystal structure of the metal at points of high stress, and progresses until minute cracks form. The fatigue crack continues to grow under repeated cyclic stress until it is either detected by inspection, or failure occurs.

As previously mentioned, there are two types of connection fatigue failure, twist-off and wash-out. A twist-off failure is most undesirable, due to the financial and technical burdens associated with a downhole drillstring separation. It occurs when a fatigue crack grows around the circumference of the connector. The crack extends under the cyclic load until the remaining material ligament is unable to support the applied load and sudden fracture occurs. The result is total separation of the drillstring, as illustrated in Fig. 1.16. Alternatively, the crack can propagate through the wall of the connector, and wash-out. Figures 1.17, 1.18 & 1.19 show a drill collar wash-out failure. The crack originated in the pin and grew through the wall thickness of the connector. The subsequent leakage of the drilling fluid eroded the material until breaking through the metal to metal seal at the connection shoulder, and thus releasing the high pressure mud into the wellbore. This type of failure is detectable from the rig floor, as shown in Fig. 1.2, and allows recovery of the damaged drillstring. Other failure modes of the drillstring, along with a more detailed explanation of the fatigue process can be found in Chapter 2.

Fatigue damage originates from areas of high stress concentration such as thread roots. This would suggest their significance as a critical zone for analysis to identify stresses that could result in fatigue crack initiation and growth.

1.5 Stress Analysis of Threaded Connections

When designing structural components for either static or dynamic loading, a stress analysis of the member is a matter of course. The usual procedure is to identify the stresses acting on the body as a whole, so therefore a global stress analysis. However, as fatigue is very much a local phenomenon, a detailed stress analysis is also required around the potential fatigue initiation sites, such as the geometrical features of a thread. Identification of these local “hot-spot” stresses are of importance.
when studying crack initiation, but less influential on the crack growth rate and general crack propagation characteristics [1.30]. The complex geometrical features of threaded connections and the accepted non-uniform load distribution within them [1.31], suggest threaded connections to be particularly susceptible to fatigue damage.

The knowledge and understanding of load distribution and stress analysis in drillstring threaded connections is based upon studies conducted in the first half of the last century concerned with axially loaded nut and bolt connections. The following sections summarise the different methods used in the stress analysis of threaded connections.

1.5.1 Theoretical Models

One of the earliest attempts to identify the distribution of stresses in a threaded connection was conducted by Stromeyer in 1918. He related the loading of thread faces to the shear loading of riveted joints, and observed that the highest load was borne by the thread or rivet that was furthest from the free end of a plate in shear. He presented a solution for this non-uniform load distribution as an exponential curve, and later suggested that non-linear load distribution could be optimised by a differential pitching between the nut and the bolt.

Following this, in 1929 Den Hartog presented a parabolic solution for the load distribution. He noted that when a nut and bolt of equal pitch are tightened, the bolt elongates and the nut is compressed. This results in the mating pitches no longer being equal, and so produces a non-uniform load distribution along the thread helix.

In 1948 Sopwith expanded Den Hartog's work and produced a detailed expression to describe the load distribution along the thread. Assuming the threads to be contacting cantilevers, he investigated the actions of axial strains within a nut and bolt connection. He proposed that their relative displacements were due to tooth bending and axial strains in the nut and bolt body. Associated with this was an axial recession due to the radial compression of the threads in the nut and bolt, and an axial recession
due to the radial contraction of the bolt and expansion of the nut caused by radial pressure between the nut and bolt. The term recession is used to refer to the axial separation of two threads originally in contact. He derived a differential equation equating the sum of the axial recessions to the axial strains in the nut and bolt.

A more comprehensive explanation to the background of load and stress distribution in threaded connections can be found in reference [1.31].

1.5.2 Experimental Stress Analysis - Strain Gauge Methods

Before the advent of electrical resistance strain gauges, the use of extensometers was commonly applied to measure strains. Goodier and Ithaca in 1940 used an optical extensometry method to determine the load distribution in a bolt by measuring the external deformation of the nut. Sopwith later compared these experimental findings to his theoretical analysis and found similar results.

However, it is now the electrical resistance strain gauge that is one of most popular methods used in experimental stress analysis. Electrical resistance strain gauges work on the principle that the change in electrical resistance of a conducting wire is directly proportional to its extension. A resistance strain gauge consists of a grid of very fine wire mounted on a backing, which is bonded to the surface under examination. Strain is found by measuring the change in resistance of the wire, which offers the potential for very accurate measurements. Yet, this method has obvious limitations when concerned with threaded connections. The nature of the joint makes it very difficult to attach gauges and their connecting wires to the critical regions of the thread.

Nevertheless, it has been reported that strain gauges were applied to the critical thread root region of a pre-loaded NC-46 drill collar connection [1.32]. In an experimental investigation to assess performance of a new thread style, the SST (Super Strength Thread) as shown in Fig. 1.9, strain gauges were reportedly attached to the thread roots of a standard NC connection and to the thread roots of an SST
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connection. Following connection make-up, it is reported that results from the test indicate that the SST connection could be made-up to higher torque levels than the API recommended value [1.28]. However, no strain gauge data is presented and there is no detail of how the strain gauges were bonded into the very difficult region of a made-up connection thread root.

Brennan and Karé [1.33] where able to apply strain gauges to the outside surfaces of a made-up 6-5/8 Reg. drill collar. The specimen was axially loaded with the purpose of detecting any opening of the shoulder pin / box interface, i.e. the overcoming of the make-up torque. Their results indicated that the pre-load in the connection was maintained and the shoulder retained its integrity. However, bending loads were not examined and considering the significance they have on RSC’s further experimentation would be justified.

1.5.3 Experimental Stress Analysis - Photoelastic Methods

One of the older methods of studying stress distribution is that of the photoelastic technique. In this method, static stresses are frozen into a photoelastic material and then observed and measured optically. Models of the component are cast and or machined from a photoelastic material, usually a synthetic resin such as Araldite or Bakelite. The model is then statically loaded and then heated and cooled in a controlled manner, which has the effect of freezing the stresses into the specimen. These are then examined under polarised light, which reveals the stress pattern, an example of which is shown in Fig. 1.20.

The first photoelastic study of the load and stress distribution within a nut and bolt connection was conducted by Hetenyi in 1943. He investigated various different nut designs and concluded that in all cases, the peak stress occurred at the first full thread of the bolt. The results of his study were later used by Sopwith, who showed a good correlation between the experimental and theoretical thread loads, except on the loaded face of the nut.
Patterson and Kenny used an Araldite bolt model to obtain an experimental load distribution and found reasonable correlation between their experimental results and Sopwith's theory, except again at the loaded face of the nut. They noted that the nut thread run-out region influences the root stresses at the loaded end of the bolt. The incomplete thread exhibits a lower stiffness and load bearing capacity than a fully formed thread, hence the discrepancy with Sopwith's theoretical solution [1.31].

In 1972 Weiner and True [1.34] conducted one of the first photoelastic studies on drillstring threaded connections. Modelling an API 4-1/8 in. I.F (see Fig. 1.9) drill collar connection under bending loads, they were able to observe the varied stress distribution within the connection. They concluded that there was little benefit to be gained in modifying the thread design. However, they did observe that the joints must be made-up sufficiently tight to keep the connection together at the shoulders under the expected bending loads.

As part of a joint industry project in 1990 [1.18], Fessier and Buchan performed a photoelastic study of NC-50 drill collar connections. They produced three Araldite models of the connection and subjected them to pre-load, pre-load and bending, and pre-load and torsion. They found that for each loading mode, the maximum stress occurred near the thread root of the pin and were within one pitch from the start of the connection. This conforms to the established uneven load distribution within the threaded connections, and confirms that the first loaded tooth of the connection to be most critical.

As Patterson and Kenny point out [1.31], the photoelastic technique is a useful tool in the stress analysis of single threaded connections. However, it becomes costly and time consuming when it is applied for a series of connections, such as in optimisation of a design.
1.5.4 Finite Element Methods

The rapid and ever advancing growth in computer technology coupled with a multitude of commercial software analysis packages has seen the finite element method establish itself as one of the principal stress analysis techniques.

One of the first finite element analyses (FEA) applied to threaded connections was performed by Pick and Burns in 1971, who analysed the stress distribution of a thick walled pressure vessel threaded connection. They assumed the model to be two-dimensional and to be axisymmetric about its longitudinal axis, and ignored the thread helix angle. As Brennan [1.30] highlights, their results compare well with the previous load / stress investigations, thus presenting the potential use of the finite element method (FEM) in the stress analysis of threaded connections.

Due to the complex geometrical form of threaded connections, a number of assumptions have become standard, particularly in the modelling of oilfield tubular connections. The two dimensional axisymmetric elastic model is one of the most popular methods of stress analysis of API threaded connectors [1.24, 1.35, 1.36], due to its relative ease of preparation and reduced solution time. Obviously, the two dimensional model fails to include any three dimensional features of the threaded connection, such as run-out geometry and helix angle. However, as Topp [1.37] mentions, in large connectors with relatively small pitches, the helix angle is small. Also, most thread designs do not utilise the thread run out as a load bearing section, therefore, the two dimensional model can be assumed to be accurate.

The NDE Centre at University College London have been modelling API threaded connections for several years, and have produced two extensive joint industry projects [1.18, 1.19] on the study of load distribution and stress concentrations in drill collar threaded connections. They have produced finite element models for a variety of common connectors, with and without pre-load, and subjected to tensile, bending and torsional loading. They have produced stress concentration factors for each of the connector types under the different loading modes. The stress concentration factor, $K_T$, is a dimensionless parameter used to describe the behaviour of a notch. It is most
commonly described as the maximum local stress divided by a nominal stress in the body, away from the region of interest and geometrical disturbances, equation (1.2).

\[ K_T = \frac{\sigma_{\text{max}}}{\sigma_{\text{nom}}} \] ...................................................(1.2)

In all cases, the maximum stress concentration factors (SCFs) were found in the thread roots of the first fully engaged loaded tooth of the pin, and the first fully loaded tooth of the box, depending upon the presence of pre-load. Their results have shown that the application of pre-load creates an alternative load path through the connection shoulder, and changes the critical component from the pin to the box connector. They also highlighted the importance of stress relief features on the pin and box connectors in reducing SCF values.

A full three-dimensional FE analysis of a threaded connection was reported by Rhee [1.38] in 1990. He produced FEA results which he compared to the traditional two dimensional model, and claimed that there was a 20% under prediction of the peak root stresses by the two dimensional model. However, his model included an extremely large pitch relative to the diameter, which was unrealistic to the real connection. This would have certainly contributed to the stress variation about the helix.

1.6. Drillstring Fatigue and Fracture

Drillstring threaded connections with their inherent regions of local stress concentrations are highly vulnerable to fatigue. Fatigue is damage caused by repeated stress cycles. In drillstring components this usually occurs when the string is rotated whilst it is bent, such as in a dogleg section. Drillstring fatigue damage may also result from downhole vibration [1.39]. Most drillstring elements will eventually succumb to fatigue unless they are first worn out or lost to other causes.
The fatigue behaviour of a component or material can be described by S-N data, which relates the applied stress, S, to the number of cycles to failure, N, as shown in Figure 1.21. Such S-N curves show that as the magnitude of the stress decreases the cycles to failure rapidly increases. The curve progressively becomes flatter and virtually parallel with the life axis as the stress level reduces. In this region, small decreases in stress produces disproportionately large increases in life, eventually implying infinite life. The stress at below which no fatigue occurs is known as the fatigue limit and a specimen reaching this limit is known as a fatigue run-out. However, when plotting S-N data for steels operating in a corrosive environment, the fatigue limit may not exist, and fatigue damage can occur even at very low stresses. S-N curves are a convenient method of comparing some of the important aspects of fatigue behaviour, such as the influence of component geometry. The detrimental effects of stress concentrations on a component fatigue life are shown in Figure 1.22.

1.6.1 The S-N Approach to Drillstring Fatigue Performance

The link between operating the drillstring in non-straight holes (doglegs) and drill pipe fatigue was first investigated in the 1960's. Investigators such as Lubinski [1.4] and Hansford [1.40] recognised the relationship between dogleg severity and premature failure of drillstem elements. Using Miner’s Rule and S-N curves they described the cumulative effects of fatigue damage on drill pipe. Their work was adopted by the API [1.28] as design guidelines for drill pipe operating in dogleg wellbores. However, their work was only concerned with drill pipe and failed to identify the BHA or the threaded connection as critical components.

The problem of drill pipe fatigue was again addressed in 1985 by Joosten et al [1.41], who dissatisfied with the earlier investigations, developed a computer program to calculate drill pipe fatigue damage. The program calculated the stresses acting on the drill pipe whilst operating in different zones of the well and counted the number of pipe rotations made. They compared this data to S-N data accumulated from their own full-scale rotating bend tests on drill pipe, and used it to predict inspection frequency for the drillstring. The limitation of this method is the unknown factor of
the drill pipe's previous load history. Key to this is the position in the wellbore of each length of drill pipe, which should be accurately recorded to identify those operating in dogleg sections.

In 1986 Zeren [1.42] continued investigating the effects of fatigue damage on drill pipe. He extended Lubinski's work and performed a more detailed stress analysis using the finite element method, and found that the use of pipe protectors between the tool joints improved the fatigue performance of drill pipe operating in dogleg sections.

The effects of a corrosive environment on drill pipe fatigue was examined by Grondin and Kulak in 1994 [1.43], who performed full scale fatigue tests in drilling mud solutions. Using a four point rotating bending test rig surrounded by an environmental chamber, they tested a common grade of API drill pipe, fitted with tool joint connectors. Results showed that fatigue damage and subsequent failure occurred in the drill pipe body away from the tool joint area. They found that fatigue cracks initiated from manufacturing marks on the outer surface of the drill pipe body. Due to the relatively thin wall thickness of the pipe body to the tool joint, the specimens rapidly failed in the pipe body.

In 1997 Baryshnikov et al [1.20] applied the S-N approach to drillstring fatigue life prediction to the more critical BHA components. They presented S-N data from a series of full-scale tests on various sizes of BHA threaded connections. It is reported that the fatigue life prediction of drillstring components is difficult in the absence of actual cyclic load history of each component. However, BHA life can be improved by control of "drilling technology factors". These are factors which can be controlled at the rig site, such as make-up torque, mud type, and tripping technique. It is also noted that the fatigue damage accumulation process, which is most difficult to control, can only be determined through regular non-destructive testing (NDT). It is reported that the cost of NDT in deep or directional wells is often more than the actual cost of downhole failure. However, they fail to specify which NDT technique(s) they compare with the cost of failure.
The S-N approach to fatigue is a good method for estimation of the “rough” life of a component. There is a vast collection of data available for most materials with different surface finishes, under different loading conditions, and in different environments. However, this approach is completely empirical and lacks the physical insights into the mechanism of fatigue. It does not distinguish between crack initiation and propagation, for which the fracture mechanics approach has been developed.

1.6.2 Fracture Mechanics Approach to Drillstring Fatigue Performance

The fatigue life of a component is made up of crack initiation and propagation stages. Fracture mechanics is concerned with the crack’s propagation behaviour. The last 40 years of fracture mechanics research has seen considerable effort directed towards the understanding of fatigue crack growth behaviour. The extension of Linear Elastic Fracture Mechanics, (LEFM) has led to the development of techniques such as, Crack Tip Opening Displacement (CTOD) and the J integral to describe various types of non-linear material behaviour.

New design philosophies, such as Defect Tolerant Design and Fail-Safe have evolved from the many fracture analysis studies. The principal concepts of these philosophies is that all structures or components contain cracks or crack like flaws from either manufacture or service, and the fatigue life of these components can be determined from knowledge of the fatigue crack growth. This fracture mechanics approach to design has been accepted and practised by various industries, principally power generation and aerospace. However, this approach is not unfamiliar to the oil industry with applications to offshore welded structures and hydrocarbon transmission pipelines [1.44, 1.45]

Fracture mechanics design methodologies have three critical variables, applied stress, flaw size and material toughness. The interaction between these variables is illustrated in what is commonly known as the fracture mechanics triangle in Fig. 1.23. In most situations there is knowledge of two of these quantities, such as applied stress
and material toughness, and by using the various fracture mechanics relationships the critical flaw size in the structure can be predicted. Knowledge of the critical crack size allows the designer to introduce a safety factor, thus presenting the possibility of an allowable flaw size. The predicted service life of the component could then be estimated by calculating the time required for the flaw to grow from its initial size to the maximum allowable size. Figure 1.24 illustrates the Defect Tolerance Design approach to the service life of a component.

Inspection and non-destructive evaluation plays a very important role in Defect Tolerant Design, as identification and monitoring of flaws are essential to avoid unsuspected failure.

Before reviewing the fracture mechanics studies applied to drillstring components, a brief overview of the principles associated with crack growth is warranted.

All fracture mechanics theories are based upon the application of Linear Elastic Fracture Mechanics (LEFM) which assumes nominally elastic material behaviour, although 'small' amounts of crack tip plasticity are allowed. Non-linear material behaviour is accounted for by theories such as Elastic-Plastic, Visco-Elastic, Visco-Plastic, and Dynamic Fracture Mechanics. However, these are all extensions from LEFM, and fundamental to this is a parameter known as the Stress Intensity Factor, K, which controls crack growth.

1.6.2.1 Stress Intensity Factor

The stress intensity factor (SIF) is a parameter that relates nominal stress, crack size and structural geometry. The SIF is most commonly expressed in the form;

\[ K = \sigma Y \sqrt{\pi a} \] (1.3)
where \( \sigma = \text{nominal stress} \)
\( a = \text{crack length} \)
\( Y = \text{geometry correction factor} \)

The SIF is an entirely different parameter from the stress concentration factor, \( K_I \), equation (1.2). The SIF has the units of stress multiplied by the square root of length, MPa√m, and is a crack parameter, whereas the stress concentration factor is a dimensionless term that describes the behaviour of a notch.

The definition of the SIF can be found in the behaviour of the linear elastic crack-tip stress field. It was Inglis in 1913 whose work on elliptical holes in flat plate led to the definition of the stresses at the tip of the major axis (root) of an ellipse as shown in Fig. 1.25, and equation (1.4).

\[
\sigma_T = \sigma \left( 1 + 2 \sqrt{\frac{a}{\rho}} \right) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots
• Shearing Mode II  The two crack surfaces slide over each other in the same plane.

• Tearing Mode III  The two crack surfaces slide over each other out of plane.

A cracked body can be loaded in any one of these modes, or a combination of two or three modes. For each of these crack movements there is an associated crack tip stress field. Following the work of Westergaard in 1939 and Irwin in 1958 the elastic stress field at the crack tip can be described as:

\[ \sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \]  

(1.5)

Where \( \sigma_{yy} \) is the stress applied normal to the crack face, mode I, \( r \) is the radial distance from the crack tip and \( K_I \) is the SIF corresponding to the mode I loading. A full solution to the stress field and displacements at the crack can be found in most fracture mechanics literature.

It can been seen that a stress singularly will exist at the crack tip, and it is obvious that no material can withstand infinite stress. Therefore, the material will yield at the crack tip, and redistribute the stresses throughout the elastic region. This plastic region at the crack tip is known as the plastic zone (\( r_p \)) and so long as it remains small in relation to the crack length (\( r_p < 10\% \) crack length), LEFM and \( K \) solutions remain valid. As mentioned previously, where there is more extensive yielding alternative solutions are available to account for this non-linear behaviour.

The ability to calculate the stress intensity factor has led to the to the concept of a critical \( K \) value (referred to as \( K_c \)) at which crack extension occurs. This \( K_c \) value or more appropriately \( K_{\infty} \) value, since tensile, mode I loading is the most common, is a measure of a materials fracture toughness. It is a material constant which is independent of the size and geometry of the cracked component.
1.6.3 Fracture Mechanics applied to Drillstring Components

The first attempt of studying crack growth behaviour in drillstring components was by Dale in 1986 [1.46]. He fatigue tested a number of popular drill collar threaded connections using a full-scale rotating four-point bend test rig, and collected crack growth data using the beach marking technique. Beach marks, sometimes referred to as clamshell marks or tide marks, are common features on fatigue fracture surfaces. They represent the advancing crack front and are often a result of changes in the component loading. Figure 1.27 shows typical fracture surface beach marking. By scaling the crack dimensions and knowing the number of cycles between each beach mark, Dale was able to determine the rate of crack growth. He noted the crack growth rate was nearly constant through the thickness of the connection. He also noted that a substantial percentage (≈ 50%) of the fatigue crack propagation life of the connector remained even after the crack had progressed halfway through the wall thickness. It must be noted that to accelerate his test programme, he used a spark eroded notch as his crack starter, and the applied stress levels were perhaps higher than those normally seen in service..

In 1992 Brennan [1.30] collected crack growth data for drill collar connections from full-scale axial tests and rotating four-point bend tests, again using the beach marking technique. Analysing the crack growth data he was able to develop theoretical models based upon the weight function theory to predict crack growth rates. The weight function concept proposes that in any symmetrically loaded body if the displacement field and the SIF, which are functions of the crack length, are known, then the SIF for any other symmetrical load system on that same body can be determined directly. In effect, the SIF can be represented as a weighted average of the applied loads. The method is complex and not presented here, but the full solution is presented in reference [1.47]. His experimental results compared well with the weight function solution for the axial test. However, there were notable differences between the experimental and theoretical crack growth rates for the rotating bend tests. He accounts for this by suggesting an over simplification of the bending stress analysis.
1.6.4 Fracture Toughness Values for Drillstring Components

As it was previously mentioned, the fracture toughness, \(KIC\) is an important variable in the fracture mechanics design approach. Szklarz in 1987 [1.48] first highlighted the importance of this material property in his proposal of the Leak-Before-Break concept for drill pipe. Using Charpy v-notch specimens, he developed an empirical relationship between Charpy impact energy and the materials fracture toughness. He concluded that there should be minimum toughness of the material to guarantee Leak-Before-Break. With his findings he and Shell Canada lobbied the API for a minimum toughness value for drill pipe. However, they were already acting on this deficiency in their standards and working with Buscemi et al [1.50] of Chervon, adopted a minimum Charpy impact toughness of 54 J, whereas Szklarz suggested a minimum toughness of 100 J.

The Charpy impact test data is not a reliable indicator of the fracture properties, unlike a fracture toughness test. The Charpy specimen contains a blunt notch, while fracture toughness specimens have sharp fatigue cracks. There is also a distinct difference in the loading of the specimens. The Charpy specimen experiences impact loading, whilst most fracture toughness tests are conducted under quasistatic conditions. Charpy v-notch tests are popular as they are cheaper and easier to perform than fracture mechanics tests. They are suitable for qualitative toughness testing of a material, but are not reliable indicators of structural integrity, and so empirical conversions should be used with caution.

1.7 Inspection and Maintenance of Drillstrings

Failure of a drillstring element whilst in service can lead to lost time, the possibility of an expensive fishing job and ultimately, the risk of abandoning the hole. To reduce the occurrence of failures, the drilling industry performs periodic non-destructive inspection to identify and remove damaged parts from service. Nevertheless, drillstring failures continue to occur, costing the operating companies and drilling contractors millions of pounds each year.
Drillstring thread inspection is typically a variety of visual, dimensional, and non-destructive testing (NDT), and the purpose of which is to classify the part for continued use, repair or scrap. NDT can be expensive and to be effective, scheduling the frequency of inspection intervals into equipment operating programmes is essential for cost-effective and trouble free operations. Traditionally drillstring inspection intervals have been based on experience from operating in areas with similar drilling conditions [1.51]. Common inspection schedules for drillstrings include, number of feet drilled and number of hours rotated. However, estimating the remaining life from these parameters maybe of little use. No two components in the drillstring will undergo the same stress and environmental histories in service. Yet, it is these histories that will determine the fatigue life of each component. Nevertheless, the industry continues to use these yardsticks for component inspection, and employs a variety of NDT techniques to inspect threaded connections.

The most common NDT technique used for inspection of oilfield threaded connections is magnetic particle inspection (MPI), sometimes known as black-light inspection. This method requires the thread surface (particularly the roots) to be absolutely clean of grease, dope, and any encrusted mud. The thread is magnetised, and a fluid containing fluorescent magnetic particles is sprayed over the connector. Any surface discontinuity attracts the iron particles suspended in the spray which become visible when viewed under ultraviolet light, as illustrated in Fig. 1.28. For non-magnetic drillstring components the dye penetrant method is employed. Both methods are often limited by the human factor such as the skill, patience, and visual accuracy of the inspector. They only provide detail of the crack length, with no possibility of measuring the crack depth. It is also difficult to obtain a permanent record of the results.

Ultrasonic inspection methods have also been used with limited success on drillstring threaded connections. Working on the principle of sending a pulsed ultrasound into the connection normal to the expected crack orientation, Fig. 1.29, the results have been spurious. Concerned with the reliability of this method, Armstrong
et al [1.52] undertook a study to establish the sensitivity of this method on samples taken from the field. Collecting data from 41 pin and box connections, they concluded that the MPI method was more sensitive than the ultrasonic method for detecting pin and box cracks.

In 1988 Dale and Moyer [1.53] evaluated the performance of the MPI technique for drillstring thread inspection. Taking the results from a number of inspection service companies, they produced Probability of Detection (POD) curves using the MPI method. POD is a statistical measure of the ability of a system to detect a defect of a certain size. Figure 1.30 shows their POD curve for the MPI technique. It can be seen that probability of detecting a crack 1 inch (25 mm) in length is approximately 50%. There is a 50% chance that the crack will be missed. They associated this poor performance to the difficulty in applying the technique, especially to the tight access of the box connector. They concluded that there was a need for an improved flaw detection method for threaded connections.

In 1991, having highlighted the deficiencies of MPI, Dale and his co-workers [1.54] developed a new automated thread inspection system (ATIS). The system was based on the electromagnetic flux leakage principle. The device is attached to a cleaned threaded region and is automatically driven around the circumference of the thread. Sensing probes detect disturbances in the magnetic field, which are associated with the presence of a defect. Any defect indication is plotted on a strip chart recorder, thus providing a permanent "hard" record of inspection. The new system is capable of measuring both defect length and depth, however its sizing capabilities are dependent upon calibration against a defect of a known depth and length. This method of sizing is often unreliable, as the calibration defect is often unrepresentative of the service defect. The inspection unit is considerably bulky, making mobility an issue for inspectors who generally work single handedly.

A new method of drillstring inspection system was presented in 1992 [1.55]. The method is based upon the use of non-contacting alternating current field measurement (ACFM). Working on the principle of electromagnetic theory, an alternating current
is introduced to the surface under inspection, which leads to a magnetic field being
induced perpendicular to the current flow. If a defect is encountered there will be a
disruption in the otherwise uniform current flow, and these current deflections cause
anomalies in the magnetic field. These disturbances have been mathematically
modelled from electromagnetic theories and can be directly related to the size of the
defect under observation, thus removing the need for calibration. As the method is
non-contacting, the reliance on surface preparation and cleanliness is not as
paramount as with other inspection methods.

The ACFM drillstring inspection system, known as ATI (Automatic Thread
Inspection), comprises of a probe containing two coils, one inducing, one sensing, a
Crack Microgauge, which contains the electronic circuitry to process the field signals,
and a laptop computer to display the results. The entire system is portable and can be
hand-carried. With the signal being displayed through the PC, inspection reports can
be saved on file, and/or printed for review, thus creating a permanent record of the
inspection, that can then be reviewed for an inspection audit as part of an effective
drillstring management programme. Typical defect signals appear on the screen as
peaks and troughs, from the background signal, and these are combined to produce a
“butterfly” plot, Fig. 1.31. The crack can be sized (length and depth) without the need
for calibration, by measuring the distance between the peaks and troughs and taking a
background reading.

In 1996 an inspection service company conducted an inspection trial of drillstring
threaded connectors using the ATI ACFM system and the MPI technique [1.7]. They
reported that the ATI inspection system consistently outperformed MPI in the
detection of flaws. Indeed, two components that were passed as defect free by MPI
were found to contain large defects, which ACFM had identified and had indicated
that they should be scrapped. Although no POD data was reported for this series of
inspections, the ACFM technique appears to have proven to be well suited to the
inspection of drillstring threaded connections.
1.7.1 Stress Measurement

It has been shown that the introduction of a compressive stress onto the surface of a component improves the metals resistance to fatigue when it is subjected to tensile or bending loads \[1.56\]. Operations such as shot peening, hammer peening, and cold rolling build residual compressive stresses into the surface of the part, these act to reduce the stress on the surface when an external tensile load is applied, as illustrated in Fig.1.32.

The benefits of introducing compressive surfaces stresses to threaded components was demonstrated by the British Shipbuilding Research Association \[1.57\]. Investigating the effects of thread rolling on the fatigue strength of large bolts used in marine diesel engines, they demonstrated that by cold rolling the thread roots after manufacture, the fatigue life could be increased by upto 2.5 times that of un-rolled bolts.

Following this the Engineering Science Data Unit \[1.58\] performed a series of cyclic axial tests on small diameter bolts, and produced some quite significant S-N results, (Fig. 1.33). It was demonstrated that the beneficial effects of cold rolling were lost when the specimens were heat treated after rolling, i.e. stress relieved. As it can be seen in Fig. 1.33, the fatigue performance of the threads heat treated after cold rolling performed considerably worst than those heat treated before rolling.

The effects of residual compressive surface treatments are not only lost due to heat-treatment, but also when the component goes into service. This phenomena was studied by Chen et al \[1.59\], who used an adaptation of the ACFM technique, known as ACSM (Alternating Current Stress Measurement) to measure the level of residual compressive stress decay of shot peened plate specimens which were cycled under axial tension.

The ACSM technique is a non-contacting method used for measuring changes in the stress state of a structure or component. The method uses the same hardware as ACFM and measures changes in the magnetic flux density on the surface of the
structure as it is loaded or unloaded. The results of Chen et al, shown in Fig. 1.34, demonstrate that the compressive stress on the surface specimen, introduced from shot peening, are gradually lost as the specimen is cycled under tension. The use of the ACSM equipment for measuring this stress decay was validated against the well established method of hole drilling.

The ACSM method was applied with success on a more practical application, to measure the level of applied stress in the threaded stud rods of an offshore platform anode clamp [1.60]. Clamps are attached to the structure of offshore platform to support sacrificial anodes, which are used for corrosion protection. The clamps are secured to the structure by threaded studs which under certification requirements, have to be periodically inspected for integrity. The ASCM technique was deployed to measure the level of tightening applied to the threaded stud. The ASCM results were validated against strain gauge results as the studs were loaded and unloaded. It was demonstrated that there was a very good correlation between the results.

As mentioned previously, new drillstring threaded connections are generally cold rolled. This process introduces compressive residual stresses into the highly stressed regions of the thread roots. However, no effort is made to monitor the levels of residual stress and its decay. Once the component goes into service, the effects of cold rolling begin to decay and the thread becomes susceptible to fatigue damage. With the continuing development of the ACSM technique, it is possible that a tool similar to the ATI will be available to measure the residual compressive stress decay in oilfield threaded connections. This may suggest the concept of an infinite fatigue life, as connections could be re-cold rolled to re-introduce the decayed compressive stresses. This is based on the fact that cracks will not initiate in compressively stress layers [1.61].

1.8 Summary & Scope of Thesis

This chapter has introduced the concepts and equipment used in oil and gas well drilling. It has identified two common failure modes of drillstring connections, twist-
off and wash-out. The threaded connection has been identified as a critical component which is highly susceptible to fatigue damage. The significance of compressive residual stresses and its effect on improved fatigue performance has been introduced. In drillstring threaded connections compressive residual stresses can be introduced to the high stress regions of the thread roots by cold rolling. However, this is still specified as an optional process. It is considered that through the use of compressive residual stresses and control of the cold rolling process, a non-critical failure, i.e. wash-out before twist-off, can be promoted in drillstring threaded connections. The main purpose of this study is to examine whether design and practice can be changed to promote wash-out failure and avoid twist-off. This is an implementation of the Controlled Failure Design process.

The following chapters investigate and discuss important factors that may contribute to the concept of a “friendly” wash-out failure. Chapter 2 discusses failure of the connection and illustrates how connection size may contribute to a critical failure. Chapter 3 details a finite element stress analysis on a number of drill collar connections, and highlights how manufacturing tolerances can influence the level of stress concentration in connection thread roots.

Chapter 4 describes the design and construction of a purpose built fatigue test rig. The rig was designed for testing full scale NC-26 drill collar connections and contains a novel facility for collecting crack growth data. Also described is the development and construction of a cold rolling device for the NC-26 pin and box connectors. The industry does not currently cold roll NC-26 connectors, due to the connections smaller size. Through the development of a “miniaturised” cold rolling device, the cold rolling procedure as a whole has also been investigated. Chapters 5 and 6 present and discuss the results of the full-scale testing and illustrate that by controlling the levels of residual stresses, by controlling the cold rolling process, a non-critical failure of the connection can be encouraged. Chapter 7 concludes by reviewing the findings of this investigation and recommends future work to continue in the promotion of the reliable operation of drillstring threaded connections.
1.9 References


[1.58] Engineering Science Data Unit, “Fatigue Strength of External and Internal Steel Screw Threads under Axial Loading. (Standard forms not Greater than 1.0 inch diameter”, Item Number 84037, Engineering Sciences Data Unit, December 1984.
Chapter 1 - Introduction & Background


### 1.10 Tables

<table>
<thead>
<tr>
<th>Mechanical Property</th>
<th>Material Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charpy V-notch impact energy</td>
<td>40.7 J (30 ft-lbs) @ R.T.</td>
</tr>
<tr>
<td>Hardness</td>
<td>285 - 341 BHN</td>
</tr>
<tr>
<td>Minimum yield strength</td>
<td>758.6 MPa (110 ksi)</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>965.5 MPa (140 ksi)</td>
</tr>
<tr>
<td>Reduction of area</td>
<td>45% min.</td>
</tr>
<tr>
<td>Elongation</td>
<td>13% min.</td>
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</table>

**Table 1.1** - Minimum specified mechanical properties for AISI 4145H [1.11].

<table>
<thead>
<tr>
<th>Element, % weight</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.42-0.49</td>
</tr>
<tr>
<td>Mn</td>
<td>0.65-1.10</td>
</tr>
<tr>
<td>Si</td>
<td>0.15-0.35</td>
</tr>
<tr>
<td>Cr</td>
<td>0.75-1.20</td>
</tr>
<tr>
<td>Mo</td>
<td>0.25-0.35</td>
</tr>
<tr>
<td>P</td>
<td>0.035 max</td>
</tr>
<tr>
<td>S</td>
<td>0.040 max</td>
</tr>
</tbody>
</table>

**Table 1.2** - Typical specified composition for AISI 4145H [1.11].
1.11 Figures

Figure 1.1 - The drillstring components.
Figure 1.2 – Example of a wash-out from the drillers surface instrumentation [1.7].
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Figure 1.4 - The box connector.
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Figure 1.17 – Pin *wash-out* and subsequent thread damage.
Figure 1.18 – Thread damage in the box due to the pin wash-out.

Figure 1.19 – Pin wash-out and resulting erosion of the shoulder seal.
Figure 1.20 – A photoelastic model of a pipe subjected to compression at opposite ends of the diameter, illustrating typical stress patterns [1.61].

Figure 1.21 – Typical S-N curve.
Figure 1.22 - The influence of SCF on fatigue strength.
(a) SCF=1; (b) SCF = 2.1, r=1.0 mm; (c) SCF = 3.2, r = 0.3 mm, (d) SCF = 6.0, r = 0.07 mm [1.62].

Figure 1.23 - The Fracture Mechanics Triangle, identifying the critical variables in fracture design.
Figure 1.24 - The defect tolerance approach to design.

Figure 1.25 – Elliptical hole in a flat plate.
Figure 1.26 – Crack opening modes.

Figure 1.27 – Beach marks, common features on a fatigue fracture surface [1.63].
Fluorescent iron particles attracted to the magnetic disturbance caused by the crack.

Figure 1.28 - Magnetic particle inspection of thread roots. Surfaces must be clean and viewed under ultraviolet (blacklight) for crack indications to be seen.

Figure 1.29 - Ultrasonic inspection, where the sound beam reflects from the defect.
**Figure 1.30** – POD data for MPI inspection of drillstring threaded connections [1.53].

**Figure 1.31** – Typical ACFM defect signal including the “butterfly plot”.

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**Figure 1.32** – Compressive stress induced on the surface of a shot-peened specimen (A) prevents surface tensile stresses from occurring after a bending moment is applied (B) [1.64].

**Figure 1.33** - Engineering Science Data Unit S-N Graph illustrating the effects of cold rolling [1.58].
Figure 1.34 - ACSM measurements for decaying residual surface stresses [1.59].
2.0 Failure of Drill Collar Threaded Connections

2.1 Introduction

The drillstring operates in a hostile downhole environment. It is subjected to combined loading, axial, bending and torsion, arising from WOB, rotation through doglegs and drive torque respectively. It may also be subjected to high temperature and high pressure conditions and / or a sweet or sour environment. The latter two conditions being caused due to the presence of CO$_2$ with organic acids and hydrogen sulfide respectively. These harsh downhole conditions may all lead to drillstring failure.

There are a number of failure modes that a drillstring may succumb to, however, fatigue has been clearly identified as the main cause [2.1, 2.2, 2.3]. The following sections will briefly review the other main failure modes, followed by a detailed investigation into fatigue crack growth in tubular sections. Structural integrity assessment procedures have been followed to identify the relative strengths of cracked drill collar connections.

2.2 Drillstem Failure

This investigation focuses on the failure of the drill collar threaded connection due to fatigue. However, the drillstem may fail in other and less frequent forms. The following sections give a brief review, in no specific order, of other drillstem failure mechanisms.
2.2.1 Tension Failure

Tensile failures usually occur in drill pipe operating in vertical or near vertical wells, at the top of the string where the highest tensile loads are found. However, variations in drill pipe wall thickness, due to wear, and material properties may result in a tension failure occurring lower down the string. They are normally a result of an excessive overpull on the drillstring, for example when the driller attempts to free a stuck pipe by pulling on the string with a load beyond the capacity of the pipe.

2.2.2 Torsion Failure

Drill pipe connections (tool joints), are particularly susceptible to torsion failure [2.4]. Torsion is transmitted through the connectors when the string is rotated, however, if the applied torsion is greater than the initial make-up torque of the tool joint then, relative rotation is produced between the pin and box connectors. This may result in torsional overload and failure. Good drilling practice requires keeping the applied torsion on a connection less than its surface make-up torque, thus ensuring that further make-up will not occur downhole. Yet, during hole problems such as working on stuck pipe, excessive torque maybe produced in attempting to free the pipe, thus potentially exceeding the torsional capacity of the connector. BHA connections are typically stronger than the tool joints above them, and so torsional failures in BHA connections are less common [2.4].

2.2.3 Stress Corrosion Cracking

Stress Corrosion Cracking, (SCC) is the general term given to environmentally assisted cracking under sustained or repeated tensile stressing. In the drillstring it is the non-magnetic, austenitic stainless steel components which are most vulnerable to SCC failure [2.5]. In austenitic stainless steels, a passive oxide layer forms on the surface of the metal and protects the underlying metal from further corrosion. However, if this passive layer is ruptured under tensile stress, an SCC crack can form at the point of rupture. Once formed, the crack may grow by an anodic corrosion reaction, and as it is an intergranular fracture mechanism, crack branching may occur.
In austenitic steels the failure mechanism is assisted by the presence of chloride ions, present in the drilling mud, which gives rise to its alternative name of Chloride Stress Cracking.

In sour gas wells, hydrogen sulfide (H$_2$S) is present which may cause Sulfide Stress Cracking. In this mechanism, H$_2$S rapidly reacts with the iron in the drill pipe to form hydrogen ions, some of which are diffused into the steel lattice. This results in the steel becoming less ductile, which may cause brittle fracture when under load.

2.3 Fatigue Failure

Fatigue is the most common cause of drillstem failure. Indeed one investigation [2.2] reported that 13% of drillstem failures examined could be directly attributed to fatigue. Fatigue damage is a cumulative process caused by repeated stress cycles. In the drillstring, cyclic loading can occur from axial tension or rotation of the string when some part of it is bent, such as in a dogleg, but damage may also result from vibration. Vibrational failures can occur when the frequency of the applied load equals the natural free vibration frequency of the drill string, resulting in resonance. Rotation at the natural resonant frequency results in excessive wear, fatigue damage and rapid deterioration of the drillstring. To avoid this, the drill bit must be rotated at a speed different from the natural frequency of the drill string [2.6]. The repeated application of these cyclic stresses results in the formation of fatigue cracks in areas of high stress concentration, such as the thread roots of the drill collar connections.

Fatigue is a progressive failure mode involving several different stages. Figure 2.1 illustrates the progression of fatigue damage, which can be generally described by the following stages;

1. Crack initiation. Local plastic strains occurring in regions of stress concentration, result in microstructural damage to the material and the nucleation of a crack. It should be noted that there is some ambiguity in the definition of crack initiation. A materials scientist may define initiation as the first signs of cyclic slip and...
discuss micrometre sized flaws, whereas an engineer usually relates it to the resolution of the inspection equipment used in crack detection, which can vary from 0.25 mm upwards.

2. Stable crack propagation. Under sufficient cyclic loading a crack will extend at a particular rate depending upon the local stress field, material properties and environmental factors.

3. Fracture. Unstable crack growth leading to structural instability or catastrophic failure.

These different stages in fatigue damage can lead to several important observations:

- For simple smooth surfaced laboratory specimens, fatigue crack initiation may occupy as much as 90% of the total fatigue life [2.7]. This characteristic indicates that crack detection and monitoring through periodic inspection may be impractical, as the inspection intervals would have to be very short.

- For complex geometries such as threaded connections, crack initiation can be rapid and stable propagation can occupy as much as 90% of the total fatigue life [2.7], contrary to smooth specimen behaviour. This is due to the initial uneven load distribution in the threaded connection, where peak loading occurs at the first thread of the pin and box members, alternatively known as the last engaged threads (LETs), as shown in Fig. 2.2. Cracking of this thread causes the load to be re-distributed to adjacent threads, thus giving a better load distribution. With the decreased stress the crack grows slowly. This type of behaviour has been seen in the fatigue testing of threaded tether connections [2.7], and in drill collar connections. Dale [2.8] observed “steady” crack growth from fatigue testing NC-46 RSCs. It is reported that up to 50% of the life of the connection remains even when the crack has progressed halfway through the wall thickness. This type of
behaviour presents ample opportunity to inspect, detect and size cracks through periodic inspection.

- Unstable crack growth involves either ductile or brittle fast fracture. The crack size at which failure occurs is dependent upon the stress level and the fracture toughness of the material.

As previously mentioned, drillstring fatigue failures can be categorised as either wash-out or twist-off, i.e. a partial through-thickness failure or a total downhole separation of the drillstring. A wash-out failure can be likened to the Leak-Before-Break scenario used in the pressure vessel and piping industry. Leak-Before-Break behaviour is given if a defect grows through wall in a stable manner to cause a detectable leak, which allows the plant to be shut down before catastrophic failure occurs. The concept of Leak-Before-Break is that the critical crack depth, which leads to leakage will be reached long before the critical crack length, i.e. local failure will precede global failure. This may be achieved by selecting a material with an appropriate fracture toughness so that a through wall crack can exist without causing catastrophic failure [2.9].

Transferring this concept directly to RSC wash-out may not be so direct, as pressure vessel plant are generally thin wall sections, whereas drill collar connections are predominantly thick walled. Also, the high surface stress concentration produced by the thread geometry may encourage long and shallow crack growth, thus making a wash-out failure unlikely. However, a local failure maybe encouraged through the use of residual compressive surface stresses, such as those introduced by thread root cold rolling. A crack could be directed through the wall of the connection by variations in the residual surface stress of the thread root. This concept of encouraging local failure by controlling the levels of surface residual stresses will be examined and discussed in Chapter 5 and 6.

The interdependence of crack size, stress and fracture toughness on failure has been incorporated into several design philosophies. The following sections describe several evaluation methods available for assessing structures with defects, and applies
one of those methods, R6, to identify the relative strengths of cracked drill collar connections.

2.4 Evaluation Methods

The concept of "living with defects" has principally been developed by the aerospace and power generation industries, who have developed and implemented theories known as Damage Tolerance Design and Defect Tolerant Design [2.10]. The various concepts, however they are known, fundamentally use fracture mechanics to quantify the critical combination of flaw size, material fracture toughness and applied stress on a flawed component.

The ability to evaluate the tolerance of a structure containing defects has a number of advantages. It may be used at the design stage, to optimise the design with respect to the properties of the material. It may also be used during service to reassess plant and equipment which have been found to contain defects, thus possibly extending the life span of the component or removing it from service to avoid catastrophic failure. It also provides the basis for an effective and economical inspection strategy. Figure 2.3 illustrates what is known as the fracture mechanics triangle, and identifies the three critical variables in fracture design. However, for the holistic design approach with safety factors, the main components in an evaluation of defect tolerance are shown in Fig. 2.4.

There are a number of evaluation methods available to determine the behaviour of structures with defects, however it must be remembered that these methods are only suitable for the appropriate situation. For example, linear elastic fracture models should not be applied to structures that exhibit significant plastic flow. The following sub-sections present a brief overview of some of the various assessment methods available.
2.4.1 The CTOD Design Curve

The crack tip opening displacement (CTOD) curve was principally developed by the British Welding Research Association (presently known as TWI) in the late 1960s. Based upon the work of Wells, who whilst attempting to measure the fracture toughness in a number of structural steels, found that the crack faces moved apart prior to fracture. He noted that plastic deformation was blunting an initially sharp crack, and the degree of blunting increased in proportion to the toughness of the material. This observation led Wells to propose the opening of the crack tip as a measure of fracture toughness, known today as CTOD. He also suggested that global strain should scale linearly with CTOD under large scale yielding conditions.

Based on this idea, Burdekin and Dawes presented a relationship correlating small scale CTOD tests and wide double-edge notched tension panels made from the same material. The wide plate specimens were loaded to failure, and the failure strain and crack size of the large scale specimens were correlated with the critical CTOD in the corresponding small scale tests. The resulting correlation led to the CTOD design curve, illustrated schematically in Fig 2.5. The critical CTOD is presented in non-dimensional terms and is plotted against the failure strain in the wide plate, normalised against the elastic yield strain, \( \epsilon_y \). The applied strain, flaw size and critical CTOD for the material are plotted on the graph. If the point lies above the design curve the structure is considered safe as observed failures occurred below the design line.

The CTOD design curve was based upon correlations with flat plates simply loaded in tension, however, real structures are rarely of this form and loading conditions can be more complex. These limitations led TWI to investigate the validity of using wide plates for correlation to smaller specimens, and it was identified that the CTOD design curve method is conservative approximately 97% of the time [2.11].
2.4.2 Failure Assessment Diagrams

The CTOD design curve generally only considers crack tip failure or brittle fracture, and does not explicitly address plastic collapse. Structures made from materials with sufficient toughness may not be susceptible to brittle fracture, but they may fail by plastic collapse if overloaded. The interaction of these two failure modes, was first described by Dowling and Townley [2.12], and Harrison et al. [2.13] in the late 1970s, and from this, two assessment approaches were developed, BS 7910 and the R6 method. The two methods bear resemblance to each other and both describe the interaction of fracture and collapse in the form of the failure assessment diagram (FAD). The FAD uses two dimensionless parameters, the stress intensity ratio, Kr, to describe fracture (ordinate) and the stress or load ratio, Sr or Lr, to describe collapse (abscissa). Figure 2.6 illustrates a general FAD. The following sections detail and describe the parameters of the FADs. As with all FADs the integrity of a structure under assessment is calculated from a point on the graph. If the point calculated lies on the curve or falls outside it, the structure is deemed unsafe, while if the point is within the curve, no failure is predicted.

2.4.3 BS 7910

This British Standard titled “Guide on methods for assessing the acceptability of flaws in metallic structures” [2.14] has evolved from the BS guidance document, PD 6493 [2.15]. The original PD 6493 (1980) was based upon the CTOD design curve. However, through recognising the limitations and the conservative nature of the CTOD approach, a three tier FAD assessment method was developed and published in 1991. The main emphasis of the document was placed on the assessment of flawed welded structures. In 1999 this guidance document was expanded and published as a full British Standard. Though still focusing on the assessment of welded fabrications, the new standard also contains procedures for assessing non-welded structures and the assessment of flaws in high temperature plant.
The procedure contains three levels of assessment all utilising failure assessment diagrams. The three levels depend upon the input data available, the level of conservatism and degree of accuracy required.

2.4.3.1 Level 1

This is a screening level, which provides a conservative estimate of acceptable flaw size, due to its simplified and conservative inputs. The FAD is simplified to the extent that it has no interaction between the two failure modes of fracture and collapse, see Fig. 2.7.

However, what is common to all failure assessment diagrams, at whatever level, is the fracture axis described as the stress intensity ratio, $K_r$, defined in equation (2.1).

$$K_r = \frac{K_I}{K_{fc}} ................................................................................. (2.1)$$

where $K_I$ = mode I deepest point stress intensity factor

$K_{fc}$ = mode I fracture toughness

A Level 1 assessment the stress intensity expression, $K_r$, may be replaced with a CTOD expression, $\sqrt{\delta_r}$.

$$\sqrt{\delta_r} = \sqrt{\frac{\delta_i}{\delta_{max}}} ................................................................................. (2.2)$$

where $\delta_i$ = applied CTOD

The plastic collapse criterion, $S_r$, is defined as the ratio of the net section stress to the flow stress. Plastic collapse occurs when $S_r = 1.0$. Equations (2.3 – 2.5) define the stress ratio.
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\[ S_f = \frac{\sigma_{\text{NET}}}{\sigma_{\text{FLOW}}} \] ................................. (2.3)

where \[ \sigma_{\text{NET}} = \frac{\text{Applied load}}{\text{CSA of component - crack area through section}} \] ........... (2.4)

\[ \sigma_{\text{FLOW}} = \frac{\sigma_{\text{UTS}} + \sigma_{\text{YIELD}}}{2} \] ................................. (2.5)

2.4.3.2 Level 2

This level of assessment is generally applied to steel structures, and uses a more accurate, less conservative FAD. The failure assessment diagram is plotted from equation (2.6), which has been derived from a modified version of the strip yield model, a description of which can be found in most fracture mechanics texts. Figure 2.8 illustrates a typical Level 2 FAD. The stress ratio, \( S_f \), is replaced by a load ratio, \( L_r \), which is described by equation (2.7), where \( \sigma_{\text{NET}} \) is described by equation (2.4).

\[ K_r = L_r \frac{\sigma_y}{\sigma_f} \left[ \frac{8}{\pi^2} \ln \sec \left( \frac{\pi \sigma_y}{2 \sigma_f} L_r \right) \right]^{-1/2} \] ................................. (2.6)

\[ L_r = \frac{\sigma_{\text{NET}}}{\sigma_{\text{YIELD}}} \] ................................. (2.7)

As can be seen in Fig. 2.8, the Level 1 FAD is always conservative compared to the Level 2 method.

2.4.3.3 Level 3

The Level 3 assessment employs a full tearing instability approach and therefore provides a more accurate description of the performance of ductile materials. Ainsworth proposed a model that reflected the flow behaviour of a material to account
for the work hardening or strain hardening of the material as it deforms plastically. A thorough review of Ainsworth’s work can be found in reference [2.11]. The description of Level 3 FAD is identical to the R6 assessment, as will be shown later.

The Level 3 FAD is related to the materials stress-strain behaviour and is plotted from equation (2.8).

\[
K_r = \left( \frac{E \varepsilon_{\text{ref}}}{L \sigma_Y} + \frac{L^3 \sigma_Y}{2E \varepsilon_{\text{ref}}} \right)^{0.5}
\]  

(2.8)

where \( \varepsilon_{\text{ref}} \) is the true strain obtained from the uniaxial tensile stress-strain curve corresponding to a true stress \( \sigma_{\text{ref}} \).

A Level 3 assessment also uses the load ratio, \( L_r \), equation (2.7). The collapse axis is normalised to yield stress and not flow stress, thus the assessment curve can extend beyond unity, and represents material strain hardening. However, the load ratio cannot exceed \( \sigma_{\text{flow}} / \sigma_{\text{yield}} \), where \( \sigma_{\text{flow}} \) is described by equation (2.5). This limiting load ratio is defined as \( L_r^{\text{MAX}} \), equation (2.9). For typical C-Mn (mild steels) \( L_r^{\text{MAX}} \) is 1.2, for austenitic stainless steels \( L_r^{\text{MAX}} \) is 1.8. These different cut-off values are due to the different strain hardening characteristics of the material.

\[
L_r^{\text{MAX}} = \frac{\sigma_{\text{flow}}}{\sigma_{\text{yield}}}
\]  

(2.9)

If a detailed stress-strain curve is not available for the material, which is often the case, especially when assessing a flaw in a structure’s heat affected zone, the following expression can be used to describe the FAD:

\[
K_r = \left( 1 - 0.14 L_r^2 \right) \left[ 0.3 + 0.7 \exp \left( -0.65 L_r^6 \right) \right]
\]  

(2.10)

This expression only requires knowledge of the material’s yield and ultimate tensile strength. The cut-off point is described as in equation (2.9). Figure 2.9 illustrates a typical Level 3 assessment curve. As fundamental to all FADs, any point
within the curve is considered safe, and any point falling outside of the curve is deemed to have failed.

2.4.4 The R6 Method

The R6 method, or by its full title “Assessment of the Integrity of Structures Containing Defects” is another procedure available to assess the integrity of flawed structures. It was developed by the UK nuclear power industry under what was then the Central Electricity Generating Board (CEGB), who are now currently operating as British Energy.

The R6 method resembles BS 7910, as it utilises failure assessment diagrams, and contains three levels of assessment depending upon the data available and the desired accuracy. However, this assessment procedure is supported by analysis software, R6-CODE. The method, as does BS 7910, allows for the identification of the limiting flaw size in a structure to be calculated under specified loading conditions. It also allows for the limiting load to avoid failure of a structure containing a known or postulated flaw to be calculated. The method has 3 options available for generating the FAD, depending upon available data.

2.4.4.1 Option 1 - The General Curve

This option for assessment uses the same expression as BS 7910 Level 3 to describe the FAD, equation (2.10). Similarly it is appropriate when detailed stress-strain data is not available, as only the yield and ultimate tensile strength of the material need be known.

2.4.4.2 Option 2 - Material Specific Curve

The option 2 FAD is based on the model of Ainsworth, and is identical to BS 7910 Level 3, requiring detailed knowledge of the stress-strain behaviour of the material.
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The FAD is described by equation (2.8), and has a cut-off point as described by equation (2.9).

2.4.4.3 Option 3 - J - Integral Analysis

The option 3 FAD requires a detailed elastic and elastic-plastic analysis, with the FAD being inferred from the J integral solution for the structure of interest. A stress analysis would be required about the region of interest that incorporates the stress-strain response of the material in question, which leads to the FAD being described by equation (2.11).

\[ K_T = \left( \frac{J_e}{J} \right)^{0.5} \]  \hspace{1cm} (2.11)

where J is the elastic plastic crack tip characterising parameter (J-integral), and J_e is the elastically calculated value of J.

Within each option there are three categories of analysis depending upon the intended use of the analysis.

- Category 1: Fracture initiation, the simplest category of analyses, used in most design cases where fracture initiation is to be avoided.
- Category 2: Allows for a limited amount of ductile tearing prior to failure.
- Category 3: Describes full ductile and unstable crack growth.

This brief overview of some of the evaluation methods available to assess the integrity of structures containing defects is by no means intended to be definitive. Readers are referred to reference [2.11] for a more detailed review. However, what has been presented is what might be considered the most frequently used contemporary assessment techniques. Following the development of the R6 method, now in it’s fourth revision [2.16], it was decided to adopt this method for assessing the relationship between flaw size, failure load and connector size for a number of popular drill collar connections.
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2.5 The R6 Assessment

As previously mentioned, the R6 assessment procedure is supported by the analysis software R6-CODE. This is primarily targeted at the nuclear industry in terms of the geometry of components, material specifications and to an extent, ease of navigation through the software. It was therefore decided to use the modern programming language MATLAB, to code all the key elements of the R6 method to form structural assessment software specifically aimed at drillstring components.

One of the failure assessment criteria is the identification of $K_r$, equation (2.1), and critical to this is the stress intensity factor (SIF). R6-CODE has its own built-in SIF solutions, programmed from standard published solutions and derived from British Energy's own in-house analysis. Therefore, the first step required referenced published SIF solutions to be coded in MATLAB and compared with R6-CODE for validation. To gain confidence in the MATLAB program and the referenced SIF solutions, the simple case of a flat plate containing a surface crack was examined prior to the cylindrical geometry of the drill collar.

2.6 Flat Plate Surface Crack SIF

Many SIF solutions exist for a semi-elliptical surface defect in a finite sized flat plate. One of the most respected and applied solutions is that of Newman and Raju of the NASA Research Centre [2.17], which features in SIF compilation handbooks e.g. [2.18]. Figure 2.10 illustrates the notation used to describe the plate and defect.

The Newman and Raju SIF solution was coded into MATLAB to produce a range of normalised SIFs for a range of crack sizes under tension loading. The results were compared to those of R6-CODE for the same plate geometry, crack depths, aspect ratios, and loading condition. Figures 2.11-2.14 show the results of the MATLAB coded Newman & Raju solution compared against R6-CODE. It can be seen that there is a good correlation of the results for shallow defects ($a/T < 0.4$), and short
defects \((a/c > 0.9)\). However, as the crack depth and length increases, the Newman and Raju solution behaves more conservatively.

Communication with British Energy [2.19] has identified that the R6-CODE model for a finite plate under tension may use a different restraint boundary condition on the plate, which could be the cause of the differences. The Newman and Raju solution contains specific limits on crack dimensions for which the solution is valid, while R6-CODE fails to define any limits. A point to be noted is that R6-CODE continues to calculate SIFs even when the crack length is beyond the length of the plate. The Newman and Raju solution is valid only for \(c/L < 0.5\), i.e. the crack remains within the area of the plate. Considering the reputation of the Newman and Raju solution and that it behaves conservatively to R6-CODE the differences were deemed acceptable.

### 2.6.1 Flat Plate - Surface Crack - Critical Load

Having established an SIF solution, it is possible to complete the failure assessment of the plate by the \(K_r - L_r\) relationship described in the R6 Option 1, as equation (2.10).

\[
K_r = \left[1 - 0.14L_r^2\right] \left[0.3 + 0.7 \exp\left(-0.65L_r^4\right)\right] \quad \text{................................. (2.10)}
\]

The failure assessment is the identification of the critical loads to cause failure in the plate for a range of crack depths and lengths. The R6 relationship was coded into MATLAB along with the \(K_r\) and \(L_r\) parameters as described in equations (2.1, 2.8, & 2.10). The material properties were identical for both assessments. Figures 2.15 and 2.16 show the critical tension load results for a number of finite sized plates. The results show good correlation for short and shallow cracks, with a divergence occurring for longer crack lengths \((a/c < 0.8)\) and greater crack depths. This again maybe due to the validity of the SIF solution, where R6-CODE continues to calculate for crack lengths greater than the plate length.
The MATLAB coded R6 assessment method displayed good general correlation with the R6-CODE assessment software. Only where crack lengths were beyond the validity of the SIF solution did minor differences occur. Having established the validity of the concept for the critical load failure assessment, the method could be applied to the problem of cracked cylindrical components.

2.7 Cylindrical Components - Drill Collar Connections

Fatigue cracks in drill collar connections generally initiate from the high stress regions of the thread roots, and can be on the external (pin) or internal (box) surface of the connector. Subsequent crack growth has been observed as semi-elliptical in shape [2.20, 2.21], and to have little influence from the thread form [2.8]. For the purpose of this study, the effect of the thread has been neglected, and the analysis is based upon uniform tubular geometry. This may be considered appropriate as drill collar connections are thick walled and as the crack depth increases there is likely to be little influence from the thread form. Cracks may also grow through the thickness of the connector, presenting a wash-out scenario, in which the effect of the thread design may be considered negligible.

A failure assessment analysis requires stress intensity factor solutions (K_i) for the cracked component under investigation. Several stress intensity factor handbooks exist [2.18, 2.22] which collate solutions from the author's own work and the "best" published solutions. However, these are by no means conclusive for all crack shapes and component geometries. Due to the difficulty in finding applicable and valid SIF solutions, only the pin connector has been assessed. Table 2.1 presents a number of popular drill collar connections that were assessed using the R6 Method in order to identify their relative static strengths. The following SIFs presented may be considered the most reliable for a range of crack shapes in thick walled drill collars.
2.7.1. Circumferential Surface Crack SIF

Surface defects in components with circular cross-sections, such as shafts, rods, and bolts, have been the focus of many stress intensity factor investigations [2.23, 2.24, 2.25]. Yet, relatively few solutions exist for cracked hollow cylinders or pipes, in particular thick walled pipes. However, Raju & Newman [2.26] presented normalised stress intensity factors at the deepest point of the crack, for pipes of different wall thickness, containing a range of crack sizes, under tension and bending loads. Figure 2.17 illustrates the notation and validity limits of the solution. The solution was not presented in the closed form format, but as tabulated data for various crack aspect ratios and crack depth to pipe wall thickness ratios. A polynomial curve fit of the tabulated data was performed by Brennan [2.21] in order to ascertain the SIF parameters.

The SIF solutions were coded into MATLAB and normalised SIF curves for a range of crack sizes were produced. Figures 2.18 – 2.23 present the results for tension and bending loads for a range of pipe and crack configurations. It can be seen that there is very good correlation between the curve fit solution and the published data points, especially for the thick walled solution.

The solution was applied to the drill collar connections listed in Table 2.1. Figures 2.24 – 2.26 present the results for a range of crack sizes. For intermediate crack aspect ratios it can be seen that the thicker walled connectors exhibit the highest SIFs. This trend is reversed as the crack aspect ratio increases, with the thinner walled connectors displaying the greater SIFs. This behaviour is repeated for the bending case.

2.7.2. Circumferential Through-Wall Crack SIF

For the wash-out scenario to be examined a circumferential through-wall crack SIF solution is required. Very few through-wall crack solutions have been published, and those which are available, have been developed by the pressure vessel and transmission pipeline industry [2.27, 2.28] and are predominantly for thin walled
sections. However, the American Petroleum Institute (API) have recently released RP 579, (Recommended Practise, Fitness-For-Service) [2.29], which contains both thin and a thick walled through crack solutions for tension and bending loads. The solution for thick walled cylinders is presented in equations (2.12 – 2.18). Figure 2.27 describes the pipe and crack geometry. The API RP 579 document is similar to BS 7910, in that it describes techniques for assessing the structural integrity of plant and equipment containing flaws.

\[ K_1 = (M_m \sigma_m + M_s \sigma_s) \sqrt{\pi c} \] ................. (2.12)

where:

\[ M_m = \max \left[ (A_m + A_{mb}), (A_{mm} - A_{mb}) \right] \sqrt{\frac{2 R_c}{c} \tan \left( \frac{c}{2 R_c} \right)} \] ................. (2.13)

\[ M_s = \max \left[ (A_m + A_{sb}), (A_{mm} - A_{sb}) \right] \] ................. (2.14)

and

\[ A_{mm} = \left[ 1.0028 + 2.7582 \lambda - 1.2070 \lambda^2 + 0.28138 \lambda^3 + 3.0813 \left( 10^3 \right) \lambda^4 \right]^{0.5} \] ................. (2.15)

\[ A_{mm} = -6.6164 \left( 10^2 \right) + 0.30309 \lambda - 0.14663 \lambda^2 + 0.022028 \lambda^3 - 0.0025285 \lambda^4 \] ................. (2.16)

\[ A_{mm} = 3.5656 \left( 10^3 \right) + 0.16678 \lambda - 0.15113 \lambda^2 + 0.074153 \lambda^3 - 0.015761 \lambda^4 + 0.0011992 \lambda^5 \] ................. (2.17)

\[ A_{mb} = \frac{1}{0.098852 + 0.45685 \lambda + 0.033905 \lambda^5} \] ................. (2.18)
Due to a lack of comparative data for thick walled through crack solutions, (API RP 579 presenting the only published solution), it was decided to compare the API thin walled solution with other published thin walled solutions [2.27], to observe its behaviour and to gain confidence in the solution. The solutions were coded in MATLAB and Figures 2.28 and 2.29 illustrate the behaviour of the different SIF solutions for tension and bending conditions. It can been seen that the API RP 579 solution is conservative compared to reference [2.27] in both loading cases. However, without further SIF solutions for increased pipe wall thicknesses, for the purpose of this study, it was considered that the API solution will be conservative for the thick walled pipe geometry.

The API solution was applied to the drill collar connections listed in Table 2.1. Figures 2.30 and 2.31 present the results for a range of crack lengths under tension and bending loads. As expected, the normalised SIFs increase significantly with crack length, with the thinner walled connectors displaying greater increases than the thicker walled connectors.

2.7.3 Crack Areas

To complete the failure assessment procedure the load ratio parameter, Lr, must be identified. This requires calculation of the crack area through the section, as shown in equation (2.4). Following the work of Peleties [2.30], who proposed a novel method for calculating the area of an elliptical shaped crack on a cylindrical section, a method exists for calculating the different crack areas on cylindrical surfaces. Peleties superimposed different size circular sections on to cylindrical sections, and through basic geometric and trigonometric relationships, was able to calculate the various resulting crack areas. These crack shape geometry definitions were coded into
MATLAB [2.31] so that the crack evolution for each crack shape could be observed. Figure 2.32 presents an example of the development of an elliptical crack shape area. A full description of the crack area calculation method along with crack shape validity limits can be found in Appendix A.

For the through-thickness crack, the crack area was calculated from equation (2.20). Figure 2.33 illustrates the notation for calculating the area of a segment of a cylinder.

\[
A = \theta T (2R - T)
\]  \hspace{1cm} (2.20)

Knowledge of the stress intensity factors and crack areas for the drill collar components, along with basic material properties, allowed a failure assessment to identify the relative static strengths of cracked connections to be performed.

### 2.7.4 Relative Strengths of Cracked Connections

The R6 – option 1, equation (2.10), failure assessment method was used to calculate the critical load to failure for a number of cracked drill collar connections. The connections analysed are listed in Table 2.1. For comparative purposes, the failure load of the cracked connection was normalised against its un-cracked failure load, thus presenting a strength ratio for the connection. Figures 2.34 – 2.36 present the relative strengths of part-through cracked connections using the Raju and Newman SIF solution for tension loading. It can be seen that the smaller connections exhibit greater relative strengths for all the crack aspect ratio values. The relative strengths appear less influenced by the section wall thickness, unlike the SIF curves, and more by the sectional area. The same behaviour is observed in the bending analysis, with the sectional area of the connections controlling the relative strengths.

Figures 2.37 and 2.38 present the relative strengths of through-cracked (washed-out) connections for tension and bending loads respectively. As was the case before, the smaller connections appear to show a greater relative strength. However, for the
tension case, the section wall thickness can be seen to influence the strength, with the thinnest walled connector displaying the lowest relative strength.

These failure assessment graphs illustrate how dimensional relationships can influence the relative static strengths of the cracked connections. It can be seen that the small, thick walled connection, NC-26, displays the best performance of all the connections examined. The geometry of the connections analysed was as specified in the API standard for drillstring elements [2.32]. However, these dimensions may not be the optimum for reliable structural integrity.

2.7.5 The Sensitivity of the Bore Size to the Relative Strength of Cracked Connections

The relationship between basic drill collar dimensions has been shown to influence the structural integrity of the cracked component. Depending upon the type of crack, part-through or through-wall, the effect of the bore size and so the section wall thickness may be seen as significant. The previous section reported that the maximum relative residual static strength maybe achieved by reducing the outer-diameter for part-through cracks and increasing the thickness for through-wall cracks. Thus suggesting optimal performance through small thick walled connections. The sensitivity of modifying the inner diameter of a connector was studied with respect to its relative static strength. An NC-46 connection was examined for a range of bore sizes in an attempt to identify an optimum inner diameter for the connector. Figures 2.39 – 2.42 illustrate the effect of modifying the bore on the SIF and the relative strength for part-through and through-wall cracks in the connector. It can be seen that a larger bore benefits the connector containing a part-through crack of intermediate aspect ratio. However, for a through-thickness defect the smaller bore connector is of benefit. This demonstrates that in order to apply the principles developed in this chapter to maximise relative residual static strength in all cases both connector size and Ri/T ratio need to be varied.
It must be noted that the analysis for the part-through crack only considers a single crack aspect ratio, for which the SIF is calculated at the deepest point. Any subsequent crack shape development, such as whether the crack will grow in depth to form a wash-out crack, or whether it will grow in length and result in a twist-off is unknown. Although many factors can effect the manner of crack growth, such as, loading, material properties and environment, crack shape evolution is mainly influenced by the stress intensity factor. A useful method, which is gaining prominence, to predict crack aspect ratio evolution is that of the RMS or average stress intensity factor. This approach considers the average SIF in the two directions of crack growth. It has been successfully applied to the prediction of crack shape behaviour in flat plates [2.33], and it is intended that future developments in the RMS stress intensity factor technique will yield solutions for cracked cylindrical components [2.33].

2.8 Conclusions

The R6 structural integrity assessment method has been applied to the problem of drill collar connections. The relative strengths of various common connections have been identified for part-through and through-cracked connections. The part-through crack analysis involved a limited SIF solution, which was only valid for intermediate and high crack aspect ratio values. However, developments in the RMS SIF technique may produce a reliable crack aspect model for a full complement of crack sizes in cylindrical geometries.

From the results presented, it can be seen that a compromise situation arises between thin and thick walled sections depending upon whether the crack is part-through or through-wall. Without knowledge of the crack aspect ratio development, it is not possible to predict how the crack shape will evolve. However, it can be seen that once the crack is through-thickness (wash-out), the smaller, thicker walled connectors exhibit greater relative strength. For total optimisation of relative static strength of cracked tubulars the trend is towards small thick walled connections.
Drillstring design depends upon several factors, such as hole size and depth, the geological structure of the formation, and the desired factor of safety for overpull. Drill collars are primarily used to supply weight to the drill bit (WOB), and are typically thick walled in order to concentrate the weight as near to the bit as possible. The drill collar bore size must also consider drill bit hydraulics to ensure sufficient mud circulation. The bore must also allow the passage of geological surveying instruments through the drillstring. However, once these criteria have been met, the design of the drillstring may also be influenced by its behaviour to defects. It has been shown that the smaller, thicker walled connections exhibit a greater relative strength. This should be a major consideration in a Controlled Failure Design of drillstring elements.
2.9 References


Chapter 2 – Failure of Drill Collar Threaded Connections


Table 2.1 – Valid drill collar connection sizes for SIF solutions [2.32]

<table>
<thead>
<tr>
<th>Connection style</th>
<th>Drill Collar size (in.)</th>
<th>Ro (mm)</th>
<th>Ri (mm)</th>
<th>Rf (mm)</th>
<th>Ri/T</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC-26</td>
<td>3-1/2 x 1-1/2</td>
<td>44.45</td>
<td>19.05</td>
<td>34.92</td>
<td>1.2</td>
</tr>
<tr>
<td>NC-38</td>
<td>5 x 2-1/2</td>
<td>63.50</td>
<td>31.75</td>
<td>49.41</td>
<td>1.80</td>
</tr>
<tr>
<td>NC-46</td>
<td>6-1/2 x 3-1/4</td>
<td>82.55</td>
<td>41.27</td>
<td>59.80</td>
<td>2.23</td>
</tr>
<tr>
<td></td>
<td>6-1/2 x 2-13/16</td>
<td>82.55</td>
<td>35.70</td>
<td>59.80</td>
<td>1.48</td>
</tr>
<tr>
<td>NC-50</td>
<td>6-1/2 x 3-1/4</td>
<td>82.55</td>
<td>41.27</td>
<td>65.21</td>
<td>1.72</td>
</tr>
<tr>
<td>6-5/8 Reg.</td>
<td>8-1/4 x 3-1/4</td>
<td>104.77</td>
<td>41.27</td>
<td>74.70</td>
<td>1.23</td>
</tr>
</tbody>
</table>
2.11 Figures

Figure 2.1 - The fatigue life cycle of a component.

Figure 2.2 – Hot-spot regions of stress concentrations in the LETs of drill collar threaded connections.
Figure 2.3 - The fracture mechanics triangle, identifying the critical variables in fracture design.

Figure 2.4 - The main components in Defect Tolerance Evaluation.
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Figure 2.5 - The CTOD design curve.

Figure 2.6 - The general Failure Assessment Diagram (FAD).
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Figure 2.7 – Level 1 Failure Assessment Diagram.

Figure 2.8 – Level 2 Failure Assessment Diagram.
Figure 2.9 – Typical level 3 Failure Assessment Diagram.
valid for:

\[ 0 \leq \left( \frac{a}{c} \right) \leq 1.0 \]
\[ 0 \leq \left( \frac{a}{T} \right) \leq 1.0 \]
\[ \left( \frac{c}{L} \right) \leq 0.5 \]

**Figure 2.10** - Newman and Raju finite sized plate notation and validity limits.
Figure 2.11 – Comparison of results for normalised SIFs. Finite sized plate - surface crack – tension – \( a/T = 0.2 \).

Figure 2.12 – Comparison of results for normalised SIFs. Finite sized plate - surface crack – tension – \( a/T = 0.4 \).
Figure 2.13 – Comparison of results for normalised SIFs. Finite sized plate - surface crack – tension – $a/T = 0.6$.

Figure 2.14 – Comparison of results for normalised SIFs. Finite sized plate - surface crack – tension – $a/T = 0.8$. 
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Figure 2.15 – Comparison of failure loads from R6-C0DE (R6) and MATLAB (ML) for finite plate (L=100 mm, T=40 mm) - surface crack – tension.

Figure 2.16 – Comparison of failure loads from R6-C0DE (R6) and MATLAB (ML) for finite plate (L=500 mm, T=100 mm) - surface crack – tension.
Figure 2.17 – Notation and validity limits for external circumferential surface crack [2.17].

Valid for:

\[
0.6 \leq \left( \frac{a}{c} \right) \leq 1.0
\]

\[
1.0 \leq \left( \frac{R_i}{t} \right) \leq 10.0
\]

\[
0.2 \leq \left( \frac{a}{t} \right) \leq 0.8
\]
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Figure 2.18 – Comparison of normalised SIFs for cylinder – $R_i/T = 1.0$ – Tension as calculated by MATLAB to the Raju and Newman results.

Figure 2.19 – Comparison of normalised SIFs for cylinder – $R_i/T = 2.0$ – Tension as calculated by MATLAB to the Raju and Newman results.
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Figure 2.20 – Comparison of normalised SIFs for cylinder – $R_i/T = 4.0$ – Tension as calculated by MATLAB to the Raju and Newman results.

Figure 2.21 – Comparison of normalised SIFs for cylinder – $R_i/T = 1.0$ – Bending as calculated by MATLAB to the Raju and Newman results.
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Figure 2.22 - Comparison of normalised SIFs for cylinder - Ri/T = 2.0 - Bending as calculated by MATLAB to the Raju and Newman results.

Figure 2.23 - Comparison of normalised SIFs for cylinder - Ri/T = 4.0 - Bending as calculated by MATLAB to the Raju and Newman results.
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Figure 2.24 – Normalised SIFs for part through cracked drill collar connections under tension for $a/c = 0.6$.

Figure 2.25 – Normalised SIFs for part through cracked drill collar connections under tension for $a/c = 0.8$. 
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Figure 2.26 – Normalised SIFs for part through cracked drill collar connections under tension for $a/c = 1.0$. 

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Valid for:

\[ 1.0 \leq \left( \frac{R_i}{T} \right) \leq 3.0 \]

\[ 0 \leq \left( \frac{1.818c}{\sqrt{R_iT}} \right) \leq 6.5 \]

Figure 2.27 – Notation and validity limits for circumferential through-wall crack [2.29].
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Figure 2.28 – Comparison of normalised SIFs for circumferential through-wall cracks

\( \frac{R_i}{T} = 10.0 \) – Tension.

Figure 2.29 – Comparison of normalised SIFs for circumferential through-wall cracks

\( \frac{R_i}{T} = 10.0 \) – Bending.
Figure 2.30 – Normalised SIFs for through-wall cracked drill collar connections – tension.

Figure 2.31 – Normalised SIFs for through-wall cracked drill collar connections – bending.
Figure 2.32 – An example of elliptical crack shape development on a cylindrical section.

Figure 2.33 – Notation for the area of a segment in a cylinder.
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Figure 2.34 – Relative static strength of various drill collar connections containing part through cracks, with crack aspect ratio (a/c) = 0.6.

Figure 2.35 – Relative static strength of various drill collar connections containing part through cracks, with crack aspect ratio (a/c) = 0.8.
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Figure 2.36 – Relative static strength of various drill collar connections containing part through cracks, with crack aspect ratio (a/c) = 1.0.

Figure 2.37 – Relative static strength of various drill collar connections containing through-wall cracks under tension loading.
Figure 2.38 – Relative static strength of various drill collar connections containing through-wall cracks under bending loading.

Figure 2.39 – Normalised SIFs for part through cracked modified NC-46 connections with crack aspect ratio (a/c) = 0.6 – Tension.
Figure 2.40 – Normalised SIFs for through cracked modified NC-46 connections – Tension.

Figure 2.41 – Relative static strength for modified NC-46 connections containing part through cracks, with crack aspect ratio (a/c) = 0.6.
Figure 2.42 – Relative static strength for modified NC-46 connections containing through-wall cracks under tension loading.
Chapter 3

3.0 Stress Analysis of Drill Collar Threaded Connections using the Finite Element Method

3.1 Introduction

It is well known that the majority of drill stem failures are attributed to fatigue damage. This is particularly the case in BHA connections where the geometric discontinuities of the thread form result in local stress concentrations. The amplitude of these peak local stresses at the thread roots is a major contributory factor in the failure of drillstrings. This chapter details the use of the finite element method to investigate the stress raising effect of the thread form for a number of common drill collar threaded connections. It characterises this stress concentration effect by means of the stress concentration factor, SCF. A detailed finite element analysis of drill collar dimensional quality control, with specific regard to the significance of bore eccentricity on the SCF, is presented. The identification of the SCF for the connection under experimental investigation (Chapter 4) is also presented.

3.2 Stress Analysis of Threaded Connections

The study of load distribution and stress concentrations in drillstring threaded connections has been well documented, from the early photoelastic studies [3.1], through to complex two and three-dimensional finite element models [3.2, 3.3, 3.4]. The finite element method is widely recognised as one of the principal methods of stress analysis. For the analysis of the complex geometrical thread form of oilfield connections, the two-dimensional axisymmetric model has become one of the most
popular. The representation of a three-dimensional threaded connection by a two-dimensional finite element model inevitably fails to include the effects of thread helix and run-out geometry. However, as Topp [3.5] mentions, in large connections with relatively small pitches, the helix angle is small. Also, most threads do not utilise the thread run-out as a load bearing section, therefore the two-dimensional model can be assumed to be accurate.

The two-dimensional axisymmetric method of modelling was adopted by Chen [3.6] who identified SCFs for a number of drillstring connectors subjected to bending loads which represented differing degrees of wellbore dogleg. The investigation attempted to predict drillstring fatigue performance through the identification of connection SCF and by use of drill collar material monotonic and fatigue properties. The predicted fatigue life results were compared to the full-scale experimental results of Weiner & True [3.7] and generally showed good agreement.

This method was also employed by Smith [3.8] who used it to analyse a popular drill pipe tool joint connection. Two models of the connector were generated, the first was to the API specification and the second model was produced with a modified thread form. In the second model, the thread root radius of the pin connector was enlarged from the standard 0.038 to 0.057 inches, and the pin taper was reduced by 16%. The results showed a 14% decrease in the peak stress of the last engaged thread (LET) of the pin, and an overall improved load distribution along the thread. The new thread design remained interchangeable with the standard connectors and was patented as an SST (Super Strength Thread) for tool joint pins. Recently, the owner/manufacturer [3.9] of this thread form has applied the thread modifications to drill collar box connections. However, the new design only includes the enlarged root radius and not the altered taper, and is known as an SRT (Stress Relief Thread). This would seem appropriate, as a reduction in the peak stress of the LET would improve the fatigue resistance of the fatigue prone BHA connections.

Amongst the other significant studies in this area is that of Tafreshi and Dover [3.4] who used two and three-dimensional models of drill collar connections subjected
Chapter 3 – Stress Analysis of Drill Collar Threaded Connections

to axial, bending and torsional loading to identify the regions of highest stress concentration. In all cases the peak stress concentration factors (SCFs) were found at the thread root of the first fully engaged loaded tooth in the pin and the first fully engaged loaded tooth in the box. They demonstrated that the SCF could be reduced by as much as 23% for a connector with stress relief features (bore back box and stress relief groove pin) compared to that of a standard connector.

Following on from the work of Smith [3.8], Tafreshi and Dover conducted a series of two-dimensional analyses on an NC-46 connector with a modified thread root geometry. They demonstrated the sensitivity of modifying individual thread root parameters. They identified that if the blend radius (the radius between the original thread root radius and the new cutback radius on the tooth) was too large, then there was an increase in the SCF.

With advances in FEA software and computing hardware it is now possible to extend analysis beyond the elastic limit and into elastic-plastic analysis. McDonald [3.10] used modified elements on a two-dimensional model to evaluate stress intensity factors for a large diameter drilling motor threaded connection. He produced a series of parametric equations of geometry correction (Y) factors for a range of crack depths in the last engaged tooth of the pin and box connector. Unfortunately, his solutions are specific for NC-61 drill collar connections. If a more generic solution had been produced it may have been applied in the failure assessment work described in Chapter 2.

3.3 FE Analysis of Drill Collar Threaded Connections

The two-dimensional axisymmetric finite element model is one of the most popular methods of stress analysis of API threaded connections. It is a useful tool in the comparative study of SCFs. For this reason, it was applied here to examine the sensitivity of manufacturing tolerances with regard to bore eccentricity, or misalignment of centres, through the threaded connections and its effect on SCF. It
has also been used to calculate the SCF for the connection under experimental investigation (Chapter 4).

The NDE Centre in the Department of Mechanical Engineering at U.C.L have been modelling oilfield threaded connections for several years [3.2, 3.3, 3.4]. From these studies they have developed a detailed FORTRAN program [3.11] which generates input files for the dedicated finite element analysis software ABAQUS [3.12]. The program generates two-dimensional axisymmetric finite element meshes for a range of different sized drill collar connections. It is able to produce models for the NC-46, NC-50, API 6-5/8 and API 7-5/8 Regular thread styles with stress relief features which can be modelled under axial load with or without connection pre-load.

The program has the option to model the connector with pre-load (make-up). By design the connection is a taper jack screw that forces the pin / box shoulder together forming a structural member by means of a metal to metal seal. In doing so, an alternative load path is created through the shoulder interface when the connection is made-up. This has the effect of transferring the critical LET from the pin to the box connector [3.2, 3.3]. In terms of FE modelling this is achieved by connecting the nodes of the pin and box at the shoulder interface, thus effectively welding the shoulder together.

3.4 Program Validation

The U.C.L. mesh generator was originally written by Sugunan [3.11] for ABAQUS v.2.0 (1991). In order to render it compatible with the current version, (v.5.8), several alterations were required in the program. Principal modifications made were associated with revised input data format and superseded ABAQUS command procedures. Once the program was functioning, it was necessary to validate the updated version against the results of the previous project. This was to confirm that the modifications would reproduce the same results for the latest release of ABAQUS.
The previous investigation [3.3] produced a range of SCF values for each thread size in the form of a three by three matrix of outside and inside diameters (Fig. 3.1), for the API connectors NC-46, NC-50, 6-5/8 Reg. and 7-5/8 Reg. It was possible to reproduce all of these results, with the application of the same axial loads and boundary conditions, to within ± 1% for all box and pin connectors, except for the 7-5/8 Reg. box. The results for this connection showed a consistent difference of approximately 15% below the SCFs found by the previous investigation, as shown in Tables 3.1 - 3.6. Recent correspondence with a co-author of the previous study has revealed that the authors were made aware of the differences of the SCFs in the 7-5/8 Reg. box some time after publication of the final report. However, these differences have very little effect on the parametric equations that were derived from the FE analysis. The parametric equation produced results that were within ± 0.12% of the SCF values obtained from this study [3.3].

Having updated and validated the mesh generation program, it could be used with confidence to examine the sensitivity of manufacturing tolerances on SCF.

3.5 Drill Collars and Bore Eccentricity

Following the previous full-scale experimental investigation into drill collar connections [3.13], a noticeable misalignment of the inner bore with the outer diameter was observed in a number of newly procured specimens. This observation led to consideration of the effect of bore eccentricity on the SCF. Drill collars are thick walled, heavy duty pipes with relatively large outside diameters. Bore eccentricity can arise due the misalignment of the centres of the inner and outer circles of the drill collar. It is an inevitable error that occurs during mass production where the bore is machined into the datum from both ends, which will always result in some degree of eccentricity in the final product.

The American Petroleum Institute (API), the unofficial yet globally accepted standards body for the petroleum industry, specify the properties of drilling tools and equipment. The API specification [3.14] for bore eccentricity restricts eccentricity to
0.094 in. (2.38 mm) at the ends and 0.25 in. (6.35 mm) at the centre of non-magnetic collars only. This is an absolute dimensional restriction and is not expressed as a proportion of the datum (or outer) diameter, thus it will obviously be of greater concern for users of smaller collars. There is no bore eccentricity specification for magnetic collars of which there is a larger inventory. It is only specified in the non-magnetic collars for the purpose of ensuring reasonable alignment of survey instruments, which are often run inside non-magnetic collars. For this reason, it was decided to examine the relationship between bore eccentricity and SCF.

3.5.1 Concept Validation

With the standard application of extended reach and horizontal drilling the drillstring is subjected to large bending loads. It was considered that bending could be represented on the 2D FE model by the application of variable distributed axial point loads, as shown in Fig. 3.2. In order to confirm the validity of this idea several finite element analyses were performed on simple tube geometries. To accomplish this an alternative software, I-DEAS [3.15], was used for its rapid geometry construction tools and FE mesh generation.

A simple concentric tube was constructed and free meshed using 10 noded solid tetrahedral elements (Fig. 3.3). Free meshing the tube gave greater flexibility in defining the mesh area over that of mapped meshing, which requires defined 'edges' over which to mesh. The mesh was automatically generated by an algorithm which attempts to minimise element distortion, i.e. deviation from the perfect element. Element distortion was kept to a value of 0.6, where 1.0 represents the perfect element. Values of 0.5 to 1.0 are considered satisfactory [3.15]. Badly distorted elements result in the failure of the model due to highly distorted nature of the elements being unable to transmit the forces from node to node. A convergence study to identify the density of the mesh, i.e. the number of elements, to give a suitably accurate answer in the regions of interest, found that a model with 1054 elements was satisfactory.
3.5.2 Boundary Conditions

Boundary conditions were applied to the model to generate pure bending, as illustrated in Fig. 3.4. Calculations based on simple beam theory, equations (3.1, 3.2, 3.3), were performed to identify the magnitude of the applied load so that the stress at the outer most fibre would be unity.

\[
\sigma_{\text{max}} = \frac{M}{I} y_{\text{max}} ......................................................... (3.1)
\]

with

\[
I = \frac{\pi}{64} (OD^4 - ID^4) ......................................................... (3.2)
\]

and

\[
M = F \times d ................................................................. (3.3)
\]

The results from the FEA confirmed that the maximum stress occurred at the outer diameter (maximum "y" value) and decreased linearly from tension to equal and opposite compression, as shown in Figure 3.5.

The boundary conditions were then modified so that one end of the tube was constrained in X and Z translation and in Y and Z rotation, so eliminating any shear effects. Two opposing point loads were applied along the axis of the free end of the model, at the appropriate distance from the neutral axis. The magnitude of the loads were calculated by equations (3.4, 3.5, 3.6) to give a stress distribution similar to that of a four point bend model.

\[
F = \int_{r_{ID}}^{r_{OD}} \int_{0}^{\pi} \sigma(r, \theta) (r \cdot dr \cdot d\theta) ......................................... (3.4)
\]

where

\[
\sigma = \frac{M}{I} r \sin \theta ................................................................. (3.5)
\]
giving

\[ F = \frac{M}{l} \int_{r_{ID}}^{r_{OD}} r^2 \, dr \int_0^{\frac{\pi}{2}} \sin \theta \, d\theta \] ................................. (3.6)

Figures 3.6 and 3.7 show the boundary conditions and the resultant stress distribution diagrams, which are identical to that of the model under four point bend test conditions, thus confirming the principle that axially applied point loads can simulate pure bending.

3.5.3 Eccentricity

Eccentricity is defined as “A load or component of a load normal to a given cross section of a member is eccentric with respect to that section if it does not act through the centroid. The perpendicular distance from the line of action of the load to either principal central axis is the eccentricity with respect to that axis” [3.16]. Eccentricity (Fig. 3.8) brings with it changes in the position of the neutral axis and second moment of area of the body. To confirm the definitions for the shift of neutral axis, equation (3.7), and the Parallel Axis Theorem, equation (3.8), another simple tube was constructed with an eccentric bore.

\[-\bar{y} = \frac{A_1y_1 - A_2y_2}{A_1 - A_2} \] ................................................................. (3.7)

\[ I_T = I_1 + A_1(y_1 - \bar{y})^2 - [I_2 + A_2(y_2 - \bar{y})^2] \] ...................................................... (3.8)

Four point bending boundary conditions were applied to the model, with the magnitude of the loads being so that the stress would be unity at the maximum 'y'
position. Figures 3.9 and 3.10 show the results for two eccentric models, 6% and 12% respectively and verify the theory of equations (3.7, 3.8).

### 3.5.4 Finite Element Model

Having confirmed the theory, using a simplified geometry, it could now be applied to the complex models of the API connector. The popular NC-50 connection with stress relief features was selected for analysis. Typical drill collar connection dimensions of 7 in. (177.8 mm) outer diameter and 3-1/4 in. (82.55 mm) inner diameter were selected for the connection.

Local stresses in a threaded connection subjected to bending are relatively high compared to the nominal stress in a region away from the thread form. This localisation of stresses is known as a stress concentration. The stress concentration factor (SCF) is a dimensionless measure of the maximum local stress and is defined by equation (3.9) (consistent with all previous models [3.2, 3.3, 3.4]). The nominal stress is defined as the stress in a region suitably far away from any geometrical variation.

\[
\text{SCF} = \frac{\text{maximum } \sigma_{\text{local}}}{\sigma_{\text{nominal}}} \tag{3.9}
\]

The purpose of the FEA was to determine the level of increase of SCF in the connection as a result of increasing bore eccentricity. The FORTRAN mesh generation program allows the user to input a number of variables such as type of connector, joint dimensions, and the application (or not) of pre-load. Eight noded quadrilateral elements were used for the general mesh with two noded gap elements being used for contact between the thread teeth. The pin and box materials were assumed to be linear elastic with the general properties of steel, a Modulus of Elasticity, \(E = 203,000 \text{ Nmm}^{-2}\) and Poisson’s ratio, \(\nu = 0.3\).
3.5.5 Boundary Conditions

Bending loads corresponding to different degrees of bore eccentricity were simulated via the application of variable distributed axial point loads that were determined by analytical stress analysis, via the application of the Engineers Theory of Bending, as given by equation (3.1). The axial point loads were calculated at appropriate intervals of "y" (Table 3.7) for the increasing eccentricity, such that they were applied linearly along the 21 nodes of the meshed models box end. A sample mesh, Figure 3.11, illustrates the loading and boundary conditions applied to the model, with Figure 3.12 showing a close up of the mesh.

As mentioned previously the nominal stress should be in a region suitably far away from any geometrical differences. The previous study [3.3] used a model of length 2.5 times the outer diameter of the connection, and a nominal stress definition of, uniform applied axial load divided by the cross sectional area of the connector. However, the values obtained using this definition of nominal stress barely met those found in a region suitably away from the thread form. It has been found that increasing the length of the connection to at least three times the outer diameter will stabilise the values of nominal stress. The result is a plateau in the values in a region well away from the thread form and boundary conditions, as shown in Figure 3.13. The nominal stress was always measured against the 0% eccentric case, as the designer must work to the ideal design situation of 0% eccentricity.

The finite element model is axisymmetric about the z - axis and is therefore a simplification of the actual case. It has been assumed in this analysis that the applied load distribution to the boundary, simulating the shift in neutral axis, takes account of the worst case (tension) face of the connection under bending, and that the axisymmetry of the model has little effect.

3.5.6 Computational Facilities

The FORTRAN program produces an input file that generates a mesh for the ABAQUS FE package. A typical analysis of a model containing 3336 elements can
be obtained in 240 seconds of CPU time. All analyses were performed on a Digital DEC Alphastation 400 MHz, running the UNIX Tru64 operating system.

Twenty eight models of increasing eccentricity were analysed ranging from 0% to 10% eccentricity, for the connection under pre-loaded and unpre-loaded conditions. The SCF results are presented and discussed in the following section.

### 3.5.7 Eccentricity Stress Analysis Results

As can be seen in Tables 3.8 and 3.9, the maximum local stress occurs in the 1st fully engaged thread root of the pin in the unpre-loaded condition and in the 1st fully engaged thread root of the box in the pre-loaded condition. Figure 3.14 illustrates the stress contours of the loaded joint, and shows the location of the maximum local stress in a pre-loaded connection. The “hot spot” may be seen just out of centre of the 1st loaded thread root in the box connector.

The effects of bore eccentricity can be seen to be of significance as a 10% eccentricity gives rise to a 23.66% increase in SCF. Figures 3.15 and 3.16 show the effects of increasing bore eccentricity on the SCFs. A 3.5% eccentricity, which is acceptable under API jurisdiction for non-magnetic collars (there is no restriction for ferritic collars), still gives rise to a 7.36% increase in SCF for the unpre-loaded connection, and 7.32% increase in SCF for the pre-loaded connection. The significance of an increase in SCF would be an expected decrease in fatigue life. Indeed, results have shown [3.17] that an eccentricity of 2.39 mm at the drill collar end, which is allowable under the API, can lead to as much as a 35% reduction in the life of the collar.

### 3.6 FE Analysis of Experimental Specimen

The primary focus of this FE study was on the sensitivity of bore eccentricity on SCF, and the NC-50 connection with stress relief features was analysed. However, a smaller, NC-26, connection was selected for experimental investigation (Chapter 4).
The NC-26 connection has the same shape and thread form as its larger NC family members, the main difference, apart from the nominal dimensions, is that stress relief features are not recommended. The API specification for drill collars [3.14] recommends that stress relief features are not added to connections NC-31, 26, 23, due to insufficient material. The purpose of the finite element study was to obtain stress concentration factors for the threaded connection under experimental investigation (Chapter 4). The SCFs for the experimental tests needed to be known before the test loading parameters could be defined.

3.6.1 The NC-26 Finite Element Model

The mesh generation program had to be modified for the NC-26 connection. The NC-26 rotary shoulder connection is the same thread form, pitch and taper as the larger NC-46 and NC-50 connectors. Therefore, modifications to the mesh generation program were concerned with dimensional inputs from the API specification [3.14] for the standard connection geometry.

The FE model represented a standard API NC-26 connector of 3-1/2 in. (88.9 mm) outer diameter and 1-1/2 in. (38.1 mm) inner diameter, as shown in Fig. 3.17. As with the previous models, eight noded quadrilateral elements were used for the mesh, with two node gap elements for contact between the teeth. The pin and box materials were assumed to be linear elastic, with the general properties of steel, i.e. Modulus of Elasticity, E = 203 GPa, and Poissons ratio = 0.3.

Boundary conditions representing bending were applied to the model. The experimental investigation (Chapter 4) would involve testing the specimens under bending conditions. Using equations (3.1 – 3.3) variable distributed axial point loads corresponding to the appropriate node (“y”) position were applied linearly along the box end. Two models of the NC-26 connection were produced, one with pre-load and the other without.
3.6.2 SCF Results

The SCF results can been seen in Table 3.10, with the maximum local stress occurring in the 1st fully engaged thread root of the pin in the un-preloaded connection, Fig. 3.18, and in the 1st fully engaged thread root of the box in the pre-loaded connection, Fig. 3.19. Figure 3.20 and 3.21 show the SCF distribution along the thread. It can be seen that the critical tooth changes from the pin to the box under the effect of pre-load.

3.7 Conclusions

Stress concentration factors have been found for an NC-50 drill collar connection exhibiting increasing amounts of bore eccentricity. The effect of bore eccentricity can be seen as significant in increasing the magnitude of the maximum SCF. Currently, there is no manufacturing specification for the amount of bore eccentricity allowable in new magnetic drill collar members. The only specification reported is for non-magnetic collars. As with many API specifications for drilling tools, it is often the manufacturers who specify their own manufacturing tolerances. This may lead to a considerable array in the quality of drillstring elements.

The SCFs for the NC-26 connector have been computed, thus allowing the design calculations for the full-scale experimentation (Chapter 4) to be performed.
3.8 References


### Chapter 3 - Stress Analysis of Drill Collar Threaded Connections

#### 3.9 Tables

<table>
<thead>
<tr>
<th>Connector</th>
<th>Dimensions</th>
<th>Pre-load</th>
<th>Max. SCF ABAQUS v.2.0</th>
<th>Max. SCF ABAQUS v.5.8</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC-46 Pin</td>
<td>6-1/2 x 3-1/4 in. 165.1 x 82.55 mm</td>
<td>WITHOUT</td>
<td>14.39</td>
<td>14.36</td>
<td>-0.21 %</td>
</tr>
<tr>
<td>NC-46 Box</td>
<td>6-1/4 x 2-1/4 in. 158.75 x 57.15 mm</td>
<td>WITHOUT</td>
<td>10.79</td>
<td>10.78</td>
<td>-0.09 %</td>
</tr>
<tr>
<td>NC-46 Pin</td>
<td>6-1/2 x 2-13/16 in. 165.1 x 71.4 mm</td>
<td>WITH</td>
<td>3.236</td>
<td>3.195</td>
<td>-1.30 %</td>
</tr>
<tr>
<td>NC-46 Box</td>
<td>6-1/4 x 3-1/4 in. 158.75 x 82.55 mm</td>
<td>WITH</td>
<td>5.434</td>
<td>5.435</td>
<td>+0.02 %</td>
</tr>
</tbody>
</table>

**Table 3.1** - Comparison of maximum SCF results for NC-46 for modified mesh generation program.

<table>
<thead>
<tr>
<th>Connector</th>
<th>Dimensions</th>
<th>Pre-load</th>
<th>Max. SCF ABAQUS v.2.0</th>
<th>Max. SCF ABAQUS v.5.8</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC-50 Pin</td>
<td>6 x 2-1/4 in. 152.4 x 57.15 mm</td>
<td>WITHOUT</td>
<td>9.629</td>
<td>9.631</td>
<td>+0.02 %</td>
</tr>
<tr>
<td>NC-50 Box</td>
<td>6-1/2 x 3-1/4 in. 165.1 x 82.55 mm</td>
<td>WITHOUT</td>
<td>9.642</td>
<td>9.631</td>
<td>-0.11 %</td>
</tr>
<tr>
<td>NC-50 Pin</td>
<td>7 x 2-13/16 in. 177.8 x 71.4 mm</td>
<td>WITH</td>
<td>3.572</td>
<td>3.532</td>
<td>-1.12 %</td>
</tr>
<tr>
<td>NC-50 Box</td>
<td>6 x 2-1/4 in. 152.4 x 57.15 mm</td>
<td>WITH</td>
<td>9.438</td>
<td>9.438</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 3.2** - Comparison of maximum SCF results for NC-50 for modified mesh generation program.

<table>
<thead>
<tr>
<th>Connector</th>
<th>Dimensions</th>
<th>Pre-load</th>
<th>Max. SCF ABAQUS v.2.0</th>
<th>Max. SCF ABAQUS v.5.8</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-5/8 Reg. Pin</td>
<td>7-1/2 x 2-1/2 in. 190.5 x 63.5 mm</td>
<td>WITHOUT</td>
<td>14.45</td>
<td>14.49</td>
<td>+0.27 %</td>
</tr>
<tr>
<td>6-5/8 Reg. Box</td>
<td>8-1/4 x 2-13/16 in. 209.55 x 71.4 mm</td>
<td>WITHOUT</td>
<td>14.17</td>
<td>14.13</td>
<td>-0.28 %</td>
</tr>
<tr>
<td>6-5/8 Reg. Pin</td>
<td>7-7/8 x 2-1/2 in. 200.25 x 63.5 mm</td>
<td>WITH</td>
<td>4.94</td>
<td>4.90</td>
<td>-0.81 %</td>
</tr>
<tr>
<td>6-5/8 Reg. Box</td>
<td>8-1/4 x 3-1/4 in. 209.55 x 82.55 mm</td>
<td>WITH</td>
<td>7.838</td>
<td>7.785</td>
<td>-0.60%</td>
</tr>
</tbody>
</table>

**Table 3.3** - Comparison of maximum SCF results for 6-5/8 Reg. for modified mesh generation program.
### Table 3.4 - Comparison of maximum SCF results for 7-5/8 Reg. for modified mesh generation program.

<table>
<thead>
<tr>
<th>Connector</th>
<th>Dimensions</th>
<th>Pre-load</th>
<th>Max. SCF ABAQUS v.2.0</th>
<th>Max. SCF ABAQUS v.5.8</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-5/8 Reg. Pin</td>
<td>8-1/2 x 2-1/2 in. 215.9 x 63.5 mm</td>
<td>WITHOUT</td>
<td>15.17</td>
<td>15.14</td>
<td>- 1.98 %</td>
</tr>
<tr>
<td>7-5/8 Reg. Box</td>
<td>9-1/2 x 2-1/2 in. 241.3 x 63.5 mm</td>
<td>WITHOUT</td>
<td>16.61</td>
<td>14.12</td>
<td>- 14.99 %</td>
</tr>
<tr>
<td>7-5/8 Reg. Pin</td>
<td>9 x 3 in. 228.6 x 76.2 mm</td>
<td>WITH</td>
<td>5.31</td>
<td>5.10</td>
<td>- 3.90%</td>
</tr>
<tr>
<td>7-5/8 Reg. Box</td>
<td>9-1/2 x 3-3/4 in. 241.3 x 95.25 mm</td>
<td>WITH</td>
<td>8.00</td>
<td>6.88</td>
<td>- 14.00 %</td>
</tr>
</tbody>
</table>

### Table 3.5 - Further comparison of maximum SCF results for 7-5/8 Reg. (without pre-load) for modified mesh generation program.

<table>
<thead>
<tr>
<th>Connector</th>
<th>Dimensions</th>
<th>Max SCF ABAQUS v.2.0</th>
<th>Max SCF ABAQUS v.5.8</th>
<th>% Difference</th>
<th>Parametric SCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-5/8 Reg. Box</td>
<td>8-1/2 x 3 in. 215.9 x 76.2mm</td>
<td>14.26</td>
<td>12.23</td>
<td>- 14.23 %</td>
<td>14.25</td>
</tr>
<tr>
<td>7-5/8 Reg. Box</td>
<td>8-1/2 x 2-15/32 in. 215.9 x 87.72 mm</td>
<td>13.62</td>
<td>11.64</td>
<td>- 14.54 %</td>
<td>13.60</td>
</tr>
<tr>
<td>7-5/8 Reg. Box</td>
<td>9 x 3-3/4 in. 228.6 x 95.25 mm</td>
<td>13.60</td>
<td>11.57</td>
<td>- 14.92%</td>
<td>13.74</td>
</tr>
</tbody>
</table>

### Table 3.6 - Further comparison of maximum SCF results for 7-5/8 Reg. (with pre-load) for modified mesh generation program.

<table>
<thead>
<tr>
<th>Connector</th>
<th>Dimensions</th>
<th>Max SCF ABAQUS v.2.0</th>
<th>Max SCF ABAQUS v.5.8</th>
<th>% Difference</th>
<th>Parametric SCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-5/8 Reg. Box</td>
<td>8-1/2 x 3 in. 215.9 x 76.2mm</td>
<td>9.81</td>
<td>12.23</td>
<td>- 11.93 %</td>
<td>9.83</td>
</tr>
<tr>
<td>7-5/8 Reg. Box</td>
<td>8-1/2 x 2-15/32 in. 215.9 x 87.72 mm</td>
<td>9.27</td>
<td>8.13</td>
<td>- 12.30 %</td>
<td>9.37</td>
</tr>
<tr>
<td>7-5/8 Reg. Box</td>
<td>9 x 3-3/4 in. 228.6 x 95.25 mm</td>
<td>8.66</td>
<td>7.57</td>
<td>- 12.60%</td>
<td>8.64</td>
</tr>
</tbody>
</table>
Table 3.7 - Geometrical values for increasing degrees of eccentricity.
<table>
<thead>
<tr>
<th>% Eccentricity</th>
<th>$\sigma$ nom.</th>
<th>$\sigma$ max.</th>
<th>$\sigma$ max location</th>
<th>SCF</th>
<th>% Increase in SCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$4.5024 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>6.885</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$4.5922 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>7.022</td>
<td>1.99</td>
</tr>
<tr>
<td>1.5</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$4.6388 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>7.093</td>
<td>3.02</td>
</tr>
<tr>
<td>2</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$4.6862 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>7.166</td>
<td>4.08</td>
</tr>
<tr>
<td>2.5</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$4.7337 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>7.238</td>
<td>5.13</td>
</tr>
<tr>
<td>3</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$4.8152 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>7.363</td>
<td>6.94</td>
</tr>
<tr>
<td>3.5</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$4.8320 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>7.389</td>
<td>7.32</td>
</tr>
<tr>
<td>4</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$4.8795 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>7.461</td>
<td>8.36</td>
</tr>
<tr>
<td>5</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$4.9869 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>7.625</td>
<td>10.75</td>
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<tr>
<td>6</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$5.0938 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>7.789</td>
<td>13.13</td>
</tr>
<tr>
<td>7</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$5.1960 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>7.945</td>
<td>15.39</td>
</tr>
<tr>
<td>8</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$5.3274 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>8.146</td>
<td>18.31</td>
</tr>
<tr>
<td>9</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$5.4420 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>8.321</td>
<td>20.85</td>
</tr>
<tr>
<td>10</td>
<td>$0.6539 \times 10^{-2}$</td>
<td>$5.5681 \times 10^{-2}$</td>
<td>1st Thread root on BOX</td>
<td>8.514</td>
<td>23.66</td>
</tr>
</tbody>
</table>

Table 3.8 - Results of FEA for NC-50 connection with pre-load.
<table>
<thead>
<tr>
<th>% Eccentricity</th>
<th>$\sigma_{\text{nom.}}$</th>
<th>$\sigma_{\text{max.}}$</th>
<th>$\sigma_{\text{max location}}$</th>
<th>SCF</th>
<th>% Increase in SCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$0.6606 \times 10^{-2}$</td>
<td>$9.2452 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>13.99</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>$0.6606 \times 10^{-2}$</td>
<td>$9.4298 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>14.27</td>
<td>2.00</td>
</tr>
<tr>
<td>1.5</td>
<td>$0.6606 \times 10^{-2}$</td>
<td>$9.5253 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>14.41</td>
<td>3.00</td>
</tr>
<tr>
<td>2</td>
<td>$0.6606 \times 10^{-2}$</td>
<td>$9.6227 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>14.56</td>
<td>4.07</td>
</tr>
<tr>
<td>2.5</td>
<td>$0.6606 \times 10^{-2}$</td>
<td>$9.7202 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>14.71</td>
<td>5.15</td>
</tr>
<tr>
<td>3</td>
<td>$0.6606 \times 10^{-2}$</td>
<td>$9.8875 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>14.96</td>
<td>6.93</td>
</tr>
<tr>
<td>3.5</td>
<td>$0.6606 \times 10^{-2}$</td>
<td>$9.9219 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>15.02</td>
<td>7.36</td>
</tr>
<tr>
<td>4</td>
<td>$0.6606 \times 10^{-2}$</td>
<td>$10.020 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>15.17</td>
<td>8.43</td>
</tr>
<tr>
<td>5</td>
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<td>$10.240 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>15.50</td>
<td>10.79</td>
</tr>
<tr>
<td>6</td>
<td>$0.6606 \times 10^{-2}$</td>
<td>$10.460 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>15.83</td>
<td>13.15</td>
</tr>
<tr>
<td>7</td>
<td>$0.6606 \times 10^{-2}$</td>
<td>$10.670 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>16.15</td>
<td>15.45</td>
</tr>
<tr>
<td>8</td>
<td>$0.6606 \times 10^{-2}$</td>
<td>$10.940 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>16.56</td>
<td>18.37</td>
</tr>
<tr>
<td>9</td>
<td>$0.6606 \times 10^{-2}$</td>
<td>$11.170 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>16.91</td>
<td>20.87</td>
</tr>
<tr>
<td>10</td>
<td>$0.6606 \times 10^{-2}$</td>
<td>$11.430 \times 10^{-2}$</td>
<td>1st Thread root on PIN</td>
<td>17.30</td>
<td>23.66</td>
</tr>
</tbody>
</table>

*Table 3.9 - Results of FEA for NC-50 connection without pre-load.*
### Table 3.10 - Maximum SCF results for standard NC-26 under bending load.

<table>
<thead>
<tr>
<th>Connector</th>
<th>Dimensions</th>
<th>Pre-load</th>
<th>PIN</th>
<th>BOX</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC-26</td>
<td>3-1/2 x 1-1/2 in. 88.9 x 38.1 mm</td>
<td>WITHOUT</td>
<td>10.45</td>
<td>9.15</td>
</tr>
<tr>
<td>NC-26</td>
<td>3-1/2 x 1-1/2 in. 88.9 x 38.1 mm</td>
<td>WITH</td>
<td>4.18</td>
<td>6.45</td>
</tr>
</tbody>
</table>
3.10 Figures

<table>
<thead>
<tr>
<th>ID</th>
<th>OD</th>
<th>6 in. (152.4 mm)</th>
<th>6-1/4 in. (158.7 mm)</th>
<th>6-1/2 in. (165.1 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1/4 in.</td>
<td>6 in.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-13/16 in.</td>
<td>6-1/4 in.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-1/4 in.</td>
<td>6-1/2 in.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.1** - Illustration of SCF matrix for NC-46 connection.

**Figure 3.2** - Pure bending conditions simulated by the application of axial point loads.

**Figure 3.3** - I-DEAS 10 node tetrahedral element.
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Figure 3.4 - Pure bending boundary conditions.

Figure 3.5 - Stress distribution through centre of tube.

Figure 3.6 - Axial point load boundary conditions.

Figure 3.7 - Stress distribution through centre of tube.
Figure 3.8 - Illustration of eccentricity.

Figure 3.9 - Stress distribution through centre section of 6% eccentric tube.
Figure 3.10 - Stress distribution through centre section of 12% eccentric tube.

Figure 3.11 - Model boundary conditions applied to NC50.
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**Figure 3.12** - Close-up of mesh.

**Figure 3.13** - Location of nominal stress.
Figure 3.14 - Maximum local stress in 1st thread root of box connector for pre-loaded NC50 under bending.

Figure 3.15 - Increase in SCF with bore eccentricity for NC-50 without pre-load.
Figure 3.16 - Increase in SCF with bore eccentricity for NC-50 with pre-load.

Figure 3.17 - FE mesh of API NC-26 connection.
Figure 3.18 – Location of maximum SCF on NC-26 pin connector without pre-load.

Figure 3.19 - Location of maximum SCF on NC-26 box connector with pre-load.
Figure 3.20 - SCF distribution for NC-26 connection without pre-load.

Figure 3.21 - SCF distribution for NC-26 connection with pre-load.
Chapter 4

4.0 Experimental Design & Set-up

4.1 Introduction

The earlier studies on the fatigue behaviour of drill collars [4.1-4.4], have focused on the larger sizes of collar, (upwards of 5 in. outer diameter), as these sizes are most commonly used in the drill string to apply weight on the drill bit (WOB) and so make new hole. However, with the current industry initiative of reducing well costs, the application of slimhole drilling is now common practice. Slimhole drilling is identical to conventional drilling, the only difference being that smaller diameter drill pipe and collar are used to support the bit. Typical slimhole drill collars are 4 inches in. outer diameter and below. This method of drilling has been successfully applied to numerous field developments. One of the most notable being the Hibernia project on the Grand Banks, offshore Newfoundland, where it has reportedly reduced drilling costs by 50% when compared to conventional drilling [4.5].

Despite the increasing use of slimhole tubulars, there is little or no published data on their fatigue performance, for this reason it has been decided to study their fatigue behaviour. The advantage of using slimhole tubulars can not only be found in the field, laboratory tests also benefit from their smaller size, in reduced make-up torque, (a major consideration) and reduced price per unit. Therefore, the NC-26 connection, 3-1/2 in. outer diameter and 1-1/2 in. inner diameter, was selected for investigation.

This chapter details the design and construction of a full-scale purpose built fatigue test rig for NC-26 drill collars, which for the first time includes the facility for periodic thread inspection using a modern NDT technique. With the facility to extract
periodic crack growth data from the connection it is intended that fracture mechanics models used to predict crack growth behaviour can be refined and made more accurate.

Also described is the development and construction of a “miniaturised” thread cold rolling device. The cold rolling of thread roots after manufacture is a method of increasing the component’s fatigue life [4.6], by introducing beneficial residual compressive stresses in regions of stress concentrations. Drill collar manufactures currently only cold roll threaded connections above and including NC-38 (> 5 in. OD and 2-1/4 in. ID), therefore, the NC-26 is left as machined and un-rolled. However, developing a device to cold roll the smaller geometry of the NC-26 has allowed investigation of the cold rolling procedure of drill collar threads as a whole.

4.2 Fatigue Testing of Rotary Shouldered Connections

The drillstem manufacturers have led the way in the experimental testing of oilfield threaded connections. One of the earliest and most intensive studies was performed by Bachman [4.7] of the Hughes Tool Company, who over a 15 year period collected fatigue test data from reportedly over 1000 full scale rotating bend tests. The investigation was focused on the development of an improved tool joint design and methods of attachment to the drill pipe body. His work represented a substantial part of the fatigue information published on downhole tool joints at that time.

One of the first published investigations into the fatigue prone drill collar connections was by Trishman [4.1] of the National Supply Company in 1952. This investigation focused on methods of improving connection fatigue life by surface treatments and modifications to the geometry. He used a rotating cantilever beam type machine, similar to Bachman, to test connections that were surface treated by nitriding and cold rolling. Nitriding was rejected as an improvement method as the nitride layer at the thread root created a very hard surface that cracked when the connection was torqued up. The cold working of thread roots to improve fatigue
performance was just being considered as a surface treatment method for drill collar connectors. Recognising the potential benefits of cold working, Trishman developed a thread root rolling device for the popular, and fatigue prone 4-1/2 in. FH connection. The device used mechanical force to drive a hardened roller, of the same profile and root radius as the FH thread form, into the thread root creating up to 0.254 mm (0.010 in.) deformation in the root. This resulted in a 50% improvement in fatigue life over an equivalent un-rolled connection. However, he found that the fatigue life of the connection could be improved further if stress relief features were added to the pin and box connections. By machining a groove in the region behind the last engaged thread (LET) of the pin and box, the fatigue life could be improved by 100% over the standard connection. His work, as he mentions, was only the starting point for investigating the fatigue behaviour of drill collar connections, with many more elements needing to be investigated.

Tsukano et al [4.8] of the Nippon Steel Corporation modified an API NC connection by reducing the height of the pin connector’s last engaged thread (LET). Results from full scale rotating bend tests on NC-40 connections demonstrated that the re-designed connection had a fatigue life of up to 3 times that of a standard connection. Their new design removed material from the LET of the pin and was effectively a stress relief groove, which was already a feature on many drill collar connections.

Other notable experimental investigations into drill collar connection fatigue behaviour have come from Baryshnikov et al [4.9]. Using a resonant type fatigue testing machine to apply cyclic bending loads, they assessed the relative fatigue strength characteristics of the different drill collar connectors, with the intention of developing a recommended practise for downhole tool analysis under dynamic loading. Brennan [4.10] performed a series of axial and rotating bend tests on large diameter connections. Using a 2.5 MN dynamic test machine for the axial tests and a custom built rig for the rotating bend tests, he was able to collect crack growth data, using the beach marking technique, for magnetic and non-magnetic NC-50 and 6-5/8
Regular connections. These results were used to validate his fracture mechanics weight function models.

### 4.3 Design of Full-Scale Test Rig

The investigations summarised in the previous section, report the success of the rotating bend test arrangement for the fatigue testing of drill collar connections, as this best simulates the primary operating conditions of the drillstring. The following sections detail the author’s design and construction of a custom built four-point rotating bend test rig for the fatigue testing of 3-1/2 in. OD x 1-1/2 in. ID slick drill collars with NC-26 connections. As the rig contained many component parts the computer aided design software package I-DEAS [4.11] was used throughout the design process, providing a powerful tool for the virtual assembly of the rig. The test rig was located in the Marine Technology Laboratory in the Department of Mechanical Engineering at UCL.

#### 4.3.1 Loading Conditions

Four-point bend loading conditions were selected for the test programme as they result in pure bending being generated in the connection without any shear effects, as seen in the shear force and bending moment diagram, as shown in Figure 4.2. Following the identification of the SCF for the connection (Chapter 3) and by using the engineers’ theory of bending equations (4.1 – 4.3), the test rig design loads could be calculated.

\[
\sigma_{\text{max}} = \frac{M}{I} y_{\text{max}} \quad \text{................................................................. (4.1)}
\]

with

\[
I = \frac{\pi}{64} \left(OD^4 - ID^4\right) \quad \text{................................................................. (4.2)}
\]
and \[ M = F \times d \] \hspace{1cm} (4.3)

The test rig footprint was 2.75 m x 1.83 m on to which the specimens, loading points and load applicator were located. The specimens were supported and rotated in a set of four roller bearings, and in order to generate the four point bending conditions, the two in-board bearings were loaded equally, and the two out-board bearings were restrained, Fig. 4.2. The external force was generated through a horizontal displacement servo-hydraulic 1000 kN actuator loading the in-board bearings.

The ability to torque-up the connection was a key parameter, and a means to accurately achieve this was designed into the test rig from the outset. The ability to make and break the connection was an essential feature in order to allow access to the pin and box connectors for periodic inspection. On modern drilling rigs this ability to torque and un-torque the connection is achieved by the use of an iron roughneck and or hydraulic power tongs, as shown in Figures 4.3 and 4.4. However, such specialist equipment can be very bulky and expensive, therefore the time-honoured rig technology of a chain block, weight indicator and manual tongs was utilised for making and breaking the connection in the laboratory.

4.3.2 Connection Make & Break

The NC-26 connection has a recommended make-up torque of 4,668 ft-lbs (6,329 N.m) [4.11]. This was applied to the connection with the use of a two tonne overhead gantry crane and a set of manual rig tongs. A set of 3-1/2 in. OD drill collar tongs, as shown in Fig. 4.5, were obtained from an offshore tool rental company. As make-up torque is a product of the tong arm length and line pull force, a weight indicator was added in order to measure the applied line pull from the overhead crane. Figure 4.6 illustrates the make and break procedure with manual tongs. Using the K-30 type rig tongs (Fig. 4.5) a line pull of 800 kg was required to torque the connection to the recommended level. The metal to metal contact of the pin and box connection
requires substantial lubrication for reliable make and break performance. Though the connectors were supplied with an anti-gall coating, this only serves to protect the connection on the initial make-up. For reliable and repeated make and break operations heavy duty thread lubrication (dope) is required. The commercially available and recommended brand of Shell Malleus STC1 thread compound was used as the lubricant for all make and break operations.

In order to make and break the connection for inspection at set intervals during the test, one of the connectors needed to be moved or retracted from the other after breakout, to provide clearance for the inspection equipment. Also, to allow clearance and positioning of the tongs for the breaking and making process, the load applying actuator had to be moveable. To provide simple and rapid linear motion of these components, heavy duty roller track was used.

4.3.3 Hydraulic Actuator

A servo-hydraulic horizontal displacement INSTRON actuator was used to apply the external load. The actuator was a double acting cylinder with a capacity of ± 1000 kN, and a stroke length of 100 mm. It was intended to run the tests with the actuator under load control. The actuator was fitted with a ± 500 kN dynamic load cell. However from the theoretical stress analysis the maximum load that would be applied to the specimens would amount to 6% of the load cell capacity, considered too low for reliable load control operation. Therefore, a smaller load cell, ± 50 kN was fitted to the actuator, “piggy-backing” it onto the larger load cell. However, this smaller load cell required a separate output controller, therefore the tests were run with the actuator under position control, with the load measured from the smaller capacity load cell on a separate controller. An electrically powered pump operating at 21 bar (300 psi) provided hydraulic power to the actuator. Figure 4.7 illustrates the hydraulic circuit.
4.3.4 Bearings

To support the rotating drill collar (shaft), roller element bearings were required. To reduce downtime during specimen change over at the end of each test, split spherical roller bearings were selected for their rapid assembly and dismantling, see Fig. 4.8. Following various manufacturers specifications on size, load capacity and operating speeds, FAG 3-7/16 in. split spherical roller bearings with steel housings were selected. Table 4.1 describes the bearing specification. By having split bearings the amount of precision machining of the shafts surface (for the fit) was kept to a minimum, as shown in Fig. 4.9.

Angular misalignment between the shaft and bearing housing would occur when the two in-board bearings were being loaded. Misalignment can lead to premature deterioration of the bearing in service, however, the split spherical roller bearing has a greater capacity to accommodate misalignments than rigid bearings. The angle of misalignment is a function of shaft deflection. The amount of deflection in the shaft was calculated from the Flexure Equation (4.4).

\[-M = EI \frac{d^2v}{dx^2}\]

where \(v\) = deflection
\(x\) = position along beam

The design load of 30 kN produced a 5.78 mm deflection, which resulted in a 0.34° angle of misalignment with the out-board bearing, which was well within the capacity of the bearing.

The bearings needed to be supported with a clearance above the base plate so that the tongs for the make and break could be attached. The bearings were therefore mounted on standard steel rectangular hollow sections. To allow the shaft to deflect the two in-board bearings needed to be free to slide over the top surface of the
supporting rectangular section. To minimise resistance to this motion, flange fitting ball transfer units were fitted to the surface of the two in-board supports.

Vertical alignment was also important in order to maintain reliable performance from the bearings. With the ball transfer units fitted to the two in-board bearing supports, packing plates were required to make up the height on the two out-board bearings. With the use of a laser level and shims the vertical alignment of the shaft in the four bearings was ± 0.2 mm over 2.5 m. The bearings were packed with Spheerol MP2 lithium soap grease as recommended by the manufacturer.

4.3.5 Electric Motor

Rotational motion was provided to the shaft by means of a 14 kW variable speed 3-phase electric motor, mounted on a rigid base adjacent to the main test rig base plate. Rotational drive from the motor to the shaft was via a simple follower mechanism. This eliminated any alignment problems between the rotating centres, allowing independent rotation to be transferred between motor drive shaft and the specimen. An electronic counter was fitted to the drive shaft of the motor to record the number of rotations (cycles) of the specimen.

The complete virtual assembly of the test rig can been seen in Figures 4.10 and 4.11, with actual test rig shown in Figure 4.12.

4.4 Test Specimens

The test specimens were obtained via standard procurement procedures from an API licensed drill collar manufacturer. Nominal dimensions of 3-1/2 in. (88.9 mm) OD and 1-1/2 in. (38.1 mm) ID and a length of 2.5 m were specified, Figure 4.13. API NC-26 pin and box connections were machined into the ends of the collar, details of which are shown in Figure 4.14.
The specimens were manufactured from the standard drill collar material of AISI 4145 H. This is a heat treated chromium molybdenum alloy steel that conforms to the minimum material requirements in the API specification [4.13]. The chemical composition from the batch of specimens is detailed in Table 4.2. An independent spectrographic analysis confirmed the chemical composition of the material, Table 4.3. The mechanical properties and heat treatment details are listed in Table 4.4.

4.5 Experimental Stress Analysis

In order to confirm and calibrate the design loads and load cell it was necessary to attach strain gauges to a specimen in the test rig. Electrical resistance strain gauges are one of the most popular measuring approaches used in experimental stress analysis, and offer the possibility of making very accurate strain measurements. Working on the principle that change in electrical resistance is proportional to gauge extension, a resistance strain gauge consists of a grid of very fine wire mounted on a backing, that is bonded to the surface under examination. Strain is found by measuring the change in resistance of the wire, which is commonly through a wheatstone bridge circuit. Strains in different planes can be measured and analysed using Mohr's circle, which gives the magnitude and orientation of the principal strains, and hence the principal stresses.

The strain gauges applied to the drill collar specimen were of the three-element rectangular rosette type, which employs gauges at the 0°, 45° and 90° positions, as illustrated in Fig. 4.15. Following make-up of the connection, two gauges, one on the pin member and one on the box member were positioned on the external surface of the specimen, as indicated in Fig. 4.16.

The pre-wired strain gauges were connected to a P-3500 portable strain indicator, which gives a direct readout of micro-strain. The specimen was rotated so that the gauges were in the position of maximum tensile stress and was loaded up to the maximum design load, pausing at suitable intervals to record the strain for each gauge. The load was then reduced at the same intervals and the strain recorded again.
The specimen was rotated through 180°, to the position of maximum compressive stress, and the loading procedure was repeated. The strains were then analysed using Mohr's circle to give the principal and shear stresses. As expected, the maximum principal stress was along the drill collar axis, and was of equal and opposite magnitude between the tensile and compressive gauge sites. The stress results were within 4% of those expected by simple beam theory. Fig. 4.17 shows the resultant load calibration graph.

4.6 Thread Inspection

As mentioned previously, this series of tests included periodic thread inspection. To the knowledge of the author, this was the first time that any drill collar experimental fatigue investigation had the facility to detect, monitor and size cracks during testing. The inspection facility was considered from the outset of the design process. Access to the threaded regions was made possible by the torque/untorqueing system of the tongs and overhead crane, with the linear roller track providing the clearance for one of the members. The non-destructive testing (NDT) method of inspection used was the ACFM (Alternating Current Field Measurement) technique, with MPI (Magnetic Particle Inspection) applied as a secondary method.

4.6.1 The ACFM Technique

ACFM is an electromagnetic technique capable of detecting and sizing (length and depth) defects in metal components. It was developed within the NDE Centre, Department of Mechanical Engineering at UCL [4.14], and is an extension of the ACPD (Alternating Current Potential Drop) crack detection and measurement technique. The basis for both techniques is that an alternating current flows in a thin "skin" near the surface of any conductor. If the surface under examination is defect free, the current flow will be undisturbed. However, if a crack is encountered, the current will flow around the ends of the crack and down the faces of the crack, as shown in Fig. 4.18. Associated with the surface current flow is a three-dimensional
magnetic field in the free space above the surface, which, like the current flow, is disturbed by the presence of a defect, Fig. 4.19.

The difference between the two techniques is that ACPD relies on measurements in the electric field on the surface under inspection, whereas ACFM measures and interprets perturbations in the magnetic field above the surface under examination. The sizing capability for both methods is based on mathematical modelling of the electric and magnetic fields that surround a crack. Theoretically predicted disturbances have shown good correlation with those actually measured [4.15]. This has provided the ability to make quantitative measurements of the magnetic field disturbances and to relate them directly to the size of the defect that would have caused such a disturbance. This has eliminated the need for calibration of the system prior to inspection. These field perturbations are interpreted through a Crack Microgauge [4.16] and displayed through software on a PC.

An ACFM inspection considers two component parts of the magnetic field above the surface, X and Z in Fig. 4.19. The X component, \( B_x \), is parallel to the crack, and the Z component, \( B_z \), is perpendicular to the metal surface. With uniform current flow in the Y-direction, and no defect present, the magnetic field in the X-direction, \( B_x \), is uniform. The presence of a surface discontinuity diverts the current away from the deepest part and concentrates it near the ends of the defect. This produces a strong peak in the \( B_z \) signal above the ends of the crack, while the \( B_x \) signal drops in strength. Figure 4.20 illustrates the nature of the \( B_x \) and \( B_z \) signals above a surface defect. Interpretation of crack depth is based upon the ratio of background to minimum \( B_x \) levels, whilst crack length is determined from the peaks and troughs in the \( B_z \) signal. The magnitudes of these two parameters are recorded as a function of time, as the ACFM probe traverses the surface under inspection. Removal of the time base for the measurement of \( B_x \) and \( B_z \) and plotting one against the other, results in what is known as a "butterfly plot". The "butterfly plot" assists in defect detection, as when a defect is encountered the "butterfly plot" will form a loop starting and finishing in the same region of the output display. This enables the operator to
distinguish between spurious indications and true crack signals. Figure 4.21 illustrates a typical ACFM defect indication.

ACFM thread inspection equipment has been available for several years [4.17], and can be either a single or an array of miniature probes designed for detecting cracks in thread roots. The probe incorporates an induction coil for the generation of surface current, and a pick-up coil for the measurement $B_x$ and $B_z$ in the vicinity of a defect. As ACFM is a non-contacting technique the thread probe can be operated with a “shoe”. This is a piece of moulded plastic in the shape of the thread root profile, which is fitted over the probe coils to protect them from wear. For this series of tests, a single thread root probe, Fig. 4.22, was used for all inspections. This was connected to a U9 Crack Microgauge and laptop computer, as shown in Fig. 4.23. Results of the inspections are presented in chapter 5.

4.6.2 Magnetic Particle Inspection

The most common method for detecting defects in rotary shouldered connections is the wet fluorescent magnetic particle inspection (MPI) technique [4.17]. Indeed, this method is often the first choice of NDT on ferromagnetic materials [4.18].

The component to be inspected is magnetised either by bringing it into contact with the poles of a strong magnet, often a hand held yoke, or by passing a heavy alternating current through a coil wrapped around the surface under inspection. Where a discontinuity is encountered in the path of the magnetic field minute poles are set up at the discontinuity. The surface under inspection is covered in fine magnetic particles, which are attracted to the poles of the discontinuity. The magnetic particles can be applied to the surface either dry or wet. For a dry inspection, the particles are in the form of powder which is dusted over the surface. The particles for wet inspection are smaller than those used in the dry method and are suspended in a light petroleum distillate, which is sprayed onto the surface. Because of the small particle size the wet method is more sensitive to fine surface defects. The magnetic particles are coloured or fluorescent in order to make them visible, and are detected
either through contrast with the surface or under ultraviolet light (for the fluorescent particles). Implicit to this is that the surface must be clean and free from dirt and grease, and as close to “bright metal” as possible.

In this series of tests, MPI was only applied as a secondary NDT method to the pin connector, after a positive defect indication from the ACFM system. A line of sight to the defect is required, therefore it was impossible to inspect the NC-26 box thread roots due to the tight geometry of the connection. The technique is also restricted to the measurement of the defect length. No estimate of crack depth can be made, which is important when considering crack aspect ratio at connection failure.

4.7 Thread Root Cold Rolling

It is widely accepted that introducing a compressive surface stress to a component exposed to fatigue loading will improve the performance of that component. Cold working (shaping the metal at room temperature) by drawing, peening and rolling are typical methods of introducing beneficial compressive surface stresses. It is common practise to cold work parts which exhibit inherit stress concentrations by design. In machine cut threaded components, often the root radii are cold rolled in order to introduce residual compressive stress and improve fatigue performance.

It should be noted that the term thread rolling used in this thesis refers to the cold rolling of the thread root radius after machining, and should not be confused with the thread production method of form rolling. Form rolling a thread is a hot process in which a cylindrical blank is fed through a set of dies that shape the thread form with very large plastic deformations. Form rolling is a mass production method of thread manufacture that is generally used in small diameter parallel thread manufacture.

4.7.1 The Development of Thread Root Rolling

The idea of cold rolling cut threads in order to improve the fatigue performance was first investigated at the Wöhler Institute, Germany in the early 1930’s. It is
reported [4.19] that these early investigations demonstrated a clear benefit of cold rolling the thread root radius, where between a 20 to 65% improvement in fatigue strength was observed. It was noted that rolling the thread flanks resulted in no increase in fatigue strength. There is very little detailed data available from these early studies, however, it is mentioned that the radius of the roller should be a little less that the thread root radius. This is an interesting point that will be expanded upon later in this section.

By the mid-1930’s the American railroad industry was actively researching and practising surface stressing of components to reduce fatigue failures [4.19]. Their cold rolling activities focused on fillet radii and relief grooves on large diameter crank pins, which are not too dissimilar to thread roots, as shown in Fig. 4.24 and 4.25.

Tests were performed in a rotating cantilever bent fatigue rig, on rolled and un-rolled specimens. The pins were cycled for 85 million revolutions (equivalent to 300,000 miles), unless they fractured first. Results report that they were able to double the fatigue strength of the crank pins by cold rolling the fillets and relief grooves. The run-out samples, those reaching 85 million cycles, were sectioned. Under microscopic examination fatigue cracks were found in all the specimens. It was noted that the crack depths in the rolled pins were only a fraction of the crack depths in the un-rolled pins, as shown in Fig. 4.26. It can be seen that some very small cracks were measured, however it is not mentioned how the 9-1/2 in. (241.3 mm) diameter pins were sectioned in order to allow such accurate depth measurements. A significant and noteworthy point raised from their investigation is that, “for surface rolling to be effective in increasing fatigue resistance must plastically deform the surface layers” [4.19]. This is explained by the establishment of a compressive residual stress field which counteracts the tensile stresses arising from service loading.

The problem of rolling tapered threads was first investigated by Trishman in the early 1950’s [4.1]. As mentioned earlier in this chapter, Trishman worked for an oil tool manufacturer and was investigating methods to improve drill collar fatigue performance. After several attempts, he was able to produce a self-contained rolling
unit capable of deforming the thread root by 0.010 in. (0.254 mm). It is reported that 0.010 in. is the optimum deformation of the thread root to maximise fatigue endurance, however, further details of his rolling procedure are excluded from the report.

The first reported investigation into thread rolling in the UK was by the British Shipbuilding Research Association (B.S.R.A.) in the 1950’s [4.20, 4.21]. It was reported that the fatigue strength of 1 in. diameter lathe cut bolts could be doubled by cold rolling the thread roots after rolling. It is again stated, in line with the previous investigations, that for rolling to be effective in enhancing fatigue strength it must produce a visible plastic deformation in the thread root. The amount of deformation is dependent not only on the material properties, but the roller shape, applied force and the number of passes made. Unlike the previous investigations, the roller had a slightly larger radius than that of the thread root, 0.020 in. (0.508 mm), compared to the root radius of 0.017 in. (0.432 mm). The reason for this is not explained, however, it may be due to the fact that a larger root radius would reduce the stress concentration compared to that of a sharper root radius.

From the available published work on cold rolling, there appears to be no hard and fast rules that can be applied for successful rolling, except that to be effective, the rolling process must produce visible evidence of plastic deformation.

4.7.2 Cold Rolling Drill Collar Threaded Connections

The oil industry has generally adopted cold rolling drill collar connections in an attempt to reduce fatigue failures, however, there is no international standard for the procedure and not all connections are recommended to be rolled. The American Petroleum Institute (API), the petroleum industry’s “think tank” and guardian of drilling equipment standards and specifications, makes no detailed reference to the benefits of cold rolling. To quote: “cold working of thread roots is optional” [4.13]. Without any guidance from regulatory authorities, certain oil companies, clearly seeing the benefit of rolling, have taken to specifying that: “drill collar thread roots
shall be cold rolled after final machining” [4.22]. This is an improvement on the API standard [4.13], but still lacks any definitive information on the process.

It is therefore the drillstring manufacturers who have developed their own in-house cold rolling equipment and procedures to meet the demand for rolling from the oil operators. Indeed, most service yards and repair shops have followed the manufacturers by equipping themselves with facilities to cold roll connection re-cuts to meet the specifications defined by the operators.

Due to the fact that the manufacturers have developed their own equipment and rolling techniques, there is very little information available in the public domain. However, through private communications with drillstring manufacturers and service yards, it has been possible to obtain a limited amount of information regarding workshop equipment and procedures. The cold rolling equipment and procedure adopted by the industry are very similar throughout. All use a basic hydraulic system to apply force to the roller, and all follow a very similar rolling procedure. Figures 4.27 and 4.28 illustrate the typical cold rolling equipment used in many manufacturer and service yard workshops. A summary of the available data regarding the rolling procedure is presented in Table 4.5.

4.7.3 NC-26 Thread Root Rolling

Drill string manufacturers do not cold roll slimhole (below 4 in. OD) connectors, this is due to the dimensional restrictions of the smaller inner diameter [4.23, 4.24]. However, as seen in chapter 3, these connectors contain significant SCFs, which are an obvious crack initiation site under fatigue loading. Therefore, it was apparent that in order to perform a full series of fatigue tests that included an investigation into the effects of residual stress, it would be necessary to design and fabricate a compact cold rolling device.
4.7.3.1 Box Rolling System Design

The major factor in designing a “miniaturised” cold rolling device was that there was very little space in which to apply a very large force. The clearance diameter at the LET of the box is only 50 mm, and for effective thread rolling the applied forces must be large enough to produce plastic deformation of the material. For this reason, hydraulic power was selected, as it offers high power to weight and power to bulk ratios, along with efficient transfer of energy from one point to another.

The first design was very much a prototype, which incorporated a single acting push cylinder connected to a hydraulic hand pump. The device was designed for the tool post of a large centre lathe. A small cylinder was brazed into a supporting body, a car brake pipe was brazed to the rear of the cylinder, which acted as the transmission conduit for the hydraulic fluid. This was then coupled to a flexible hydraulic hose and connected to a hand pump. A small piston and roller was fabricated to locate into the cylinder and was sealed using a car brake cylinder seal.

This “Mark I” box rolling equipment, Fig. 4.29, produced some notable thread root deformation. However, repeated operation of the equipment exposed some weaknesses in this prototype, and a more substantial design was manufactured. The “Mark II” device was machined from a solid hexagonal bar, with the hydraulic cylinder fitted and brazed into it, along with the car brake pipe supply line, Fig. 4.30. However, the braze and the car brake pipe were unable to withstand repeated high pressurisation of the system, resulting in considerable leakage. Therefore, a “Mark III” design was manufactured which removed these fabrication weak spots. The cylinder and hydraulic supply line were machined out of the solid hexagonal bar. The pump supply hose was attached directly to the solid body, as seen in Fig 4.31.

4.7.3.2 Pin Rolling System Design

Without the internal dimensional constraints, the external thread rolling device was considerably easier to design. Having identified the weak spots of the hydraulic system from the box rolling device, the piston cylinder and supply line were machined
from solid bar. In order to maintain consistency and interchangeability between the female and male thread rolling equipment, the piston bore was machined to receive the piston from the box rolling device. Figure 4.32 presents the pin rolling equipment in operation.

4.7.3.3 The Roller

The two primary roller design criteria were hardness and size. The roller needed to be hard enough, to deform the parent material, without itself becoming damaged, and small enough, to fit into the tight geometry of the box connection. However, the roller can also be used to modify the thread root geometry, as with the B.S.R.A. investigation [4.20], in which the edge radius of the roller was larger than the root radius of the thread form. The current oilfield practice is to cold roll with a roller of the same edge radius and thread root radius [4.23, 4.24]. A larger root radius has the benefit of a reduced SCF, and so improved fatigue performance as shown in Figure 4.33 [4.25].

Modification of a standard thread root radius to improve fatigue strength has been reported by Yukushev [4.26], in which the root radius of an M10 was increased by 35%, as shown in Fig. 4.34. This resulted in a doubling of the fatigue strength over a standard metric thread form. However, it is stated that due to difficulties in production, such a thread form is not recommended for industrial use. Yet one drillstring manufacturer has successfully managed to modify an existing oilfield connection thread form and take it to full scale production. The Super Strength Thread (SST) thread form is a modified NC thread with an enlarged root radius, Fig. 4.35. The radius is machined into the thread root, enlarging the radius from the standard 0.038 in. (0.9652 mm) to 0.057 in. (1.4478 mm). The new root radius reportedly reduces the maximum SCF by 45% and greatly improves fatigue performance [4.27].

The benefit of an enlarged the root radius has been demonstrated. However, enlarging the root radius by plastic deformation, as in the B.S.R.A. investigation,
rather than by material removal, has the advantage of a lower SCF, combined with a layer of compressive stress in the thread root. Therefore, the NC-26 roller was manufactured with a 0.048 in. (1.219 mm) edge radius, 0.010 in. (0.254 mm) larger than the root radius of the NC thread form. The dimensions, mechanical properties and heat treatment details of the roller are listed in Table 4.6. The complete piston and roller assembly can be seen in Figure 4.36.

4.7.3.4 Rolling Forces & Thread Deformation

In order to determine a suitable force for rolling some preliminary tests were performed on small sections of the thread. Visual evidence of thread root deformation was found using a hydraulic pressure of between 2000 and 4000 psi (135 and 275 bar). From basic hydraulic theory, the force a hydraulic cylinder can generate is equal to the hydraulic pressure multiplied by the cross-sectional area of the cylinder. However, this does not account for any losses in the system. It was therefore necessary to calibrate the forces of the system empirically. The piston force and pump pressures were calibrated with the use of a digital pressure transducer and a 50kN load cell, as shown in Figure 4.37.

The rotary shouldered connection is tapered from between 2 and 3 inches per foot. If the thread is cold rolled (from the LET to the free end) with equipment that runs parallel to the thread form, the system would encounter a pressure drop as the roller moved down the taper. It was found that rolling the length of the NC-26 connector produced a 35% drop in roller force, due to moving down the taper. To overcome this pressure / force loss, a hydro-pneumatic accumulator was fitted to the system. This energy storage device was charged to the operating pressure of the system, thus enabling the working pressure to be maintained along the length of the thread. Figure 4.38 illustrates the significance of working with an accumulator fitted to the system.

Effective cold rolling requires permanent thread root deformation. The amount of deformation was measured using a deep throat micrometer fitted with anvil tips, which allowed access to the thread root. The measurement of thread root deformation
is the only practical non-destructive method of assessing the effectiveness or quality of rolling. Current industry targets for thread root deformation range from 0.001 to 0.010 in. (0.0254 to 0.254 mm) [4.29, 4.30]. This range may suggest a lack of consistency in the rolling procedure within the industry.

Due to demands on time, oilfield thread manufacturers and service yards only roll over the threaded section once [4.23, 4.24]. Yet, from the earliest reports of thread root rolling from the Wöhler Institute [4.19], multi-pass rolling has been mentioned. It is reported that thread roots were rolled a number of times, with one investigator going so far as to roll the thread root ten times. However, the reported results fail to mention the optimum number of passes required for maximum fatigue performance. The effect of multi-pass rolling was mentioned by the B.S.R.A. investigators [4.20, 4.21], who double pass root rolled, on the basis that multi-passing increased deformation and improved surface finish. Indeed, the Engineering Science and Data Unit (ESDU) investigation into the fatigue strength of large diameter bolts [4.28] recommends a minimum of 4 roller passes, and states that additional passes produce insignificant benefit to the fatigue strength of the component. Figure 4.39 shows the level of deformation produced in an NC-26 box thread for increasing hydraulic pressure and by repeated roller passes. The level of thread root deformation was confirmed by sectioning the connection, and measuring the thread form on an optical projector. Figure 4.40 shows the level of thread root deformation for a box thread rolled 3 times at 4000 psi.

4.7.4 Measurement of Residual Stress

It has been shown that the cold rolling of thread roots produces a certain amount of material deformation. Associated with this is the introduction of beneficial residual compressive stress to the surface of the component. Over the past few decades various techniques have been developed that allow the measurement of residual stress in a component. In general, these are categorised as destructive or non-destructive methods. One of the most widely used techniques that falls into both categories is that of X-ray diffraction [4.29].
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The X-ray diffraction method is based upon the measurement of lattice strains in the surface region. Plastic deformation of a metal results in distortion of the lattice plane spacing. It is the measurement of these lattice displacements by a diffracted X-ray beam that allows the surface stress to be determined. Sub-surface measurements can be made only if layers of the material are removed to expose a new surface for X-ray examination. Obtaining a stress depth profile compromises the non-destructive nature of the method. A thorough review of the X-ray diffraction technique can be found in reference 4.29.

The effect of multi-pass cold rolling was investigated using the X-ray diffraction method. A cold rolled NC-26 pin connector was sent for analysis to the Design Unit, Department of Mechanical, Materials and Manufacturing Engineering at the University of Newcastle upon Tyne. The Design Unit is one of the few UK establishments equipped with facilities for X-ray stress measurement, as shown in Figure 4.41. The pin connector was sub-divided into three zones, each of which were cold rolled with a different number of passes, ranging from single to triple pass. A rolling pressure of 4000 psi was used for all 3 regions. Figure 4.42 illustrates the different rolling zones. X-ray stress measurements are time consuming and expensive, therefore surface readings were taken only at four points around the circumference of each zone, i.e. 0°, 90°, 180°, and 270°, as shown in Fig.4.43. A stress depth profile was produced at the 0° position in the triple pass zone.

The surface stress measurements are shown in Figure 4.44. It can be seen that there is a greater level of compressive residual stress with the increasing number of roller passes. This is consistent with the increasing amount of deformation from the rising number of roller passes. It can also be seen that there are large variations in the level of residual stress around the circumference. The single pass cold roll exhibits the greatest variation, with the differences reducing with the increasing number of roller passes. This may suggest that multi-pass rolling not only increases the magnitude of the compressive stress, but also improves the quality of the process by producing a more consistent residual stress distribution around the circumference.
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The sub-surface stress measurement results for the triple pass zone are shown in Figure 4.45. A chemical layer removal technique [4.29] was applied to expose each new surface. The results show typical residual stress depth profile behaviour for cold worked components with the maximum compressive stress below the surface.

Residual stress measurements can be difficult, complex and costly, and like many inspection techniques there is no universal method that will solve every problem. Indeed, the X-ray diffraction technique is limited, as the volume of material analysed is very small, giving very localised measurements. It is also sensitive to the surface texture of the component under examination. However, observations from this study may suggest the advantage of multi-pass rolling.

4.8 Summary

The design and set-up of a full-scale rotating bend test rig for the fatigue testing of NC-26 drill collar connections has described in this chapter. Included in the test rig is the facility periodic thread inspection for the collection of crack growth data. Also described is the development and manufacture of a thread root cold rolling device. The equipment has been effective in producing significant amounts of thread root deformation in the male and female connectors. To the knowledge of the author, this is the first time that the NC-26 connector has been cold rolled. Key parameters of the cold rolling process have been identified, and are investigated in the following chapter, which describes the fatigues tests performed in this test rig.
4.9 References


[4.6] Engineering Science Data Unit, "Fatigue Strength of External and Internal Steel Screw Threads under Axial Loading. (Standard forms not Greater than 1.0 inch diameter)", Item Number 84037, Engineering Sciences Data Unit, December 1984.


[4.28] Engineering Science Data Unit, “Fatigue Strength of Large Steel Bolts and Threaded Connections under Axial Loading”, Item Number 80028, Engineering Sciences Data Unit, October 1980.


4.10 Tables

<table>
<thead>
<tr>
<th>Nominal Shaft Diameter</th>
<th>Shaft Tolerance</th>
<th>Max. Radial Load Rating</th>
<th>Max. Speed min⁻¹</th>
<th>Weight (each)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-7/16 in.</td>
<td>+ 0.000 in.</td>
<td>11,636 lbf</td>
<td>700</td>
<td>49.6 lb</td>
</tr>
<tr>
<td>87.312 mm</td>
<td>- 0.004 in.</td>
<td>51.77 kN</td>
<td></td>
<td>22.49 kg</td>
</tr>
<tr>
<td></td>
<td>+ 0.000 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- 0.102 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
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**Table 4.1 - Specification for FAG split spherical bearings [4.32].**

<table>
<thead>
<tr>
<th>Element</th>
<th>% weight</th>
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<tbody>
<tr>
<td>C</td>
<td>0.462</td>
</tr>
<tr>
<td>Mn</td>
<td>1.037</td>
</tr>
<tr>
<td>Si</td>
<td>0.204</td>
</tr>
<tr>
<td>S</td>
<td>0.023</td>
</tr>
<tr>
<td>P</td>
<td>0.014</td>
</tr>
<tr>
<td>Ni</td>
<td>0.224</td>
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<td>Cr</td>
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<tr>
<td>Mo</td>
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</tr>
<tr>
<td>Al</td>
<td>0.015</td>
</tr>
<tr>
<td>Va</td>
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</tr>
<tr>
<td>Cu</td>
<td>0.202</td>
</tr>
<tr>
<td>Sn</td>
<td>0.015</td>
</tr>
</tbody>
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**Table 4.2 - Chemical composition for test batch material (AISI 4145H).**

<table>
<thead>
<tr>
<th>Element</th>
<th>% weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
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<tr>
<td>C</td>
<td>0.459</td>
</tr>
<tr>
<td>Mn</td>
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</tr>
<tr>
<td>Si</td>
<td>0.200</td>
</tr>
<tr>
<td>S</td>
<td>0.020</td>
</tr>
<tr>
<td>P</td>
<td>0.015</td>
</tr>
<tr>
<td>Ni</td>
<td>0.216</td>
</tr>
<tr>
<td>Cr</td>
<td>1.090</td>
</tr>
<tr>
<td>Mo</td>
<td>0.281</td>
</tr>
<tr>
<td>Al</td>
<td>0.020</td>
</tr>
<tr>
<td>Va</td>
<td>0.009</td>
</tr>
<tr>
<td>Cu</td>
<td>0.197</td>
</tr>
<tr>
<td>Sn</td>
<td>0.012</td>
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**Table 4.3 - Independent chemical composition for test batch material (AISI 4145H).**
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#### Mechanical Property

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Yield Strength</td>
<td>922 MPa</td>
</tr>
<tr>
<td>Ultimate Strength</td>
<td>1033 MPa</td>
</tr>
<tr>
<td>% Elongation</td>
<td>20.2</td>
</tr>
<tr>
<td>% Reduction of Area</td>
<td>52.0</td>
</tr>
<tr>
<td>Hardness</td>
<td>321 BHN</td>
</tr>
<tr>
<td>Charpy Impact Energy</td>
<td>68.8, 72.3, 68.1 J @ 20°C</td>
</tr>
</tbody>
</table>

#### Heat Treatment

<table>
<thead>
<tr>
<th></th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardened</td>
<td>1.5 hours @ 875°C water quenched</td>
</tr>
<tr>
<td>Tempered</td>
<td>3.0 hours @ 630°C air cooled</td>
</tr>
</tbody>
</table>

**Table 4.4** - Mechanical properties & heat treatment details for test batch material.

### Table 4.5 - Summary of available data for cold rolling drill collar connections.

<table>
<thead>
<tr>
<th>Property</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>Hydraulic - single acting push cylinder</td>
</tr>
<tr>
<td>Connections Rolled</td>
<td>All NC's upwards NC-35</td>
</tr>
<tr>
<td></td>
<td>Min. OD 5 in. (127 mm)</td>
</tr>
<tr>
<td></td>
<td>Min. ID 2-1/4 in. (57.15 mm)</td>
</tr>
<tr>
<td>Working Pressure</td>
<td>2000 psi (138 bar) for steel</td>
</tr>
<tr>
<td></td>
<td>1000 psi (69 bar) for non-magnetic steel</td>
</tr>
<tr>
<td>Roller Edge Radius</td>
<td>The same as the thread root radius</td>
</tr>
<tr>
<td></td>
<td>e.g V-0.038 thread uses a roller with a 0.038 in. (0.9652 mm) radius</td>
</tr>
<tr>
<td>No. of Passes</td>
<td>1 - direction from LET to free end</td>
</tr>
<tr>
<td>Target Deformation</td>
<td>0.001 to 0.0015 in. (0.0254 to 0.0381 mm) [4.30]</td>
</tr>
<tr>
<td></td>
<td>0.002 to 0.010 in. (0.0508 to 0.0254 mm) [4.31]</td>
</tr>
</tbody>
</table>

**Table 4.5** - Summary of available data for cold rolling drill collar connections.
### Table 4.6 - Details of NC-26 roller.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>0.669 in (17 mm)</td>
</tr>
<tr>
<td>Edge radius</td>
<td>0.048 in. (1.219 mm)</td>
</tr>
<tr>
<td>Material</td>
<td>Silver Steel (BS 1407)</td>
</tr>
<tr>
<td>Heat Treatment</td>
<td></td>
</tr>
<tr>
<td>Hardened</td>
<td>30 min. @ 820°C oil quenched</td>
</tr>
<tr>
<td>Tempered</td>
<td>20 min. @ 350°C oil quenched</td>
</tr>
<tr>
<td>Mechanical Properties</td>
<td></td>
</tr>
<tr>
<td>Hardness</td>
<td>549 HV</td>
</tr>
</tbody>
</table>
4.11 Figures

Figure 4.1 - Shear force and bending moment diagrams for four point bending.

Figure 4.2 - Schematic of loading points on in-board bearing housing and restraint on out-board bearing housings.
Figure 4.3 - Iron roughneck used for rapid connection make / break.

Figure 4.4 - Power tongs used for rapid connection make / break.
Figure 4.5 - Manual tongs used in laboratory.

Figure 4.6 - Procedure for make/break with manual tongs.
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Figure 4.8 - Split spherical roller bearing [4.32].

Figure 4.9 – A section of the outer diameter of specimen machined for a precision fit in the bearings.
Figure 4.10 - 'Virtual' set-up of test rig.
Figure 4.11 - 'Virtual' set-up of full test rig.
Figure 4.12 – Rotating bend test rig.

Figure 4.13 - Dimensions of test specimen.
Figure 4.14 - Dimensions of NC-26 connector (dimensions in mm).

Figure 4.15 – Typical rosette strain gauge.
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**Figure 4.16** - Strain gauges on specimen in test rig.

**Figure 4.17** - Load cell calibration graph.
Figure 4.18 - Current flow around a defect.

Figure 4.19 - Current and field flow around a defect.
Clockwise current flow gives $B_z$ peak

Anticlockwise current flow gives $B_z$ trough

Induced uniform input current

Current lines close together give $B_x$ peak

Current lines far apart give $B_x$ trough

Figure 4.20 – The nature of $B_x$ and $B_z$ above a defect [4.16].
Figure 4.21 – Typical ACFM defect signal including the “butterfly plot”.

Figure 4.22 - ACFM thread root probe.
Figure 4.23 - ACFM inspection equipment – U9, laptop and probe.

Figure 4.24 - Cold rolling of a fillet by the American railroad industry [4.19].
Figure 4.25 - Cold rolling of a relief groove by the American railroad industry [4.19].

Figure 4.26 - Final crack depths in railroad crank pins after 85 million cycles [4.19].
Figure 4.27 - Typical oil industry pin cold rolling equipment.

Figure 4.28 - Typical oil industry box cold rolling equipment.
Figure 4.29 – “Mark I” NC-26 box cold rolling equipment.

Figure 4.30 – “Mark II” NC-26 box cold rolling equipment.
Figure 4.31 – "Mark III" NC-26 box cold rolling equipment.

Figure 4.32 – Cold rolling NC-26 pin connection.
Figure 4.33 - The influence of root radii on fatigue strength [4.21].
(a) SCF=1; (b) SCF = 2.1, r=1.0 mm; (c) SCF = 3.2, r = 0.3 mm, (d) SCF = 6.0, r = 0.07 mm.

Figure 4.34 - Modified M10 thread root [4.26].

Figure 4.35 - SST modified NC thread form [4.27].
Figure 4.36 - Piston and roller assembly for NC-26 cold rolling equipment.

Figure 4.37 - Calibration of roller piston forces.
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Figure 4.38 - Comparison of rolling loads over NC-26 connector.

Figure 4.39 - Comparison of rolling loads over NC-26 connector.
Figure 4.40 - Typical thread root deformation of after triple-pass cold rolling at 4000 psi.

Figure 4.41 - X-ray diffraction equipment of Newcastle upon Tyne University.
Figure 4.42 - Different cold rolling zones for pin connector.

Figure 4.43 - Location around thread circumference for X-ray stress measurements.
Figure 4.44 - Surface stress measurements around thread circumference.

Figure 4.45 - Depth profile of residual stresses in triple pass zone.
Chapter 5

5.0 Experimental Tests & Results

5.1 Introduction

Fatigue is a progressive failure mode, described by crack initiation, followed by stable crack growth and then final fracture [5.1], this often means that fatigue tests are very time absorbing. Indeed, in this series, test duration was extended further by the periodic thread inspection, and quite significantly as a result of thread root rolling. The following sections describe 10 full-scale rotating bend tests performed in the custom built fatigue test rig described in the previous chapter.

5.2 Crack Detection & Sizing Methods

Crack detection and measurement was one of the main objectives in this series of tests. Indeed, this was the first time that an attempt was made to collect crack growth data for drill collar connections during testing. The principal NDT method used throughout this series was the Alternating Current Field Measurement (ACFM) technique. This inspection method is capable of detecting and sizing (length and depth) surface cracks in both pin and box connectors. This method, unlike many other NDT techniques, provides a permanent digital record of the inspection. An approved ACFM procedure [5.2] was used throughout all inspections. This requires an operations check of the equipment prior to inspection, which involves scanning and sizing a defined crack in a test block to ensure correct functioning of the equipment.
Inspections for both pin and box connections started in the last engaged thread (LET), at the point of full thread depth, approximately 180° around the circumference from the thread run out, Fig. 5.1. This position was marked with a datum line along the axis of the pipe. The technique used for scanning was to rotate the connection in the bearings whilst maintaining the probe in a stationary position, as shown in Figures 5.2 and 5.3. The datum line provided a reference point for the inspection probe, and each revolution around the thread was marked with a clock-point on the recording software, as the probe passed the datum line. These clock-points enabled defect indications to be located when re-inspecting the connection.

Magnetic particle inspection (MPI) was used as the secondary NDT method on the pin connector only. MPI requires a line of sight to the surface under examination, making inspection of the NC-26 box thread roots impossible due to the tight geometry of the connector. Under the correct conditions MPI can provide excellent crack length indications, however it cannot indicate crack depth. This method has another drawback, which is that the system does not detect cracks itself. This method makes it possible for the inspector to register indications, which may or may not be cracks. In this series of tests, MPI was applied only after a positive signal from the ACFM system.

As with all NDT methods, knowledge of where to inspect is an essential requirement. The FE stress analysis (Chapter 3) and experience \([5.3, 5.4]\) has identified the LET of the pin and box as the regions mostly likely to develop fatigue cracks. The crack detection methods applied in this series of tests were manually operated, therefore inspections were performed at set intervals throughout the tests. Once an initial crack had been detected and sized, the time between inspections was appropriately set according to the crack size, with intervals between inspections being reduced, as the crack became larger.

The test rig was designed to run under displacement control. This provided an opportunity for crack growth indications to be observed whilst the tests were running, through changes in specimen compliance, (the reciprocal of stiffness). As the crack
advanced through the section the compliance increased, resulting in a reduction of the load, due to the fixed displacement. A schematic illustration of this is shown in Figure 5.4. When a reduction in load was observed the test was stopped and the connection inspected.

5.3 Test Parameters

Due to the limited number of specimens and the considerable number of test variables, the parameters were set to maximise the collection of comparable data. The test objectives were two-fold, the first being the collection of crack growth data, the second was the assessment of the cold rolling technique, with the aim of optimising the process to result in the reliable operation of the connectors.

As mentioned previously, rotary shouldered connections are made-up to a recommended torque, as defined in the specification [5.5]. This recommended make-up torque value may be increased by 10% under extreme drilling conditions [5.5]. For this series of tests the make-up torque was maintained constant throughout the 10 tests, at the recommended value, 4,668 ft-lbs (6,329 N.m). All specimens were walked-in prior to testing. It is considered good rig practise to walk-in a new drill collar connection [5.6]. The procedure involves making and breaking the connection several times, followed by a thorough inspection, to ensure no thread damage prior to service operation.

For control purposes, tests C1 to C3 were performed on un-rolled connections, tests C4 to C10 were subjected to varying degrees of cold rolling. The applied loads for tests C1 to C3 represented a maximum stress of approximately 50% to 70% of the material yield strength. Following the considerable life extension due to the cold rolling of test C4, it was considered futile to test at the lower load values. Therefore tests C5 to C10 were tested at the upper load level (70%) and above. The test series parameters are summarised in Table 5.1.
5.4 Test Results

The inspection methods provided crack length and crack depth data, so allowing crack growth and crack aspect ratio curves to be presented. However one specimen failed before the first scheduled inspection, and two others failed in locations which were not inspected, thus reducing the amount of data that could be obtained. The fatigue life of each specimen, in S – N format is also presented. Failure for all tests was defined as a through-thickness crack - a wash-out. A discussion of the following results is presented in Chapter 6.

5.4.1 Test C1

The first test was very much an observation test to get a “feel” for the material and the operation of the test rig. The first inspection was scheduled for 200,000 cycles. However, there was total failure, a twist-off, in the box connector at 189,000 cycles, as shown in Fig. 5.5. Visual examination identified multiple cracking between thread roots five, six, and seven, Fig. 5.6. There were two large semi-elliptical cracks in thread root six, as shown in Fig. 5.7, which jumped across to thread roots five and seven. A large crack, 2.2 mm in depth and 120 mm in length, was also found in thread root two of the pin connector. Due to the rapid and unexpected failure of this specimen no crack growth data was collected.

Examination of the box thread roots revealed that the root radii were not the recommended 0.038 in. (0.9652 mm) [5.7], as shown in Figure 5.8. It is obvious from sectioning this connection that the poor root radii were a result of poor machining. The pin thread roots was of better quality and conformed to the specification [5.7]. The connections were cut on a numerical control centre lathe using a carbide insert cutting tool. The probable cause of this poor finish was a broken tool tip [5.8]. The specimens were supplied from a licensed API machine shop, and were issued with a quality control certificate assuring that they had been inspected and met the requirements for API NC-26 connections. It is very unlikely that the supplier would perform 100% inspection on their production line, and it is apparent that this specimen had not been inspected.
The NC-26 connection is not cold rolled by the industry. However, cold rolling over the remaining section of this box thread with the equipment described in chapter 4, returned the thread root to the recommended radius, as shown in Fig. 5.9. The technique used for cold rolling this section was to make three passes at 2000 psi. This demonstrated that thread root cold rolling is not only beneficial in applying residual compressive stress, but also improves the quality of the thread root, by removing and smoothing machining marks and scratches.

The poor thread root profile of specimen C1 produced a substantial stress raiser, effectively resulting in no crack initiation life for the connector. The crack(s) is likely to have propagated from the outset of the test, hence the low number of cycles to failure.

5.4.2 Test C2

A latex mould of the box connector was taken prior to testing. This was the only non-destructive method for assessing the quality of the box thread roots. Examination of a section of the mould under an optical projector indicated evidence of poor root radii, similar to box C1. The test load was reduced in an attempt to prolong the fatigue life of the connection. Following the sudden fracture and loss of crack growth data for test C1, the first inspection was made at 50,000 cycles. No defect indications were reported.

At 150,000 cycles the first indications were recorded. Multiple cracks around thread root six of the box were found. The ACFM signals indicated the presence of two distinct cracks around the circumference of thread root six. Without previous knowledge of crack propagation rates for this material, inspection intervals were kept short, to every 1000 cycles. As expected the crack measurements advanced every 1000 cycles. However breaking and making the connection for inspection may have also advanced the crack front, due to the large forces involved in connection make-up. Therefore, at every 1000 cycle interval the connection was broken-out, inspected,
made-up, then broken-out and inspected again. Crack measurements recorded during this phase of the test show that the crack front advanced during connection make-up. Figure 5.10 shows the crack growth curve. The influence of make-up torque as a crack driving force can be seen. The process of double break and make at each inspection interval was labour intensive and time consuming, therefore it was only repeated five times. However, both crack indications increased during this time, suggesting that connection make-up influences crack growth.

The test was stopped at 361,000 cycles when the specimen was unable to maintain the applied load. A visible through crack was observed, as shown in Figure 5.11. The final ACFM scan showed the two cracks of thread root six had coalesced. Figures 5.12 to 5.14 show the ACFM signals at various stages throughout the test.

The connection was sectioned using liquid nitrogen, however, as can be seen from Fig. 5.15, there was very little remaining ligament to break. Examination of the fracture surface revealed a very large, almost fully circumferential crack, which remained in the same plane, thread root six.

5.4.3 Test C3

A latex replica of the box connector was produced prior to testing to assess the thread root quality. Optical projection of the moulded thread profile confirmed the thread root radius was as specified. The first inspection was taken at 50,000 cycles, no defects were found. The first indication of a defect was at 200,000 cycles. A crack of 0.6 mm depth and 29 mm length was measured in the second thread root of the pin connector. A second smaller crack was identified in the same thread root at 300,000 cycles. The two cracks coalesced at 350,000 cycles, and the connector failed (through-thickness crack) at 375,000. Figures 5.16 to 5.18 show a selection of ACFM signals for this defect. The crack growth curve and crack aspect ratio curve are shown in Figs. 5.19 and 5.20 respectively.
Sectioning the connector using liquid nitrogen revealed a sickle shaped crack, as shown in Fig. 5.21. Crack shapes in circular cross sections have been widely observed to take up various kinds of shape [5.9]. The shape of the growing crack is dependent upon the section geometry and type of loading, as shown in Fig. 5.22. The sickle crack shape of C3 displays the typical fracture surface characteristics of a notched section under rotational bending with a low applied nominal stress. Closer visual examination of the fracture surface revealed further typical characteristics, a smooth surface in the fatigue zone, and ratchet marks radially pointing towards the centre. The presence of ratchet marks suggests multiple crack initiation sites, which are not uncommon for a shaft under uniform rotating bending loads.

5.4.4 Test C4

Following the preliminary cold rolling tests described in chapter 4, a hydraulic pump pressure of between 2000 and 4000 psi was found to be effective in causing permanent thread root deformation. The pin connector was cold rolled with a pressure of 2000 psi and the box connector was rolled at a pressure of 4000 psi. Both connectors were triple-pass rolled, each time starting at the LET and rolling towards the free end of the thread. The connection was cold rolled prior to walking-in. The test was run under the same load as C1. The inspection intervals were at every 50,000 cycles. The first defect indications occurred at 550,000 cycles in the pin. Two small crack indications were found, 1mm deep and 2 mm deep in second thread root from the shoulder.

The inspection intervals were reduced to maximise the collection of crack growth data. MPI indications showed the two cracks to have coalesced at 620,000 cycles, this is consistent with the ACFM output signals. Typical MPI crack indications for this test can be seen in Fig. 5.23. AFCM measurements taken at 660,000 cycles indicated that the crack was through-thickness. Visual inspection of the inside bore of the connection confirmed that the crack had penetrated through the section thickness. The thread lubricant, dope, generously applied at each connection make-up had penetrated along the crack front and appeared visible on the inside surface of the pipe,
as seen in Fig. 5.24. The crack length was approximately 60% of the external circumference. The test was continued for a further 40,000 cycles until twist-off. The final crack length was approximately 85% of the external circumference and 50% of the internal circumference. The crack growth and crack aspect ratio data are shown in Figures 5.25 and 5.26 respectively.

The fracture surface revealed the existence of two semi-elliptical cracks, consistent with the ACFM and MPI indications. The fracture surface also contained beach marks. Beach marks can be a common characteristic on fatigue fracture surfaces and are often a result of interruptions in crack propagation. The beach marks on the C4 fracture surface are probably a result of breaking and making the connection for inspection. They provided an opportunity to confirm the crack depth measurements recorded by the ACFM inspection equipment. Figure 5.27 shows good correspondence of the ACFM crack depths to the beach marks.

The specimen failed in the pin at 660,000 cycles. The box connector remained un-cracked. This test resulted in a considerable fatigue life extension over that of the "as received" specimen, C1, as shown in Fig. 5.28. The increased fatigue resistance may be attributed to the improved thread root profile and the residual compressive stress resulting from the cold rolling. This result may also suggest, as the box connector remained un-cracked, that a higher rolling force may result in a longer fatigue life.

### 5.4.5 Test C5

The connection was walked-in prior to cold rolling. The pin and box connectors were triple-pass cold rolled at a pressure of 4000 psi. The inspection intervals were initially set at every 50,000 cycles, however after 300,000 cycles without any defect indications, the inspection period was increased to every 100,000 cycles. The test continued without any defect indications until 5,100,000 cycles, upon which the test was stopped and the specimen considered a fatigue run-out. This represented fatigue life improvements of 27 times over that of test C1.
The test load was increased 20% and the test re-started. Inspection intervals were maintained at every 100,000 cycles. The test was stopped at 199,000 cycles following a sudden load drop. Upon visual inspection, a large crack was observed in the thread run-out region of the pin, Fig. 5.29. The pin thread run-out region was un-inspected, and un-rolled. The proximately of the thread run-out to the connection shoulder meant that the inspection probe and pin cold rolling equipment were unable to access this region.

5.4.6 Test C6

The significance of cold rolling over an existing crack was investigated in this test. The connection was *walked-in* and tested “as received”, until an initial defect was recorded. At 250,000 cycles a defect of 2.2 mm depth and 23 mm length was identified in thread root two of the pin connector. The pin and box members were then removed from the test rig and cold rolled. The rolling procedure was triple pass rolling at a pressure of 4000 psi. The connectors were re-inspected prior to continuation of the test, and it was found that the ACFM defect signal had reduced. The crack depth reading was only 0.9 mm. The large compressive forces applied during cold rolling reduce the diameter of the section. This geometric modification of the thread root may account for the reduced AFCM depth reading. It may also suggest that the ACFM technique is sensitive to changes in the stress field around a defect.

The subsequent crack depth measurements remained under the original depth measurement for a further 125,000 cycles. A through-thickness crack was measured at 445,000. The evidence of dope on the inside bore, confirmed the *wash-out*. The test was continued for a further 18,000 after which the specimen *twisted-off*. Figures 5.30 and 5.31 show the crack growth and crack aspect ratio data. Figures 5.32 to 5.36 show the ACFM signals at various stages throughout the test.
5.4.7 Test C7

The connection was walked-in after cold rolling. The pin and box were cold rolled with a single pass, from the LET to the free end of the thread, at a pressure of 4000 psi. Following the success in fatigue life enhancement of the previous cold rolled connections, the first inspection was scheduled for 400,000 cycles. No indications were reported. Subsequent inspections were scheduled at every 100,000 cycles. The specimen failed at 602,000 cycles with catastrophic failure, a twist-off, of the pin connector. The connection had cracked and separated in the thread run-out of the pin, as seen in Figs. 5.37 and 5.38. As with test C5, the thread run-out was un-inspected and un-rolled. Inspection of the remainder of the pin thread did not indicate the presence of any further defects. The box connector remained un-cracked. The unexpected failure of the connector resulted in the loss of crack growth data for this specimen.

5.4.8 Test C8

Following the two unexpected failures of the pin connector in the thread run-out (C5 and C7), the pin cold rolling equipment was modified so to allow the roller to pass along the thread until the start of the run-out. Cold rolling the thread run-out would ensure that the entire threaded region was "protected" by the compressive residual stress.

This test was a repeat of test C7. The connection was walked-in after cold rolling. The pin and box were cold rolled with a single pass at 4000 psi. The first inspection at 400,000 cycles, identified a defect of 3 mm depth and 28 mm length in the pin connector, at the datum line between thread roots two and three. The inspection intervals were reduced to every 15,000 cycles in order to maximise crack growth data collection. ACFM measurements taken at 495,000 cycles indicated that the crack was through-thickness. This was confirmed by the presence of dope on the inside bore, as shown in Figure. 5.39. The external crack length at wash-out was approximately 40% of the external circumference. The test was continued for a further 45,000 cycles.
until twist-off. Figures 5.40 and 5.41 show the crack growth and crack aspect ratio data. The box connector remained un-cracked.

5.4.9 Test C9

The concept of controlling crack shape was investigated in this test. Data from the previous tests have indicated that variations in the level of residual compressive surface stress may lead to longer or shorter crack lengths at the point of wash-out. In test C4, cold rolled at 2000 psi, the wash-out crack length was 60% of the circumference. In test C8, cold rolled at 4000 psi, the crack length, at the point of wash-out, was only 40% of the circumference. This suggests that the intensity of the cold rolling influences the amount of surface crack growth. Therefore, if a crack growing around the surface of the thread root were to encounter a region of higher residual compressive stress it may stop, or reduce increasing in length, and advance in depth only. This would promote a desirable wash-out failure. This process of controlling cold rolling by applying differing intensities of compressive residual stress has been coined “stitch rolling”.

The connection was walked-in prior to cold rolling. As this was the first attempt to control crack shape by “stitch rolling”, the specimen was rolled with a maximum contrast in the levels of compressive stress. The pin connector was triple-pass cold rolled at 4000 psi, except for a 30 mm long region in the thread root of the LET, which was left un-rolled. To ensure crack growth in this region, a starter notch was cut approximately 15 mm long and 3 mm deep, in the centre of the un-rolled region, as illustrated in Figure 5.42. An ACFM scan over the notch confirmed the dimensions, Fig 5.43. Inspections were performed at every 15,000 cycles.

Initial inspections did not reveal any significant change in the defect dimensions. This period maybe attributed to the development of crack tip acuity. At 60,000 cycles the crack indications (length and depth) increased. However, the ACFM crack depth signal ($B_x$) was not as “clean” as with previous scans. The background $B_x$ reading displayed a distinct step over the defect, Fig. 5.44, this made accurate sizing difficult.
At 95,000 cycles the crack was 30 mm in length, and to the limit of the un-rolled region, the ACFM depth reading was 4.8 mm. At 135,000 cycles the crack had grown into the rolled section, to a length of 45 mm, and a measured depth of 6.1 mm. However, examination of the inside bore revealed the presence of dope, signifying a through-thickness crack.

The test was stopped and the connection sectioned using liquid nitrogen. The fracture surface exhibited clear beach marks, as seen in Figure 5.45. These surface markings enabled the crack depth to be measured from the crack length data recorded at each inspection. The ACFM depth measurements did not correspond well to the beach marks. As with test C6, that the ACFM technique appears to be sensitive to stress levels around an existing defect. Figure 5.46 shows the crack growth data from the ACFM system and the beach marks. The crack aspect ratio data is presented in Figure 5.47.

The specimen failed with the shortest wash-out crack length, however the result maybe unrepresentative due to the starter notch

5.4.10 Test C10

This test was a second attempt at controlling the crack shape through stitch rolling. The experiment was a repeat of test C9, however, without the starter notch for crack initiation. For maximum effect and contrast in surface stress conditions, the connection was triple pass cold rolled at 4000 psi, except of a region 30 mm in length in the LET, as shown in Fig. 5.48.

The first defect indication was recorded at 290,000 cycles, Fig. 5.49, and occurred where anticipated, in the un-rolled (stitch) section of the thread. The defect measured 0.9 mm in depth and 12 mm in length. The use of MPI verified the presence of a defect and confirmed the crack length measurement. The defect indications continued to increase with subsequent cycling, however, the ACFM depth measurements (Bx trace) were again not as “clean” as with previous scans, Fig. 5.50. At 390,000 cycles
the crack length was to the limit of the un-rolled region (approximately 30 mm), the depth reading was 3.9 mm.

Continued cycling saw the crack length extend into the cold rolled, “protected”, region with little advance in the crack depth readings. This would either suggest that the idea of controlling the crack shape through control of the surface stresses was not working, or that the ACFM depth readings were inaccurate. It was supposed that the ACFM depth sizing capabilities may have been compromised by the presence of a large residual stress field around the defect. At 435,000 cycles, a visible through thickness crack was observed on the inside bore of the connection. The ACFM depth reading was 9 mm. Sectioning the connection using liquid nitrogen revealed a series of beach marks, as shown in Fig. 5.51, which enabled accurate crack depth measurements to be recorded. Figures 5.52 and 5.53 present the crack growth and aspect ratio data respectively.

The wash-out crack length was 60 mm, which was the shortest through-thickness crack length in this series of tests, excluding test C9.

5.5 Summary

The test rig design has proven itself successful in the fatiguing of drill collar threaded connection, and has withstood the test of any purpose built fatigue test rig, of fatiguing the specimen and not itself. The novel inspection facility demonstrated itself as a reliable means of accessing the threaded members for periodic inspection, and has allowed valuable crack growth data to be collected.

A CD-ROM containing video footage of the rotating bend test rig (testrig.mov), inspection of an NC-26 connection (inspection.mov), and the cold rolling of an NC-26 pin connector (coldrolling.mov) can be found in Appendix B in the pocket attached to the rear inside cover of this thesis.
Table 5.2 summarises the tests described in the above sections. Fatigue crack initiation is defined as the fraction of life to produce a crack of 1 mm depth, this being the approximate resolution of the ACFM inspection equipment. Where the initial crack depth was detected greater than 1 mm, the values were obtained by extrapolating the crack growth data to that depth.

The fatigue test data for all the specimens is presented in Figure 5.54. The influence of cold rolling can be seen by the improvement in the fatigue life of the rolled specimens over the un-rolled specimens. The different rolling techniques can be seen to have influenced the fatigue performance of the connections. Observations and results from these tests are discussed in the following chapter.
5.6 References


5.7 Tables

<table>
<thead>
<tr>
<th>Test</th>
<th>Applied nominal stress (MPa)</th>
<th>Cold rolled</th>
<th>Roller pump pressure (psi)</th>
<th>No. of roller passes</th>
</tr>
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<tr>
<td>C1</td>
<td>100</td>
<td>No</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C2</td>
<td>85</td>
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<td>-</td>
<td>-</td>
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<td>C3</td>
<td>75</td>
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<td>-</td>
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<td>Yes</td>
<td>Pin - 2000</td>
<td>3</td>
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<td>Yes</td>
<td>4000</td>
<td>3</td>
</tr>
<tr>
<td>C5-restart</td>
<td>120</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C6</td>
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<td>4000</td>
<td>3</td>
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<td>100</td>
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<td>4000</td>
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<td>100</td>
<td>Yes</td>
<td>4000</td>
<td>1</td>
</tr>
<tr>
<td>C9</td>
<td>100</td>
<td>Yes - stitch rolled</td>
<td>4000</td>
<td>3</td>
</tr>
<tr>
<td>C10</td>
<td>100</td>
<td>Yes - stitch rolled</td>
<td>4000</td>
<td>3</td>
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Table 5.1 – Summary of fatigue test parameters.
<table>
<thead>
<tr>
<th>Test</th>
<th>σ nom. (MPa)</th>
<th>Location of Failure</th>
<th>N to initiation (0 - 1 mm)</th>
<th>N of propagation to wash-out †</th>
<th>N to failure (twist-off)</th>
<th>N Total</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>100</td>
<td>Box – Thread root 6 - 7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>189,000</td>
<td>Not cold rolled. Multiple cracks. Unexpected failure. Poor box thread root profile.</td>
</tr>
<tr>
<td>C2</td>
<td>75</td>
<td>Box – Thread root 6 – 7</td>
<td>90,000</td>
<td>271,000</td>
<td>-</td>
<td>361,000</td>
<td>Not cold rolled. Multiple cracks. Poor Box thread root profile. Cracks coalesced at failure.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crack 1</td>
<td>150,000</td>
<td>211,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crack 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>85</td>
<td>Pin – Thread root 2 – 3</td>
<td>240,000</td>
<td>135,000</td>
<td>-</td>
<td>375,000</td>
<td>Not cold rolled. Multiple cracks. Crack 2 coalesced with crack 1 at 350,000 cycles*.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crack 1</td>
<td>280,000</td>
<td>70,000*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crack 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4</td>
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<td>Pin – Thread root 2 – 3</td>
<td>500,000</td>
<td>160,000</td>
<td>40,000</td>
<td>700,000</td>
<td>Cold rolled - Pin at 2000 psi x 3 passes – Box at 4000 psi x 3 passes. Multiple crackers. Crack 2 coalesced with crack 1 at 620,000 cycles*.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crack 1</td>
<td>550,000</td>
<td>70,000*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crack 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td>100</td>
<td>No Failure – Run-out</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5,100,000</td>
<td>Cold rolled – Pin at 4000 psi x 3 passes – Box at 4000 psi x 3 passes.</td>
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<tr>
<td>C6</td>
<td>120</td>
<td>Pin – Thread run-out region</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>199,000</td>
<td>Re-start of C5. Unexpected failure in thread run-out region, which was not cold rolled.</td>
</tr>
</tbody>
</table>

† wash-out defined as through-thickness crack

Table 5.2 – Summary of fatigue test results (continued).
<table>
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<tr>
<th>Test</th>
<th>( \sigma ) nom. (MPa)</th>
<th>Location of Failure</th>
<th>( N ) to initiation ((0 - 1 \text{ mm}))</th>
<th>( N ) of propagation to wash-out (\dagger)</th>
<th>( N ) to failure (twist-off)</th>
<th>( N ) Total</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>C6</td>
<td>100</td>
<td>Pin - Thread root 2 - 3</td>
<td>222,000</td>
<td>223,000</td>
<td>18,000</td>
<td>463,000</td>
<td>Not cold rolled until initial crack detected, then cold rolled over crack – Pin at 4000 psi x 3 passes – Box at 4000 psi x 3 passes.</td>
</tr>
<tr>
<td>C7</td>
<td>100</td>
<td>Pin - Thread run-out region</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>602,000</td>
<td>Cold rolled – Pin at 4000 psi x 1 pass – Box at 4000 psi x 1 pass. Unexpected failure in thread run-out region, which was not cold rolled.</td>
</tr>
<tr>
<td>C8</td>
<td>100</td>
<td>Pin - Thread root 2 - 3</td>
<td>366,000</td>
<td>129,000</td>
<td>45,000</td>
<td>540,000</td>
<td>Cold rolled – Pin at 4000 psi x 1 pass – Box at 4000 psi x 1 pass.</td>
</tr>
<tr>
<td>C9</td>
<td>100</td>
<td>Pin - Thread root 2 - 3</td>
<td>-</td>
<td>135,000</td>
<td>-</td>
<td>135,000</td>
<td>Stitch rolled around starter notch of 3 mm depth x 15 mm length in Pin. Cold rolled – Pin at 4000 psi x 3 passes – Box at 4000 psi x 3 passes.</td>
</tr>
<tr>
<td>C10</td>
<td>100</td>
<td>Pin - Thread root 2 - 3</td>
<td>290,000</td>
<td>145,000</td>
<td>-</td>
<td>435,000</td>
<td>Stitch rolled Pin. Un-rolled region 30mm length, the remainder cold rolled at 4000 psi x 3 passes.</td>
</tr>
</tbody>
</table>

\( \dagger \) wash-out defined as through-thickness crack

Table 5.2 – Summary of fatigue test results.
5.8 Figures

Figure 5.1 - Location for the start of inspection.

Figure 5.2 - AFCM inspection of NC-26 pin connection.
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Figure 5.5 - Catastrophic failure of the box connection C1— a twist-off.

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Figure 5.17 - ACFM scan for pin C3 at 300,000 cycles, indicating 2 defects between the 2nd and 3rd thread roots.
Figure 5.18 - ACFM scan for pin C3 at 375,000 cycles indicating a large through-thickness crack.

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Figure 5.21 - Fracture surface of pin C3 revealing a sickle shaped crack.
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Figure 5.23 – MPI crack indication in pin connector C4.

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Figure 5.34 – ACFM defect indication for pin C6 after cold rolling over initial crack at 250,000 cycles.
Figure 5.35 - ACFM defect indication for pin C6 at 375,000 cycles.

Figure 5.36 - ACFM scan for pin C6 after 445,000 cycles indicating large through-wall crack.
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Figure 5.38 – Failure in thread run-out of test C7.
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Figure 5.43 – ACFM indication for scan over starter notch in C9.
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Figure 5.49 – ACFM crack indication for C10 at 290,000 cycles.
Crack depth = 1.9
Crack Length = 28.9

**Figure 5.50** – ACFM crack indication for C10 at 330,000 cycles, showing a "noisy" Bx trace.

**Figure 5.51** – Fracture surface of pin C10.
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Figure 5.53 – Crack aspect ratio data for test C10.
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Figure 5.54 – Fatigue data for all test specimens.
6.0 Discussion of Experimental Results

6.1 Introduction

The full-scale tests described in the previous chapter have provided a valuable insight into the fatigue behaviour of slimhole drill collar threaded connections. The application of the thread root cold rolling has resulted in considerable fatigue life extension, over that of "as received" connections. The control of this process has demonstrated the potential to control crack growth as so to encourage a "friendly", wash-out failure of the connection. Where the ACFM inspection technique was applied, valuable crack growth data has been collected.

6.2 Fatigue Crack Initiation

The application of thread root cold rolling has produced a significant improvement in the fatigue crack initiation lives over that of un-rolled connectors. Figure 6.1 shows all the initiation lives for this series of tests. These lives are defined as the fraction of life to produce a crack having a depth of 1 mm. However, where the initial crack depth was detected greater than 1 mm the values were obtained by extrapolating the crack growth data to that depth.

Despite the different load ranges, the results of the un-rolled specimens show good correlation. The rapid initiation of box C2, which occurred at the lowest load range, can be accounted for by the poor thread root profile, as shown in Fig. 5.8 in Chapter 5. These disturbing and significant machining marks also present in box C1, acted as additional stress raisers, thus as expected, accelerated the fatigue process.
The advantage of thread root rolling can been seen in specimens C4 (low force, multi-pass) C5 (high force, multi-pass) and C8 (high-force, single pass), in which crack initiation was delayed in all variations of the cold rolling process. From specimens C4 and C8, it would appear that multiple passing over the thread root is equally as important as the magnitude of the force applied in a single pass. Results from the X-ray diffraction stress measurements reported in Chapter 4, illustrate the significance of multi-passing. It can be seen from Fig. 4.44 that the variation in residual stress around the thread root circumference is much greater for a single pass than for multi-pass rolling. Due to the local nature of fatigue, any “weak spot” such as an area in which the residual stress was lower in magnitude than the rest of the thread, would indicate a potential crack initiation site. Multi-pass cold rolling appears to produce a more consistent level of residual stress around the thread root circumference, thus improving the quality of the process.

Specimen C5 showed the potential advantage of combining rolling force with multi-passing. The specimen was deemed a fatigue run-out, when it reached 5,100,000 cycles without any indication of a crack. This represented a fatigue life improvement of over 27 times that of an equivalent un-rolled connection. From the limited number of experiments performed in this series of tests, it may be suggested that the cold rolling method applied to specimen C5, represented the optimum cold rolling technique.

6.2.1 The Level of Pre-load

The critical tooth, according to the finite element analysis (Chapter 3) for a pre-loaded connection, was in the box connector, however, all but two specimens failed in the pin connector. Referring back to Chapter 3, Figures 3.20 and 3.21 show the SCF distribution along the thread roots of the connector. It can be seen that the critical tooth changes from the pin to box with the application of pre-load. This method of finite element modelling has successfully predicted the critical tooth in all previous experimental investigations [6.1, 6.2, 6.3, 6.4]. Therefore, it would appear that the
level of applied pre-load for this series of experiments was not of sufficient magnitude as to switch the critical tooth from the pin to the box. All the pin failures were in thread root number 2, which was the pin "hot spot" predicted from the FEA model.

The level of pre-load (from make-up torque) applied was according to the international standard [6.5], which is a reproduction and endorsement of the oilfield recommended practice published by the American Petroleum Institute (API) [6.6]. It may be apparent from the results of these full-scale tests that this value is not the optimum value. The level of pre-load is calculated from the Farr equation, Chapter 1, equation (1.1). The basis of the calculation assumed the use of a thread compound containing finely powdered lead or zinc, which produced a coefficient of friction (COF) of 0.08. However, increased environmental awareness and governmental regulation has led to the drilling industry replacing these heavy metal based dopes with thread compounds based upon graphite or non-heavy metal oxides.

The dope used for this series of tests was graphite based with a calcium thickener. It is reported [6.7] that these new "green" dopes have different frictional characteristics to the original thread compounds, and can require as much as 50% additional make-up torque above the recommended API values for optimum connection performance. With no published or available data on the frictional properties of the dope used in this study, a simple test was performed in an attempt to identify its COF. Using an inclined plane, a block of the specimen material, and the thread compound, the coefficient of static friction could be measured [6.8]. Following repeated tests, the point of slipping was measured at 10.2°, which corresponded to a COF of 0.18. It can be seen from the Farr equation (1.1) that any increase of the value of the COF would relate to an increase of required make-up torque. This preliminary finding along with the reported comments may explain the high percentage of pin failures in this series of tests. It is beyond the scope of this thesis to examine the properties of thread compounds and their effect towards connection fatigue performance.
6.3 Fatigue Crack Propagation

Once beyond the crack initiation period, the rate of fatigue crack growth to wash-out was very similar for all the specimens, rolled and un-rolled, as shown in Fig. 6.2. The influence of cold rolling appears to have little effect on the propagation lives. This maybe accounted for by the possible decay of the compressive residual stresses established from the cold rolling. The relaxation of residual stresses set up from cold working by subsequent cycles of repeated tensile stress, has been observed by several investigators [6.9, 6.10]. Referring to Figure 1.34, in Chapter 1, it can be seen that the residual stresses set up on the surface of a shot peened specimen, decay under the influences of increasing cyclic tension. It maybe suggested that the removal of these compressive residual stresses leads to crack initiation followed by a period of stable crack growth, as found in un-treated specimens.

Cold rolling over an initial fatigue crack, as in test C6, has indicated an extension in propagation life. Rolling over an initial crack of 2.2mm in depth led to a slight increase in propagation life to wash-out. The retardation of crack growth maybe accounted for by the creation of a compressive stress field around the crack as a result of the cold rolling. The crack resumes stable crack growth following the subsequent decay of the residual compressive stress under the action of increasing cycles. However, the improvement in propagation life was to the detriment of the ability to confidently size the defect using the ACFM inspection equipment. An inspection following the application of cold rolling over the initial crack reported a depth of 0.9 mm. This under sizing of the defect maybe as a result of the rolling, which caused the two crack faces to come into contact before the actual crack tip as shown in Fig. 6.3. This would result in an electrical "short" across the crack face, thus under sizing the defect. The performance of the ACFM inspection equipment will be discussed in a subsequent section of this chapter.

6.3.1 Propagation to Twist-off

Several of the specimens that were tested beyond the measurement and detection of the wash-out failure, exhibited a considerable further remaining life. Figure 6.4
illustrates the percentage of propagation life extension from wash-out to twist-off for specimens C4, C6 and C8. It can be seen that specimens C4 and C8 displayed a further residual life 25% and 35% respectively, of their propagation life from wash-out to twist-off. Figure 6.5 shows continued slowly increasing crack growth for C4 and C8 following the wash-out, whereas C6 displays more typical rapidly increasing crack growth before catastrophic failure. These specimens were able to sustain considerable section loss before twist-off (over 70%). This feature was observed in the box failure of specimen C2, which also had considerable section loss before failure, (see Figure 5.15, Chapter 5).

The ability of the connections to sustain large defects before final fracture maybe attributed to either a low stress level as a result of load shedding, or high fracture toughness values for the material. Cracking could have caused the loads to redistribute to adjacent threads and hence slow the crack growth. Also, the tests were performed under displacement control, which would have caused the load level to reduce as the crack advanced.

The material from which the connections were manufactured (4145 H) is a high strength steel, which would tend to associate it with low ductility and toughness [6.11]. However, many modern engineering alloys no longer tend towards this convention, as can be seen in Table 4.4, Chapter 4, which presents the mechanical properties for 4145 H. The fracture toughness value is not reported by the material supplier [6.12], however values of between 160 MPa√m and 170 MPa√m have been reported [6.13]. Fracture toughness tests can be costly, as they require considerable preparation. The specimen must be machined to strict dimensional limits, which are often not achievable from the available material. The specimen must also be pre-cracked by fatigue [6.14, 6.15], which adds to the complexity of the tests, hence the lack of published data. The combination of a degree of load shedding and high fracture toughness may explain the specimens ability to sustain a large loss of section before twist-off.
6.4 Crack Aspect Ratio

The ratio of crack length to crack depth (crack aspect ratio) has been improved by the application of cold rolling. Figures 6.6 and 6.7 present the crack aspect ratios for all the box and failures respectively. It can be seen that the cold rolled specimens washed-out with shorter crack lengths than the un-rolled specimen, with the shortest wash-out crack lengths occurring in the stitch rolled specimens. The shorter the wash-out crack length the greater the remaining section ligament and the greater likelihood that the connection will maintain its structural integrity until the wash-out is detected.

The crack growth behaviour appears to be considerably influenced by the surface stress field. In the un-rolled specimens, C2 and C3, the initial crack growth was long and shallow, which suggests a strong influence of the surface stress concentration produced by the thread root. The thread geometry produces a high stress field at the surface, and a lower stress field sub-surface, which has the effect of producing a long and shallow crack. The type of loading, rotational bending, would have also influenced the crack shape, with the stress gradient from the surface encouraging long and shallow crack growth, as illustrated in Figure 5.22, in Chapter 5. This type of behaviour was identified by Kermani [6.16], who examined several service failures in drillstring threaded connections. It is reported that once the crack had initiated, the growth rate was considerably faster along the length of the crack than through the thickness. Kermani utilised the data on crack length and depth to produce equations (6.1) and (6.2), which imply long crack lengths as the crack penetrates through the thickness.

\[
a = 0.2462 + 0.0313 (2c) \quad \text{................................. (6.1)}
\]

\[
\frac{a}{2c} = \frac{0.0313}{1 - 0.2462 a^{1/2}} \quad \text{................................. (6.2)}
\]
The crack growth behaviour can be seen to have been influenced by the application of cold rolling. It maybe supposed that the compressive surface stresses induced by rolling, limits the amount of surface crack growth. It can be seen from Figure 4.44, Chapter 4, that the level of residual stress induced by rolling, appears to vary around the circumference. Once initiated, the crack may encounter regions of increased compressive surface stress, thus retarding crack length growth, and decreasing the aspect ratio. The wash-out aspect ratios for the cold rolled specimens were between 30% and 50% lower than that of the un-rolled specimen.

The stitch rolled specimens, C9 and C10 failed with the lowest aspect ratios and shortest crack lengths of all the specimens. The intention of using differing intensities of surface residual stress was to encourage crack depth growth by limiting crack length growth with surface “firewalls”. These were regions of increased compressive stress either side of the crack tips that would act to retard or stop surface crack growth. Results have indicated the potential for controlling the crack shape using this technique. Both specimens exhibited a limited amount of surface crack growth into the cold rolled regions either side of the crack, however, the cracks were almost through thickness by this stage. The wash-out aspect ratios for specimens C9 and C10 were approximately 75% and 65% respectively lower than for the un-rolled specimen.

The aspect ratios for the stitch rolled specimens remained relatively constant throughout the section thickness, as shown in Figure 6.7. This type of behaviour was reported by Dale [6.17], who presented data from rotating bend fatigue tests on medium sized (NC-46) drill collar connections. Measurements taken from beach marks indicated that the aspect ratio remained almost constant throughout the section thickness. The data on crack length and depth was utilised to produce equations (6.3) and (6.4), which imply crack lengths approximately ten times shorter than those presented by Kermani.
However, it must be noted that Dale used a semi-elliptical starter notch, produced by electric-discharge machining, to initiate crack growth. Results from specimen C9, which also used a semi-elliptical starter notch, show the same behaviour, an almost constant aspect ratio. The use of a starter notch removes crack initiation, and generally precludes any other initiation sites. This reduces the opportunity of crack coalescence in the early stages of fatigue crack growth. The influence of the surface stress state would be reduced by the starter notch depth. With less influence from the surface stress field the crack may grow in a more uniform stress field, thus producing a more constant crack aspect ratio.

The equations (6.1 – 6.4) would appear to represent the extremes of crack growth behaviour. However, Brennan [6.4] tested large drill collar connections (NC-50 and 6-5/8 Reg. connections) and produced crack behavioural relations based upon simple edge and circular crack shapes, to described his experimental results. Figures 6.8 – 6.15 show the aspect ratio results for all the specimens. The un-rolled specimens may broadly be described by Brennan edge crack growth behaviour. The cold rolled specimens generally follow the Brennan edge and circular crack descriptions, while the stitch rolled specimens show Dale type behaviour.

6.5 Inspection Performance Evaluation

The ACFM technique has been successfully applied to the inspection of threaded connections for several years [6.18] and has demonstrated itself to be a versatile tool in the detection and sizing of thread root defects. From inspection reliability trials on bottom hole assembly (BHA) equipment, ACFM demonstrated itself to correctly
detect and size more defects than the traditional BHA inspection method of magnetic particle inspection (MPI) [6.19]. Indeed, in this series of tests, ACFM on the whole worked extremely well, providing crack data for defects as small as 0.6 mm depth and 12 mm length. Comparison with fracture surface beach marks, Figure 5.27, Chapter 5, confirmed the technique's ability to accurately size defects.

The performance of any inspection technique needs to be assessed for the specific application in which it will be used. The capability of a technique to detect a crack is influenced by a number of factors, such as component geometry, defect type, size and/or orientation, and the operator skill level. ACFM had not been applied or tested on stitch rolled components before. Nevertheless, it demonstrated itself to be capable of detecting the crack in the stitch region. However, the depth measurements were poorer than anticipated. Figures 5.46 and 5.52, from Chapter 5, show how the ACFM depth readings compared to fracture surface beach marks, for specimens C9 and C10. It can be seen that there is a considerable undersizing by ACFM to the true crack depth. This maybe a result of the variations in residual stress levels around the defect. The application of mechanical stress to the surface of a metal changes its electrical conductivity and, more significantly, its magnetic properties [6.20]. The presence of a substantial variation in residual stress in the vicinity of the defect may have disrupted the surface magnetic fields, and so ACFM's crack sizing capabilities. The sizing algorithms in the system use two components from the magnetic field, $B_x$ and $B_z$. It can be seen from Figure 5.44, Chapter 5, that the $B_x$ signal appears disturbed over the defect in the stitch region. It is the $B_x$ signal from which the crack depth is calculated, and hence a disruption in this field signal may result in a poor depth sizing performance. The cold rolled surface may also exhibit a different magnetic permeability to the material beneath, which may have caused irregular field behaviour. There was also a geometry change in the stitch region of the thread root, from the rolled to the un-rolled section. This may also have affected the ACFM system, which is measuring magnetic field perturbations over the component surface.

The application of cold rolling over an existing defect, test C6, also yielded unusual ACFM readings. An initial crack was detected and measured at 2.2 mm in
depth and 23 mm in length, MPI was used to confirm the crack length. However, 
readings taken after rolling over the crack only measured the crack at 0.9 mm in 
depth, with the same crack length. The cold rolling would have deformed the surface 
of the thread root, which may have resulted in the two crack faces joining together. If 
the crack surfaces came into contact before the actual crack tip, an electrical “short” 
would have been created, and so under sizing the defect. It can be seen from Figures 
5.33 and 5.34 that the before rolling and after rolling signals display different Bx 
traces. Again, it maybe suggested that the presence of a defect along with a large 
residual stress field, may complicate the ACFM sizing algorithm.

Further work is required into the behaviour of magnetic fields in the vicinity of 
defects where large variations in residual stresses are present, as results have indicated 
an influence on ACFM sizing capabilities.

6.6 Quality Control

Global demands and an increasingly competitive business environment in the oil 
and gas industry has led to improvements in the quality of oilfield equipment. Supply 
companies and manufacturers keen to demonstrate their abilities, have taken onboard 
ISO quality standards, and readily publicise their API licenses and certification, in an 
effort to demonstrate their commitment to quality. However, quality problems still 
show up in the system, and are often not revealed until it is too late, as was the case 
with specimen C1.

The manufacturing process of machine cutting threads can lead to poor thread root 
finishes, as seen on specimens C1 and C2, Figure 5.8, Chapter 5. The probable cause 
of such a poor finish would be a broken tool tip. It may have been expected that a 
company operating with a quality system would have inspected the last batch 
manufactured on discovery of the damaged tool. Any component going into service 
with such a finish would be expected to have a very short fatigue life.
Chapter 6 – Discussion of Experimental Results

It is current oilfield practise not to cold roll drill collar connectors below NC-38’s, (4-1/8 in. OD) which therefore excludes slimhole connections, such as the NC-26. It has been reported [6.21, 6.22], and can be seen from this investigation, that cold rolling not only induces a beneficial residual compressive stress in the thread roots, but also improves the surface finish. Figure 5.9, from Chapter 5, shows how a poor machine cut thread root profile is improved by cold rolling.

The drillstring manufacturing industry has traditionally worked to standards set by the API, who are seen as the international guardians of oilfield standards. The API standard for drilling tools [6.23] sets a minimum standard to which drill collars and connections shall be manufactured. It fails to specify any detail on cold rolling other than it should be performed. Many oil and gas operating companies, who are often ultimately responsible for the drillstring, have seen the shortcomings of the API specification, and have instigated improvements. This has resulted in the growth of a world-wide oilfield inspection industry. There now exists a variety of drillstring design and inspection standards [6.24, 6.25] which have been adopted by many operating companies. Many manufacturers now also work to these independent guidelines which the operating companies dictate in the contracts for new drillstrings.

However, like the API standard [6.23], it would appear that these new standards still lack an understanding of the rolling process. The manufacturers continue to cold roll with a single pass, and with a roller profile the same as the thread root [6.26, 6.27]. They also only cold roll only medium and large connections [6.26, 6.27], despite the continued growth in popularity of slimhole drill collars [6.28]. Observations from this investigation may suggest that rolling with a slightly larger roller radius to thread root radius would have the advantage of reducing the SCF (Figure 4.33, Chapter 4), and that multi-passing rolling improves the quality of the process.

It has been said that the human family in industry is always looking for a park bench along the road of progress, where a new process means new demands on design and established production practises. However, the costs of performing quality cold
rolling may be seen as incomparable to the expense of a fishing job to recover a broken drillstring.

6.7 Summary

Cold rolling the stress concentrations produced by the thread form has yielded considerable improvements in the fatigue resistance of the NC-26 drill collar connections. Results from this series of tests have indicated that the increase in fatigue life maybe be attributed to residual compressive stresses set up in the surface layers of the material by the rolling process. The magnitude and uniformity of these surface residual stresses around the circumference of the thread form may also influence the amount of surface crack growth.

The rolling technique has been manipulated in such way as to preferentially strengthen certain sections of the thread. This approach to controlling the cold rolling process has been termed stitch rolling. Results have shown the potential for controlling surface crack growth. By controlling the amount of surface crack growth it has been demonstrated that the specimen will fail (wash-out) with the shortest crack length, thus maximising the amount of remaining ligament, and so reducing the chances of catastrophic (twist-off) failure. The stitch rolled experiments performed in this series of tests maximised the contrast in the levels of residual stress, by having rolled and un-rolled sections. The approach of a controlled failure design [6.29] has been demonstrated in this series of tests. It is seen that future tests could combine rolling intensities and number of roller passes as so to enhance fatigue life and still result with a “friendly” failure.

The ACFM inspection method has been successfully applied to the collection of crack growth data. This contemporary NDT technique has proven itself to be a reliable system in the detection and sizing of thread root fatigue cracks. This has led to a greater understanding of the fatigue lives of the connection in the rolled and un-rolled condition. With the collection of crack growth data, fracture mechanics models used to describe fatigue crack growth can be expected to be improved [6.30].
The use of controlled residual compressive surface stresses has been demonstrated to considerably improve the fatigue lives of drill collar threaded connections. Manipulation and control in the application of these residual stresses has shown potential for the reliable operation of drillstring threaded connections.
6.8 References


6.9 Figures

**Figure 6.1** – Comparison of crack initiation lives. Pin connectors unless otherwise stated, (where C.R. denotes Cold Rolled).

**Figure 6.2** – Comparison of crack propagation rates for pin connectors, (where C.R. denotes Cold Rolled).
Figure 6.3 – Crack surfaces contacting before the crack tip, resulting in an electrical "short".

Figure 6.4 – Remaining life after wash-out failure.
Figure 6.5 – Comparison of crack growth around the circumference following wash-out failure, (where C.R. denotes Cold Rolled).

Figure 6.6 – Comparison of crack aspect ratios for box connector C2.
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Figure 6.7 – Comparison of crack aspect ratios for pin connectors.

Figure 6.8 – Comparison of crack aspect ratios for box connector C2.
Figure 6.9 – Comparison of crack aspect ratios for box connector C2.

Figure 6.10 – Comparison of crack aspect ratios for pin connector C3.
Figure 6.11 - Comparison of crack aspect ratios for pin connector C4.

Figure 6.12 - Comparison of crack aspect ratios for pin connector C6.
Figure 6.13 – Comparison of crack aspect ratios for pin connector C8.

Figure 6.14 – Comparison of crack aspect ratios for pin connector C9.
Figure 6.15 – Comparison of crack aspect ratios for pin connector C10.
Chapter 7

7.0 Conclusions & Recommendations for Future Work

7.1 Conclusions

The research presented in this thesis has demonstrated that the fatigue process in drill collar threaded connections can be controlled in such a manner as to encourage a non-critical (wash-out) failure. The controlled application of surface compression to the highly stressed regions of the thread roots has shown that fatigue crack growth can be directed to promote a localised failure of the connection. This Controlled Failure Design approach to the problem of fatigue in drillstring elements promotes the reliable operation drillstring threaded connections.

This investigation has identified several key factors that may influence the fatigue lives and so the reliable operation of drillstring threaded connections. These are summarised as follows;

- Connection design (Chapter 2). The R6 structural integrity assessment procedure was applied to problem of cracked drill collar connections. The failure assessment was presented in terms of a relative strength for various types of common drill collar connections. Depending upon the type of crack, part-through or through-thickness, basic connector dimensions, such as bore size and wall thickness, can influence the strength of the connection. The part-through thickness defect assessment was restricted to cracks of intermediate and high aspect ratio, due to limitations in available stress intensity factor solutions. However, assessment of connections containing through-thickness (wash-out) cracks demonstrated that smaller diameter, thicker walled connections exhibit the greatest relative strength. This may be a useful
consideration when designing a drillstring for optimum structural reliability, and when considering a Controlled Failure Design of drillstring elements.

• Manufacturing tolerances (Chapter 3). The significance of dimensional quality control with regard to drill collar bore eccentricity and its effect on increasing the stress concentration factor was examined. Under the current American Petroleum Institute (API) drillstring manufacturing specification [7.1], there is no mention of limits for bore eccentricity in standard drill collar components. The only specification given for bore eccentricity is for non-magnetic drill collar elements. A detailed finite element analysis of a popular drill collar connection has identified the significance of bore eccentricity on increasing the stress concentration factor (SCF) in the critical thread root of the connection. Results have shown that for the specified limits for bore eccentricity (non-magnetic collars only), the SCF may rise by up to 7%. However, there is a much larger inventory of standard ferritic drill collars for which there is no bore eccentricity specification, and it has been shown that the SCF may rise by as much as 23% for a 10% eccentric drill collar bore.

• Residual compressive stress (Chapters 4 and 5). The application of surface compressive stresses to the drill collar thread roots has resulted in a considerable extension in fatigue life. The current oil industry technique to apply beneficial compressive stress to the high stress region of the thread roots is to cold roll the threads. However, the API specifies this process as optional [7.1], and where it is performed, the range of drill collars cold rolled is limited to connections over 2-1/4 in. in bore size. Also, the industry practised cold rolling technique lacks detail, which suggests a lack of understanding and to an extent, care for this important process. A full-scale rotating bend test rig was designed and built for the fatigue testing of rolled and un-rolled drill collar connections. The increasingly popular [7.2] slimhole NC-26 connection was selected for testing, however, this connector size is not currently cold rolled by the industry [7.3, 7.4]. Therefore, it was necessary to design and manufacture a cold rolling device for the test specimens. This is the first time that the
NC-26 connection has been cold rolled, and from the development of the equipment, several key parameters in the cold rolling technique have been identified.

The cold rolling roller should have a larger edge radius than the root radius of the thread. This has the advantage of reducing the SCF by enlarging the root radius [7.5]. The current industry practice is to use a roller with the same edge radius as the thread root radius of the connection [7.3, 7.4]. Presently, one manufacturer produces a drillstring thread style that contains an enlarged root radius [7.6], however, this is machined into the connection. It has been shown that a similar enlarged thread root profile can be produced by cold rolling with an enlarged roller. By modifying the thread root through deformation rather chip removal, there is the benefit of reduced SCF along with the introduction of beneficial residual compressive stress.

Multi-pass cold rolling produces a greater magnitude and more consistent distribution of the residual compressive stresses. Currently, the industry only cold rolls with a single pass [7.4, 7.5]. Results have shown that variations in the level of residual stress around the thread root circumference are considerably less for threads rolled more than once, thus improving the quality of this important process.

- Controlled application of residual stress (Chapters 5 and 6). Stitch rolling has proved the concept that crack shape can be controlled by residual surface compressive stress. Through the controlling the cold rolling process, it has been demonstrated that fatigue crack growth can be controlled to produce a localised, non-critical, wash-out failure in the drill collar connection.

- Thread inspection systems (Chapters 5 and 6). The modern non-destructive inspection technique of ACFM has been used with success to detect, monitor and size (length and depth) fatigue cracks during testing. The crack growth data has shown that the NC-26 connections can sustain large defects before final fracture, suggesting a high level of damage tolerance before absolute failure. Where defects are present in
or near large residual stress fields, such as when cold rolling is applied over an existing crack, or when stitch rolling a connection, the performance of the ACFM inspection equipment has been compromised. It has been found that the ACFM system undersizes the crack depth measurement. This maybe due to a number of reasons, such as changes in the magnetic properties of the material, or the crack faces contacting before the actual crack tip, so undersizing the defect measurements. Without further research into this area, ACFM defect depth measurements in recently cold rolled or stitch rolled connections should be viewed with caution.

7.1.1 Reliable Operation of Drillstring Threaded Connections

This investigation has:

- Demonstrated the principle of a Controlled Failure Design. Drillstring threaded connections will inevitably fatigue during their service life. The proof of concept has been shown that the crack shape can be controlled by the controlled application of compressive surface stress. The result is a \textit{wash-out} failure, which is non-critical to the connection, and can be detected from the surface drilling operations, so allowing recovery of the damaged component.

- Established an optimum cold rolling procedure. Multi-pass cold rolling combined with an oversized roller, resulted in considerable increases in the fatigue life of the NC-26 drill collar connection. In this series of tests, the optimum rolling process resulted in a fatigue life improvement of over 18 times that of an equivalent un-rolled connection.

- Identified and illustrated the consequences of inadequate manufacturing tolerances in the specification for drillstring elements, with particular regard to bore eccentricity and increased SCF.

- Illustrated that when the crack is through-wall (\textit{wash-out}), the small diameter, thick walled connectors exhibit the greatest relative remaining static strength.
7.2 Recommendations for Future Work

- The development of an RMS stress intensity factor solution [7.7] for cylindrical components would provide a crack shape evolution model. This would allow a more detailed failure assessment of part-through cracked drill collar connections, and identify which connections are most likely to develop through-thickness cracks. This may be used to further optimise basic connection geometry to promote wash-out failure.

- Perform a parametric experimental study on the cold rolling of drill collar connections. Only a single connection size was investigated in this study. Future work could extend this to different sized connectors and different rolling parameters. The cold rolling technique developed for the NC-26 connection may not be optimum for different connection sizes.

- Improve the cold rolling equipment. The equipment designed for the cold rolling of the NC-26 connections was a prototype design. This was the first attempt at cold rolling the smaller slimhole connections and the results were very positive. However, the design could be improved to incorporate several rollers, which could act on different pitches of the thread at the same time. With a multi-roller design, the quality of the rolling process could be improved, as multi-pass rolling could be achieved in a single operation.

- The measurement of the co-efficient of friction for the new environmentally approved thread compounds. The level of applied make-up torque is sensitive to the co-efficient of friction of the dope used. The recommended level of make-up torque [7.1] is based upon a dope containing heavy metal oxides. Increased environmental awareness has led to the removal of these traditional thread compounds, which have been replaced by non-heavy metal compounds. These new “green” dopes exhibit different friction properties, which need to be known for the correct make-up torque.
• Investigate the behaviour of magnetic fields in the vicinity of defects where large residual stress fields exist, as results have indicated an influence on the ACFM sizing capabilities. This observation may affect the development of the ACSM equipment being developed for drillstring thread connections [7.8].

• The controlled application of surface residual stresses maybe applied by alternative techniques, such as laser peening. A new development in the surface treatment industry is that of laser peening [7.9], in which laser energy is used to induce residual compressive stress onto the surface of a metal. This technique has great potential for highly accurate, controlled application of residual stresses.
7.3 References


Appendix A

A.0 Crack Area Model for Tubulars

To complete the R6 failure assessment for cracked drill collar connections it is necessary to identify the crack area, equation (2.5).

A.1 Elliptical Crack on the Outer Surface of a Cylinder
To find angle $\theta$:
\[
\frac{\theta}{360} = \frac{2c}{\pi D} \Leftrightarrow \theta = \frac{720c}{\pi D}
\]

To find area of sector 1:
\[
\frac{\theta}{360} = \frac{S_1}{\pi D^2/4} \Leftrightarrow S_1 = \frac{\theta \pi D^2}{1440}
\]

To find length $\mu$:
\[
\mu = \sin \left( \frac{\theta}{2} \right) \frac{D}{2}
\]

To find length $v$:
\[
v = \sqrt{\left( \frac{D}{2} \right)^2 - \mu^2}
\]

To find area occupied by arc 1: $A_1 = \frac{\theta \pi D^2}{1440} - \mu v$

To find length $d$ of matching circle:
\[
\frac{d}{\sqrt{\mu^2 + \left[ a - (D/2 - v) \right]^2}} = \frac{\mu^2 + \left[ a - (D/2 - v) \right]^2}{a - (D/2 - v)} \Leftrightarrow d = \frac{\mu^2 + \left[ a - (D/2 - v) \right]^2}{a - (D/2 - v)}
\]

To find angle $\omega$:
\[
\tan \frac{\omega}{2} = \frac{\mu}{d/2 - (a - (D/2 - v))} \Leftrightarrow \omega = 2 \arctan \frac{\mu}{d/2 - (a - (D/2 - v))}
\]

To find the area of sector 2:
\[
\frac{\omega}{360} = \frac{S_2}{\pi d^2/4} \Leftrightarrow S_2 = \frac{\omega \pi d^2}{1440}
\]

To find the area occupied by arc 2: $A_2 = \frac{\omega \pi d^2}{1440} - \mu \left[ d/2 - \left[ a - (D/2 - v) \right] \right]$

Therefore the crack area is equal to:
\[
CA = A_1 + A_2 = \frac{\pi(\theta D^2 + \omega d^2)}{1440} - \mu \left[ v + d/2 - \left[ a - (D/2 - v) \right] \right]
\]
A.1.1 Validity Limits of Elliptical Shaped Crack

Crack is defined as elliptical shaped if -  \( d_1 > 0 \)

where \[ d_1 = \frac{\mu^2 + (a - (re - v))^2}{(a - (re - v))} \]

\[ \therefore \frac{\mu^2 + (a - (re - v))^2}{(a - (re - v))} \text{ must be } + \text{ve} \quad \therefore re - v \leq a \]
where \( \nu = \sqrt{r^2 - \mu^2} \quad \Rightarrow \quad r - \sqrt{r^2 - \mu^2} \leq a \)

where \( \mu = \text{re} (\sin \theta) \) for \( \theta \) in rads

\[ \Rightarrow r - \sqrt{r^2 - \left(\text{re} (\sin \theta)\right)^2} \leq a \]

where \( \theta \text{ re} = c \quad \therefore \quad \theta = \frac{c}{\text{re}} \)

\[ \Rightarrow r - \sqrt{r^2 - \left(\text{re} \left(\sin \frac{c}{\text{re}}\right)\right)^2} \leq a \]

\( \therefore \) an elliptical crack shape is valid for:

\[ \text{re} \left[ 1 - \sqrt{1 - \sin^2 \left(\frac{c}{\text{re}}\right)} \right] \leq a \quad \text{and} \quad c \leq \frac{\pi}{2} \]
Appendix B

B.0 CD-ROM Video Footage

A CD-ROM containing video footage of the rotating bend test rig (testrig.mov), inspection of an NC-26 connection (inspection.mov), and the cold rolling of an NC-26 pin connector (coldrolling.mov) can be found overleaf in the pocket attached to the rear inside cover of this thesis.

The films require a QuickTime™ Movie player, version 5, of which an installer application is included on the CD-ROM.