FRACTURE MECHANICS APPROACH FOR THE MAINTENANCE OF OFFSHORE OIL AND GAS PIPELINE

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FRACTURE MECHANICS APPROACH FOR THE MAINTENANCE OF OFFSHORE OIL AND GAS PIPELINE

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A THESIS APPROVED BY THE MATERIALS SCIENCE AND ENGINEERING DEPARTMENT

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APPROVED ________________________________

Vice president, Academic Affairs

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Date

DEDICATION

Study hard to shew thyself approved unto God; a workman that needed not to be ashamed but rightly divided the words of truth.

2 Timothy 2:15

To my Heavenly Father and Creator of the universe who taught me how to trust and obey His words, I would not have reached this far except by your mercy, grace, favor, blessings and honor. Let your name be praised.

To my church, organizations, friends, loved ones, well wishers and sponsors; thanks for your prayers and support, I pray to be the best at all times. May God bless you.

To my irreplaceable family, you stood by me, prayed for me, and contributed immensely in my academic sojourn, I love you.

To my supervisor and colleagues, you believed in me and encouraged me whenever I felt disappointed. Thank you

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ABSTRACT

Failure of offshore oil and gas pipelines occurs under certain conditions due to some applied mechanical forces. These conditions constitute a potential threat to the integrity of in-service life span of the pipelines which can lead to loss of resources and environmental pollution. Several studies have shown that pipelines fail as a result of Welding, Fatigue Crack Growth, Corrosion Fatigue, Stress Corrosion Cracking, and Erosion due to fluid flow.

This paper presents a model by using fracture mechanics to analyze the allowable applied stresses an in service pipeline needs to withstand in minimizing crack growth. Furthermore, the crack size, crack shape and hole radius with pipe thickness will be modeled. The modeling results will be validated using experimental data. The implications of the results will be discussed for the design or development of a robust oil and gas pipelines.

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CHAPTER ONE: Background and Introduction

1.1: Research Background

Oil and Gas Pipelines are used as a medium through which petroleum products are transported from the wells to the tanks. When it is under operation, it fails rarely; meanwhile, it causes extremely serious problems like loss of resources and lives if failure does occur. Over half of all in-service pipelines fail as a result of some externally applied mechanical forces which must be properly analyzed to prevent reoccurrence. Fractographic examination is to determine the causes of failures by studying the characteristics of a fracture surface.

Griffith proposed that cracks that already exist will propagate when the released elastic Strain Energy is at least equal to the energy that is required to create the new crack surface. Life prediction for Fatigue Crack by Paris has showed that range of Stress Intensity Factor, k, might characterize Sub-Critical Crack Growth under fatigue loading. He examined that Crack Growth Rate of Stress Intensity Factor gave straight line.

Also, Rice's J-integral is a commonly used Elastic Plastic Fracture parameter for the description of the local field in the neighborhood of the Stress Concentration and for the study of crack initiation and propagation. His theory is also interpreted as the potential difference in energy between two specimens that are loaded identically having slightly different crack length.

Meanwhile, Irwin proposed the Stress Intensity Factor as crack primary driving force.
Neumann and Raju estimated the Stress Intensity Factor for hollow Cylinder for specific Crack Aspect Ratios, Crack Depth to Thickness and Hole Radius to Thickness. Alexander Aynbinder

evaluated the thickness of High Temperature (HT) and High Pressure (HP) pipe walls and combined the inelastic behavior of pipe steels by using iterative computational modeling algorithm. Idriss Malik used Lame's solution to estimate stresses and Neumann and Raju solutions to calculate Stress Intensity Factor for the combined modeling of the wall thinning and crack propagation in pipelines.

Oil and Gas Pipeline reliability is affected by welding defects, corrosion and stresses that cause cracking. Therefore, the applied stresses, Stress Intensity Factor, Composition, and Temperature etc are highly considered for the prediction of the integrity of offshore pipelines. Additionally, Stresses that are resulted to Sub-Critical Crack Growth is a major challenge to the pipe, while the loss of materials can result from the interaction between erosive fluids flow and corroding pipeline.

However, the codes of most pipelines do not actually give an account on how the combined effect of erosion under corrosive conditions and Crack Growth Rate. Similarly, there had been assumption of the mechanical properties of the surface that is corroded to have the same properties of the uncorroded portion.

Therefore, the need of model is highly necessary, since it brings together the mechanical properties of corroded layers into play. For the stress analysis in pipe model, Lame` suggested that the material is elastic, isotropic, homogeneous, and it undergoes pure bending. Some models consider both elastic and plastic deformation and thus compare different plastic stress-strain laws and yield criteria.

Tensile Stress is a component for the occurrence of Stress Corrosion Cracking in pipelines. Thick Cylinder undergoes three principal stresses, namely; Radial, Hoop, and Axial Stresses. As a result of very complex loading conditions on the pipeline, it is likely for all three modes of fracture to occur at the crack front.

Pipe bending is caused by distributed and concentrated weight loads; therefore, it must be designed to withstand the maximum wind velocity expected during plant operation. Crack like flaws are described by length, typically surface breaking and a depth in the through wall direction.

Pipelines are typically subject to pressure cycle during normal operation and Fatigue Crack Growth occurs during these pressure cycles. Transit Fatigue occurs during pipe shipment or flexing the pipe during load movement. It occurs at the base metal of the welded pipe from concentrated stresses where the pipe contacts a protrusion (like rivets, bolts, weld of adjacent pipe).

1.2: Problem Statement

Crack may develop in pipelines at any time. During fabrication, cracks may originate from casting defect or plate rolling and a family of crack and crack like defects may arise during welding which are not easily noticed during pressure test. During pipeline operation, failure may occur after the growth of defects that exist in the structure in conjunction with the stress that is applied on it.

Major issues to be taking into consideration are, but not limited to, could be how these flaws present in the pipeline initiate cracking, the stress to be estimated which could fail the material, as well as the environment. Thereafter, the driving forces and the metallurgy of the pipelines are to be critically analyzed.

1.3: Objective of the study

The use of fracture mechanics concept to detect, predict and prevent failure of offshore pipelines. This aims specifically at Plane Stress and Plane Strain, Fast Stable Crack Growth, CTOD, CMOD, Fracture Toughness, Stress Intensity Factor, Stress Concentration Factor, J-integral, and most importantly; develop particular ranges of stresses that are to be applied on operating pipeline to delay the growth of cracks if it does occur. These assumptions will be examined and modeled for the upkeep of the structure in conjunction with experimental data.

1.4: Scope of the work

Chapter 1 introduces the nature of the problem, how people have contributed in addressing some mechanisms in finding solutions to these problems; and the problem itself is defined. Chapter 2 talks about failure mechanisms, introduces the approaches to be used and how these failures affect the structure. The various methods that are used to analyze the problems for predictions are applied in chapter 3. The results that are obtained are then discussed in chapter 4 based on what is observed. Therefore, conclusion and recommendation for previous work are finally made in chapter 5. This work is expected to be completed in the period of 4-6 months, holding all factors constant.

CHAPTER TWO: Literature Review

2.1: Fundamentals of fracture mechanics

Fracture Mechanics refers to the mechanics of solids containing planes of displacement discontinuities (cracks) with specific attention to their growth. In other words, it deals with the separation of bonds under the action of stress. Fracture Mechanics is concerned with how cracks are propagated in materials. It is a useful method of determining stresses and flaw sizes, to understand which flaws are safe and which are liable to propagate as cracks that could cause failure.

Fracture Mechanics can estimate the maximum crack that a material can withstand before it fails, taking into consideration the overall dimension of the structure; the value of stresses where the initiation of cracks could take place; the value of notch toughness and the growth of Fatigue Crack and cracks that form due to corrosion. Generally, there are two types of Fracture Mechanics.

1) The Linear Elastic Fracture Mechanics (LEFM) assumes that the material is isotropic and linear elastic. The stress field at the crack tip can be calculated using the theory of elasticity. In this type of fracture mechanics, most formulas are derived for either plain strain or plain strain associated with the three types of loadings on crack body (opening, sliding and tearing). Linear

Elastic Fracture Mechanics is valid only when the inelastic deformation is small as compared to the size of the crack. It basically concerns sharp cracks of elastic body.

2) The Elastic Plastic Fracture Mechanics (EPFM) must be used if there exist a large zone of plastic deformation developed prior to the growth of crack. This phenomenon needs only a very simple and small part of the theory of plasticity. When a body is subjected to a proportional loading, the stress-strain behavior of plastic deformation becomes indistinguishable from that of non-linear elastic deformation.

For a crack that extends in a body, inelasticity can be separately considered as both Messy Inelasticity (growing voids, breaking bonds, etc) and Tidy Inelasticity (model the body as fictitious non-linear elastic body).Elastic Plastic Fracture Mechanics is additionally the theory of ductile fracture which is usually characterized by Stable Crack Growth, (ductile metal).

2.2: Pipelines and their failures

The cracks that are most likely to develop in operating pipelines are due to Stress Corrosion Cracking, Fatigue Crack Growth, Corrosion Fatigue, Erosion Corrosion and probably Coplanar and Offset Coplanar cracks. In addition, cracks occur in the base material of the pipe, welds and the Heat Affected Zone adjacent to welds of pipes.

2.2.1: Fatigue Crack Growth (FCG)

In many structural components that are subjected to cycling loading, sub-structural crack growth occurs most often due to fatigue, until a critical crack size is reached thereby causing fracture.

Increase in stress results into increase in Crack Growth Rate and the fatigue life becomes shorter. Therefore, for a given initial crack size, the life to fracture is dependent on the magnitude of the applied load.

The Fatigue Crack Growth Rate, expressed as da/dN versus Stress Intensity Factor Range is basically the slope; which characterizes the resistance of a material to Stable Crack Growth under cyclic loading. The assumed concept of similitude can also be applied. This concept says that cracks that are subjected to the same nominal Stress Intensity Factor Range but with different crack lengths will advance by equal increments of cracks extensions per cycle.

Residual Stresses can influence Fatigue Crack Growth Rates, and the measurement of such growth rates as well as the predictions of Fatigue Crack Growth performance. The growth rate of Small Fatigue Cracks can differ noticeably from that of Long Cracks at given values of Stress Intensity Factor Ranges.

Fatigue Crack Growth can be divided into three regions, namely; near threshold region that indicates a threshold value below which there is no crack; Paris region which corresponds to stable macroscopic crack growth; and the last region where the FCG rate becomes very high while approaching instability. This region is primarily controlled by Fracture Toughness.

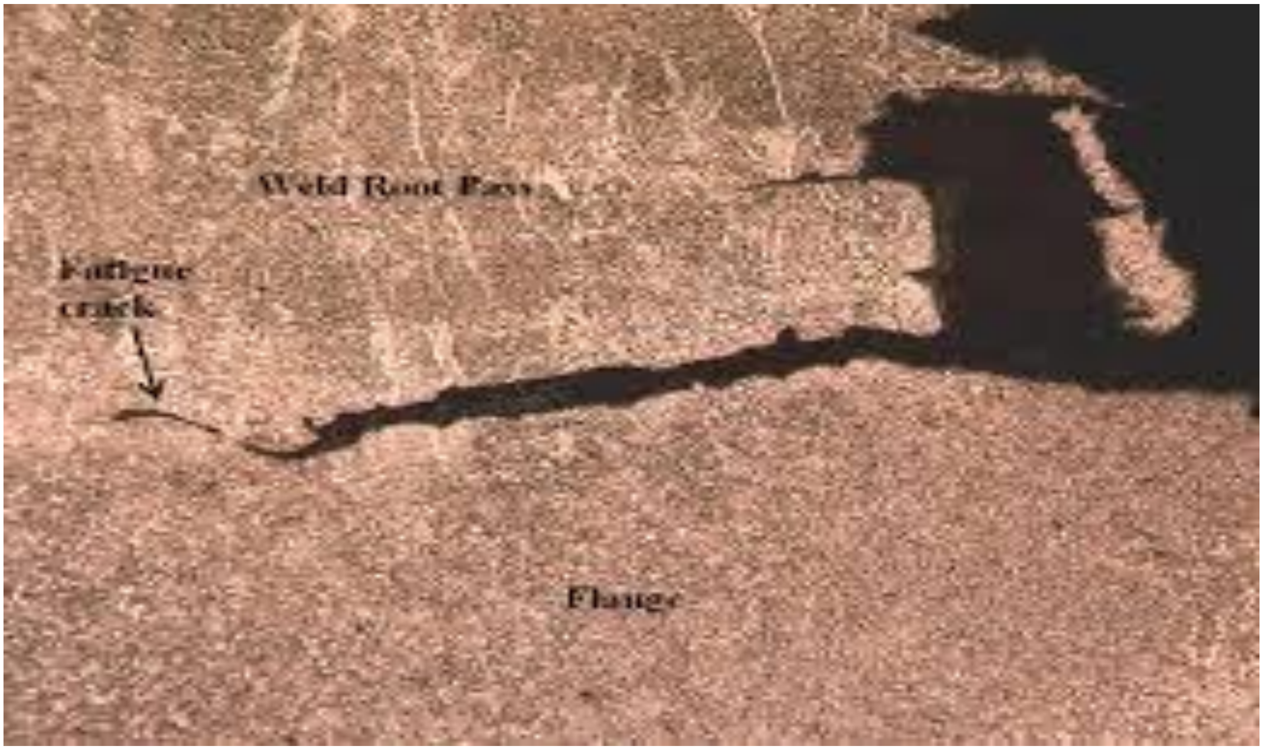

Figure 2. 1 Schematic Diagram of Fatigue Crack Growth

(Adopted from Wikipedia)

2.2.2: Corrosion Fatigue (CF)

The occurrence of Corrosion Fatigue is the result of corrosive environment and the accumulation of load cycling. Fractures are initiated either by pitting or persistent slip bands. The propagation of crack under Corrosion Fatigue is sub-divided into true corrosion fatigue and Stress Corrosion Fatigue.

The effect of true Corrosion Fatigue occurs in all regions of Fatigue Crack Growth. At all Stress Intensity Factor, the threshold is lower and there is an increase in the crack growth velocities.

Stress Corrosion Fatigue adds to crack growth velocities if maximum stress intensity factor exceeds the Stress Corrosion Cracking threshold value.

The stages of Corrosion Fatigue are Cyclic Plastic Deformation, Micro Crack Initiation, Small Crack Growth which link up and coalescence and macro crack propagation. Slip localization can be affected by electrochemical reactions.

The best requirement for Corrosion Fatigue is that the sample must be under tensile stress. Corrosion Fatigue may be reduced by Alloy Addition, Inhibition and Cathodic Protection, all of which reduce pitting. Corrosion Fatigue cracks initiates at the metal surface, and surface treatment like Cladding, Plating, Nitriding and Shot Peening need to be performed to improve the material resistance to cracking.

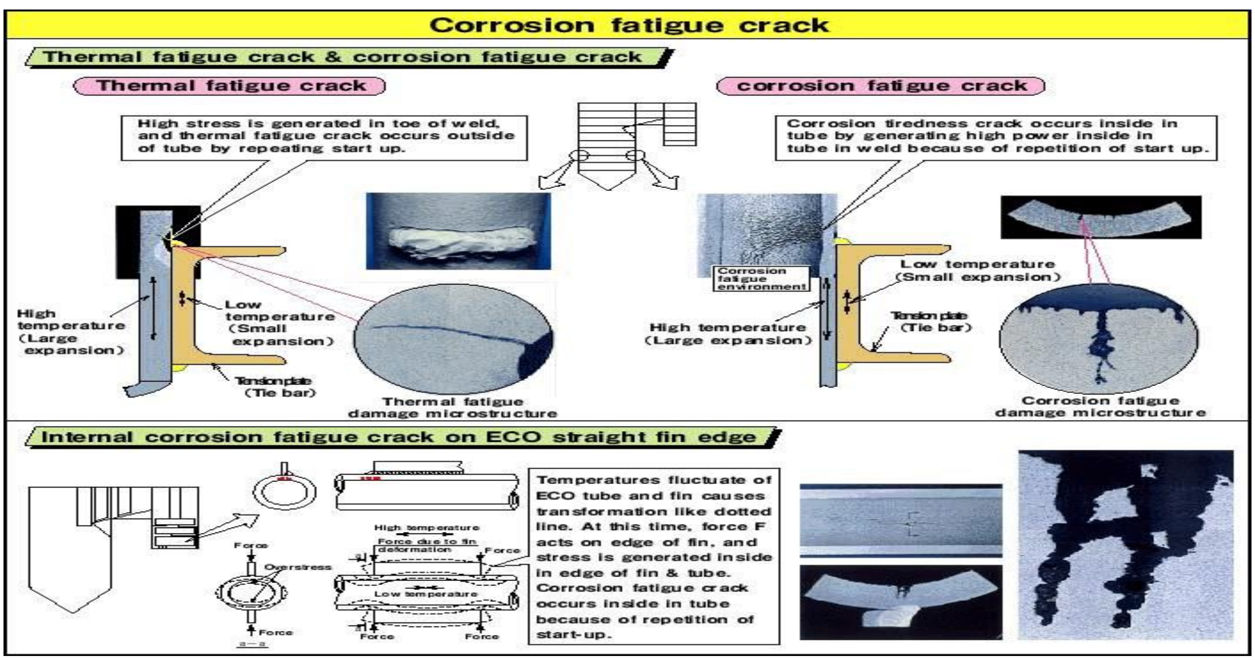

Figure 2. 2Corrosion Fatigue Crack

(Adopted from Wikipedia)

2.2.3: Stress Corrosion Cracking (SCC)

This is a progressive fracturing that occurs on metals as a result of the combined influence of tensile stress, corrosive environment etc. Structural failure due to SCC is often sudden and unpredictable, occurring after as little as few hours of exposure (months, or even year) of satisfactory service.

Virtually, under a particular set of conditions, all alloy systems are susceptible to SCC by a specific corrodent. Stress Corrosion Cracking can be controlled either by selecting a material that is not susceptible, controlling stress through careful design and minimizing stress, keeping concentration below critical value, reducing stresses through heat treatments and careful design for manufacturing, using corrosion inhibitors during cleaning operation, coating the material, and effectively isolating the material from the environment.

External Stress Corrosion Cracking on high pressure pipelines is recognized in two forms, high ph and near neutral ph. SCC cracks can initiate and grow in a range of conditions, including predominately Intergranular Cracking in Alkaline condition and Triangular Cracking in Neutral ph environment. The corrosion creates crack like features that are aligned to the principal stress at right angle. Most often, the principal stress is the result of the product pressure which makes parallel alignment of cracks to the axis of the pipeline.

Cracking in caused by the combination of certain corrosives in the moisture with normal operating stresses. Stress Corrosion Cracking in pipeline is noticed by the distinctive intergranular nature of the crack, and at imperfections in the pipe coating when under these conditions.

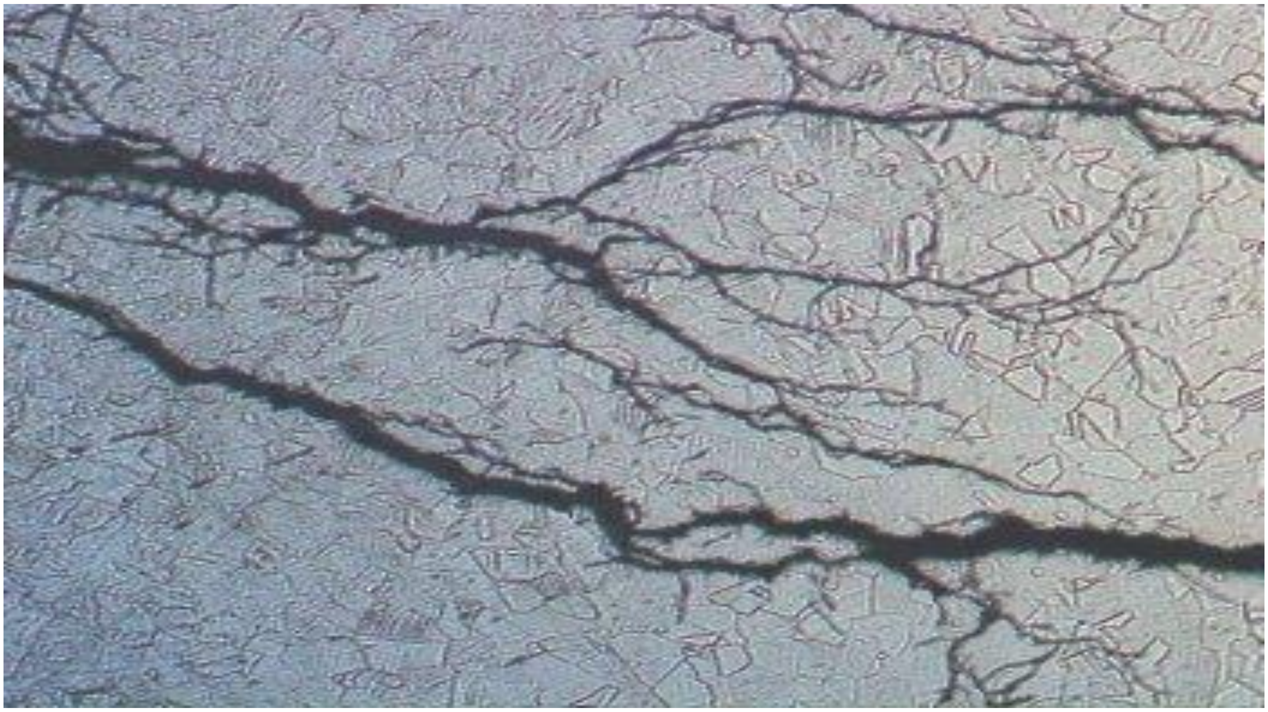

Figure 2. 3Stress Corrosion Cracking

(Adopted from Scielo.br)

2.2.4: Hydrogen Induced Cracking (HIC)

Hydrogen Induced Cracking refers to the internal cracking brought about by material trapped in budding hydrogen atoms. It involves atomic hydrogen (the smallest atom) that diffuses into a metallic structure rather than forming a gaseous reaction. Many alloys and metals may lose their mechanical properties in case a crystal lattice becoming saturated or coming into contact with atomic hydrogen.

This is sometimes called Step-Wise Cracking. Sour service pipelines are vulnerable to HIC in the presence of water, which occurs in the pipeline steels of any strength that is mostly associated with non-metallic inclusions. Crack-like feature appear within the pipeline while blisters and bump-like features appear near the surface.

Acid Corrosion occurs inside the pipeline on the water wetted areas. Hydrogen is produced by this corrosion reaction, where the atomic hydrogen diffused into the steel that forms blisters in the microscopic voids around non-metallic inclusions. The gas pressure in these blisters generates very high localized stress, thereby initiating cracks along lines of weakness in the metal. Hydrogen Induced Cracking forms as flat cracks in the rolling planes of the pipe material that leads to the development of linked crack colonies.

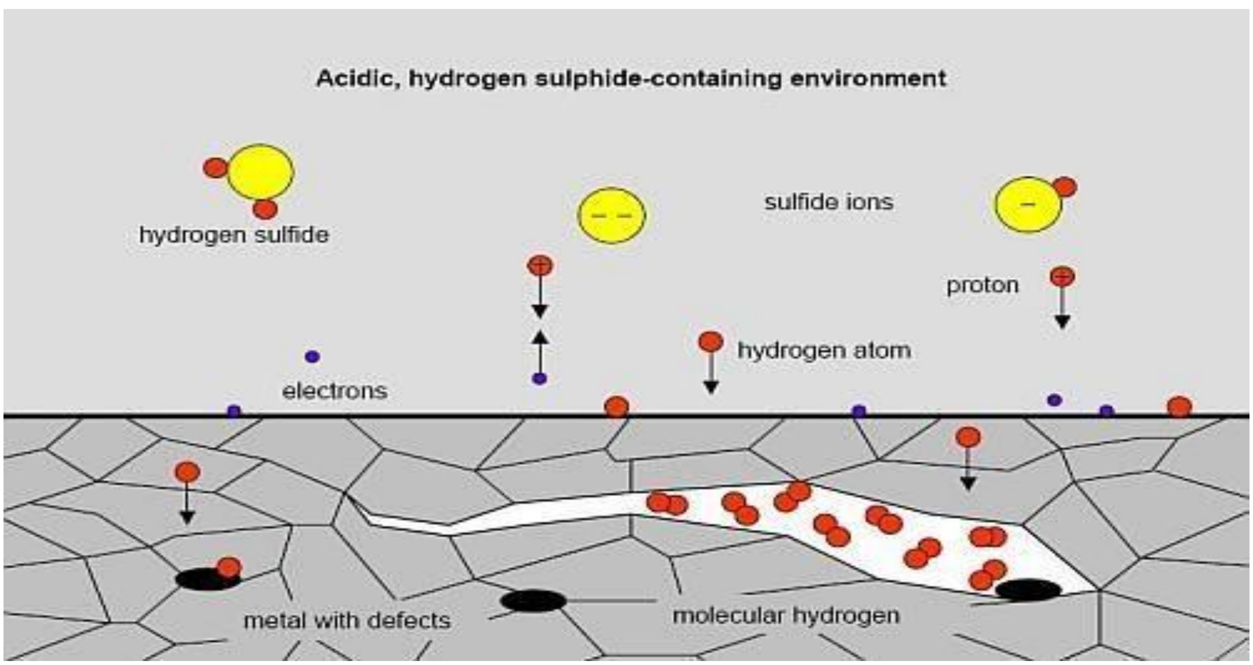

Figure 2. 4 Schematic Diagram of how Hydrogen Induced Cracking damages steel in Sour service *(Adopted from Oakley Steel Limited Sitemap)*

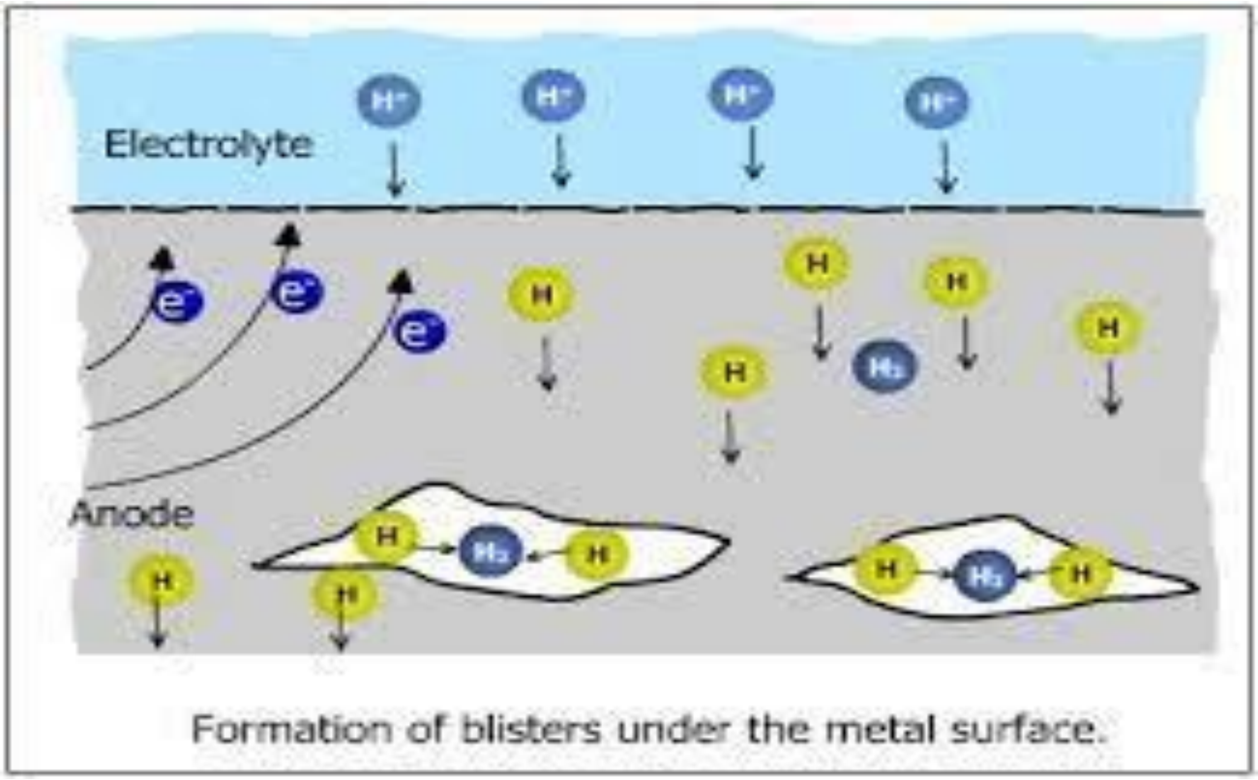

Figure 2. 5 Formation of Hydrogen Induced Cracking Beneath the Surface of the Metal (Adopted from Wikipedia)

2.2.5: Stress Oriented Hydrogen-Induced Cracking (SOHIC)

This is a special form of Hydrogen Induced Cracking that occurs as a result of Local Stress Concentration been very high in pipeline exposed to Hydrogen Sulphide and Sour Service environment. Hydrogen accumulates due to high stress field without the need of inclusion or other interfaces. It is more common to where there is high Hydrogen activity.

Stress Oriented Hydrogen-Induced Cracking can also propagate from blistering that is caused by Hydrogen Induced Cracking. This is a cracking mechanism which only affects Carbon and Low

Alloy steel in wet sour services. Meanwhile, this type of crack has been generally found adjacent to a weld, but not exclusively.

Figure 2. 6 Schematic Diagram of Stress Oriented Hydrogen Induced Cracking adjacent Girth Weld *(Courtesy of Dr. Chris Fowler, EXOVA)*

2.2.6: Erosion due to fluid flow

Erosion Corrosion is the result of corrosion attack in metals caused by relative motion of corrosive fluids to a metal surface which remove protective film or oxides. It occurs typically in pipe bends (elbow), tube constrictions and other structures that alter flow direction or velocity. The combination of erosion and corrosion can lead to extremely high pitting rate.

Pitting on the internal surface creates increased turbulence which results in rapidly increasing erosion rate and eventually a leak.

In the process of fluid flow, pipelines also come into contact with sand-bearing liquids. It is desirable generally to have a decreased in the fluid velocity and promote laminar flow, as well as having an increase in the diameter of pipes. Tank inlet pipes should be directed away from the walls of the tanks, that is, towards the center. There must be a careful alignment of welded and flanged pipe sections. Vulnerable areas must be increased in thickness. The flow rate must be slowed and reduce amount of dissolved oxygen.

Erosion-corrosion implies that the fluid medium is potentially corrosive to the metal. Erosion facilitates the corrosion process. This fact distinguishes erosion-corrosion from pure erosion or mechanical wear. Erosion corrosion influences the rate of corrosion by changing the conditions of local cell action. The corrosion process is then accelerated if the fluid speed is sufficient to remove weakly adhered corrosion products from the surface.

At the breakaway speed the fluid begins to remove the corrosion film and the corrosion rate increases. Fluid flow also maintains a uniform concentration of corrodent at the metal surfaces. Impingement of suspended hard particles can accelerate the damage to the protective film and can cause mechanical damage to the underlying metal.

The removal of these products reduces their polarizing or inhibitive effect. Several methods for preventing or minimizing damage resulting from erosion-corrosion are available. They include:

1) ***Material selection.*** Select materials with better resistance to erosion-corrosion. 2) ***Design considerations.*** Streamline the flow, avoid designs that create turbulence. Minimize abrupt changes in flow direction. Introduce smooth aerodynamic or hydrodynamic flow mediums avoid

roughly textured surfaces. Carefully align pipe sections. Avoid flow obstructions in design or obstructions that can arise under operations, increase the thickness of material in vulnerable areas, install renewable impingement plates or baffles, and design for easy repair by parts interchangeably.

3) ***Aherarion of environment.*** Decrease fluid stream speed to achieve laminar flow, regulate the concentration of dissolved oxygen in the environment to achieve optimal film-forming characteristics, provide falters for removal of suspended solids, and provide condensed moisture traps.

4) ***Specification of suitable coatings or linings.*** Use of hard-facing may be helpful in some situations and resilient barriers may be helpful in others, e.g., cavitations.

5) ***Cathodic protection.*** Provide cathodic protection whenever possible.

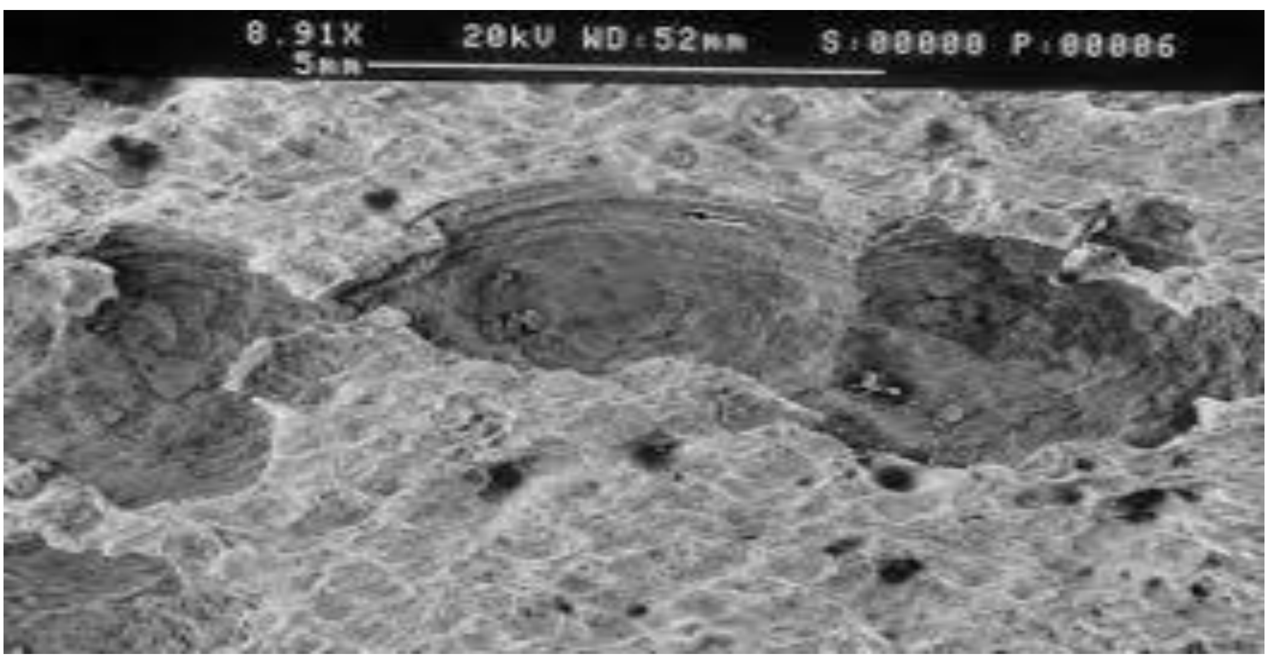

Figure 2. 7 Schematic Diagram of Erosion Corrosion

Adopted from Wikipedia

2.3: Welding

Welds are used in the making of the pipe itself, and in the joining of pipe and components during construction, as well as during maintenance and repair of the pipeline system. During the pipe manufacturing process, longitudinal welds join the edges of steel plate to form sections of pipe. Also during manufacture, girth (or circumferential) welds sometimes join sections of pipe (called double-jointing) to speed installation.

In addition, many welds have to be performed at the construction site to join together pipe sections and other components to create a pipeline system; these are almost always girth welds. And during maintenance and repair, many other types of welds are also used. Material or Weld Failures can result in both public safety and environmental hazards due to the release of petroleum and natural gas products.

Of recent, continuous improvements in the manufacture of steel and pipe and in welding processes in general have occurred since pipe was being mass produced for the oil and gas industries. Pipe manufacturers pressure test each pipeline section before it is delivered to a construction site. And the welds of new pipeline construction are non-destructively tested to ensure they have no defects. Equally so, cracks can still initiate in a welded joints of the pipeline.

2.3.1: Laps

These are like surface defects that initiate during the rolling process used to produce the plate or strip from which the pipe is fabricated. Surface cracks in the hot slab become oxidized, which prevent them from welding to the adjoining metal during subsequent rolling. The crack stays on the outer surface of steel and are rolled over which become surface breaking defects at a very shallow angle. They can occur in any position around the pipe.

2.3.2: Hook Cracks

They are also defects in the longitudinal weld that occur during manufacturing of the pipe, when inclusions at the plate edges are turned out of the plane of the steel during the welding process. Hook Cracks may pass the manufacturer's initial hydro-test, but may fail later due to metal fatigue. It is turning out of the metal at the welds that gives the characteristic "hook" or "J" shape to the crack.

2.3.3: Girth Weld Cracks (GWC)

These cracks can occur in any position around the weld, but are most often found at the 6:00 (clock) mark inside the pipe, which is the position of maximum stress during movement of internal clamp, when only the root bead has been made. The cracks are found almost exclusively during construction because of inadequate fit up and excessive stress.

2.4.4: Narrow Axial External Corrosion (NAEC)

It is not strictly a major crack mechanism, but it's associated with welds that are also difficult to detect because of their axial orientation, which is caused when the pipe wraps "tents" over the seam weld bead.

2.4: Stress Intensity Factor

The major driving force of cracks is the Stress Intensity Factor, which can be calculated for typical crack geometries of interest. It deals directly with crack tip stresses and strains. The Stress Intensity Factor presented by Neumann and Raju for an embedded elliptical crack, a semi elliptical surface crack, quarter elliptical corner crack, a semi elliptical surface crack along the bore of a circular hole and a quarter elliptical corner crack at the edge of a circular hole when the Hollow Cylinder is subjected to bending and tension.

The range of equation was extended by using Stress Intensity Factor equation. The ratios of crack depth to thickness (a/t) ranged from 0 to 1; crack depth to crack length (a/c) ranged from 0.2 to 2 and hole radius to thickness ranged from 0.5 to 2. The Stress Intensity Factor at any point along the crack front was taken to be $K= (S_t + H_j S_b)\sqrt{\pi a}/q \times F_j$; where q is the shape factor for an ellipse, H_j and F_j are the boundary correction and subscript j denotes the crack configuration, J=c for corner crack, j=e for embedded crack, j=s for surface crack, j=sh for surface crack around the hole, and j=ch for corner crack around the hole, St and Sb are the stresses due to tension and bending respectively.

CHAPTER THREE: Modeling

3.1 Introduction

Model making is at the heart of advanced analytics. Model and Simulation is the process of getting information about how something will behave without even putting it under test in real life. It involves the use of model, prototypes, simulators etc, which actually develops data as a basis of making judgment.

This procedure of analysis is even as accurate and realistic as traditional experiment. In the case of pipelines damage due to crack, it is feasible not to only detect damage, but to also characterize the significance of damage. The data obtained from experiment and assumed adjusting model parameters can possibly be predicted by the use of modeling and simulation for future behavior of a structure.

Moreover, much of the observed experimental behavior (such as maximum applied stress, crack length etc) are explained. These methods will monitor the crack growth rate and stress intensity factor range of different crack geometries of offshore pipeline; for the estimation of appropriate maintenance schedules. The damage growth is simulated using finite element method to calculate the stress intensity factor as well as Paris model to grow the crack. Consequently, the Stress Intensity Factor (SIF) were calculated numerically by using the Neumann and Raju Solutions for semi elliptical crack and an assumed bending and tension stresses ratios for hollow cylinders before simulation.

3.2: Analytical Modeling of crack growth

This is a mathematical modeling technique that is used to simulate, explain and make predictions about the mechanisms that are involved in physical processes that are complex. The solutions that are obtained in this model are expressed as mathematical analytic functions, which are then used as the parameters for the finite element analysis. In this technique, relationship among variables in a historical data set is simply described. The equation estimates or classifies data values.

Additionally, a computer programming system (FORTRAN) was used for the coding of a specified Stress Intensity Factor Range and Fatigue Crack Growth of hollow structure due to bending and tension, as well as different crack geometries. The data sets and variables that are selected are then critically analyzed with the information obtained from the Finite Element Analysis.

Meanwhile, OriginPro 8 is another program that was used. It performs data analysis, statistics and graphing. This program provides the most frequently used advanced statistical test, which includes expanded parametric and non-parametric hypothesis testing tools, survival analysis tool, etc. For the data analysis, OriginPro8 includes additional mathematics, curve fitting and peak analysis operation. It also offers FFT option, short time Fourier Transformation and other problems.

The calculations used for Fatigue Crack Growth were: a) Stress intensity Factor equation, K=g*F(a/c, a/t, r/t)$\sqrt{\pi a}$; where g is the ratios of applied stresses due to bending and tension; Stress Intensity Factor Range, ;$\Delta K = K_{max} - K_{min}$, Fatigue Crack Growth Rate, da/dN=C (($\Delta K)^{m}$ and fracture Toughness, K_c=g_c*F(a/c, a/t, r/t)$\sqrt{\pi ac}$.

3.3: Finite Element Modeling of Pipelines

In an attempt to better understand the behavior of Pipelines and capacities under different loading conditions, the development and of an all inclusive Finite Element method was performed. This addresses the behavior of cracks, or factors leading to the nucleation and propagation of cracks. This model can accurately predict pipe danger or safety under various loading conditions. Finite Element method permits the study of both cracks that are stationary and fatigue cracks.

Abaqus is a powerful easy to use suite of fatigue analysis software for Finite Element Model that provides reliable, accurate fatigue life predictions regardless of the complexity of the analysis. It was sold by Dassault Systemes as part of their Simulia Product Life Cycle Management (PLM) software tools. This model was used to create the geometry required, which was obtained from the analytical model. The material property of my analysis were defined and assigned to the available parts.

CHAPTER FOUR: Results and Discussions

4.1: Introduction

This chapter presents the results and discussions of specific values of Aspect Ratios, Crack Depth to Thickness of the structure and Hole Radius to the structure Thickness as determined by Neumann and Raju; and the estimated applied stresses on the pipeline. The pipeline considered was made of X65 graded steel. The diameter and thickness was 1.5mm and 0.25mm respectively. The Material constants (C and M) depend on the microstructures and environmental parameters. That is, these constants are experimentally determined in an aggressive environment (such as PH, corrosion etc) under cyclic loading. These values were used to determine the Crack Growth Rate since they have already been obtained under such environmental conditions; which means the material used is already infected.

4.2: Crack Aspect Ratios (a/c)

The Crack Aspect Ratio (sometimes called the Crack Shape) is the ratio of the Crack Depth, a, to the Crack Length, c, that exist in a material. There was a need to examine the accuracy of the predictions of Stress Intensity Factor for offshore pipelines with different ranges of Aspect Ratios subjected to both bending and tension. Analytical Model was presented to determine the Stress Intensity Factor using the Numerical Analysis of Aspect Ratio and assumed ranges of the ratios of stress due to bending to that of stress due to tension; since offshore pipeline is subjected to these two loading conditions. A three Dimensional Finite Element Method is then employed to derive a solution to Analytical Models. The behavior of the Crack Growth Rate was determined.

a/c ratios	**Applied Stress Ratios (Sb/St)**	**Stress Intensity Factor**	**Stress Intensity Factor Range**
0.2	0.5	0.1778	6.9140
0.38	0.65	0.4379	6.6534
0.56	0.8	0.7942	6.2970
0.74	0.95	1.2463	5.8450
1.92	1.1	1.7941	5.2972
1.1	1.25	2.4376	4.6536
1.28	1.4	3.1769	3.9144
1.46	1.55	4.0119	3.0794
1.64	1.7	4.9426	2.1486
1.82	1.85	5.9690	1.1222

Table 4. 1 Crack Aspect Ratio (sometimes called Crack Shape)

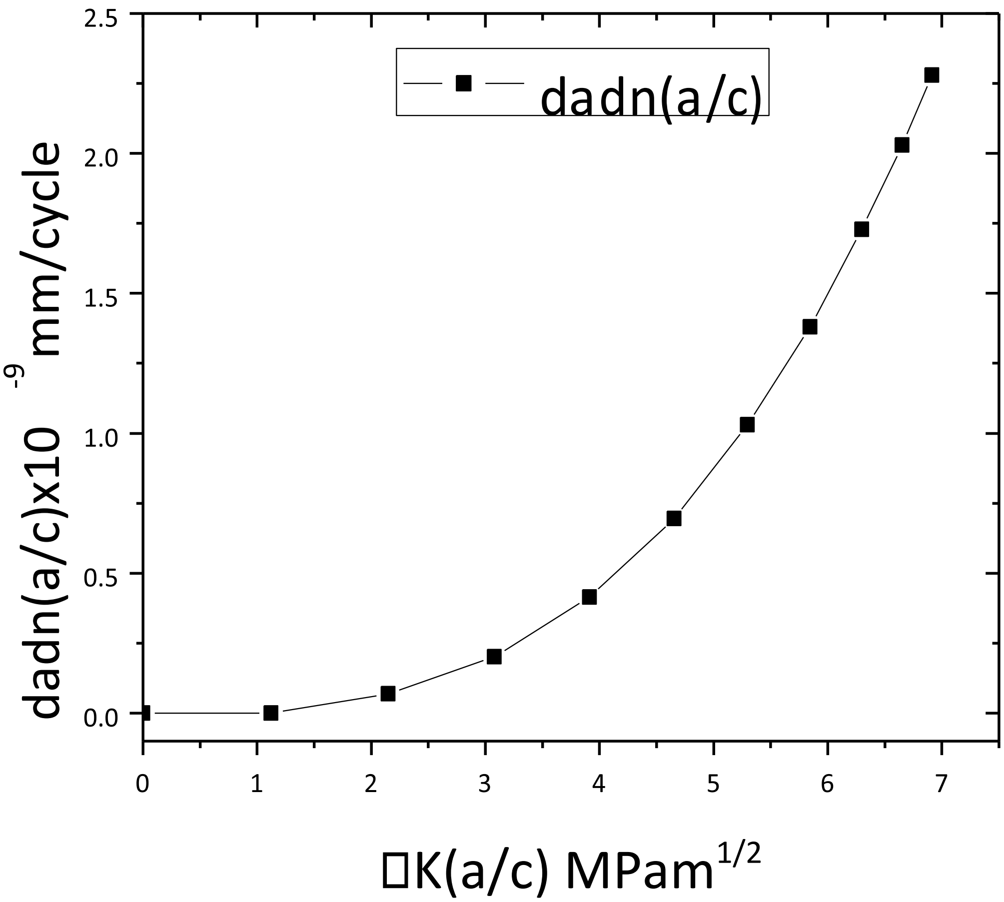

Figure 4. 1 Graphical Plot of Fatigue Crack Growth Rate against Stress Intensity Factor Range

This indicates that there will be a delay of crack growth in the near threshold and Paris regions, and cracks will actually start initiating in the third region. This is because, the Fatigue Crack Growth Rate which is the slope is found to be in the third region.

4.3: Crack Depth to Pipe Thickness (a/t)

The Crack Length to pipe Thickness (sometimes called Crack Size) is the ratio of the Crack Depth, a, to the thickness of the pipe. It was also understood that for the prediction of the Stress Intensity Factor for different ranges of Crack Depth to the thickness of the material needs to be critically analyzed. The loading conditions are both bending and tension predicted by Numerical

Analysis made by Neumann and Raju, in conjunction to the assumed ratios of applies stresses due to bending and tension. Thereafter, a three dimensional Finite Element Approach is employed to derive a solution to Analytical Models. The Crack Growth Rate was also determined.

a/t ratios	**Applied Stress Ratios (Sb/St)**	**Stress Intensity Factor**	**Stress Intensity Factor Range**
0	0.5	0	3.5456
0.1	0.65	0.1152	3.4304
0.2	0.8	0.2836	3.2620
0.3	0.95	0.5053	3.0404
0.4	1.1	0.7800	2.7656
0.5	1.25	1.1080	2.4376
0.6	1.4	1.4892	2.0565
0.7	1.55	1.9235	1.6221
0.8	1.7	2.4110	1.1346
0.9	1.85	2.9517	0.5939

Table 4. 2 Crack Depth to Pipe Thickness

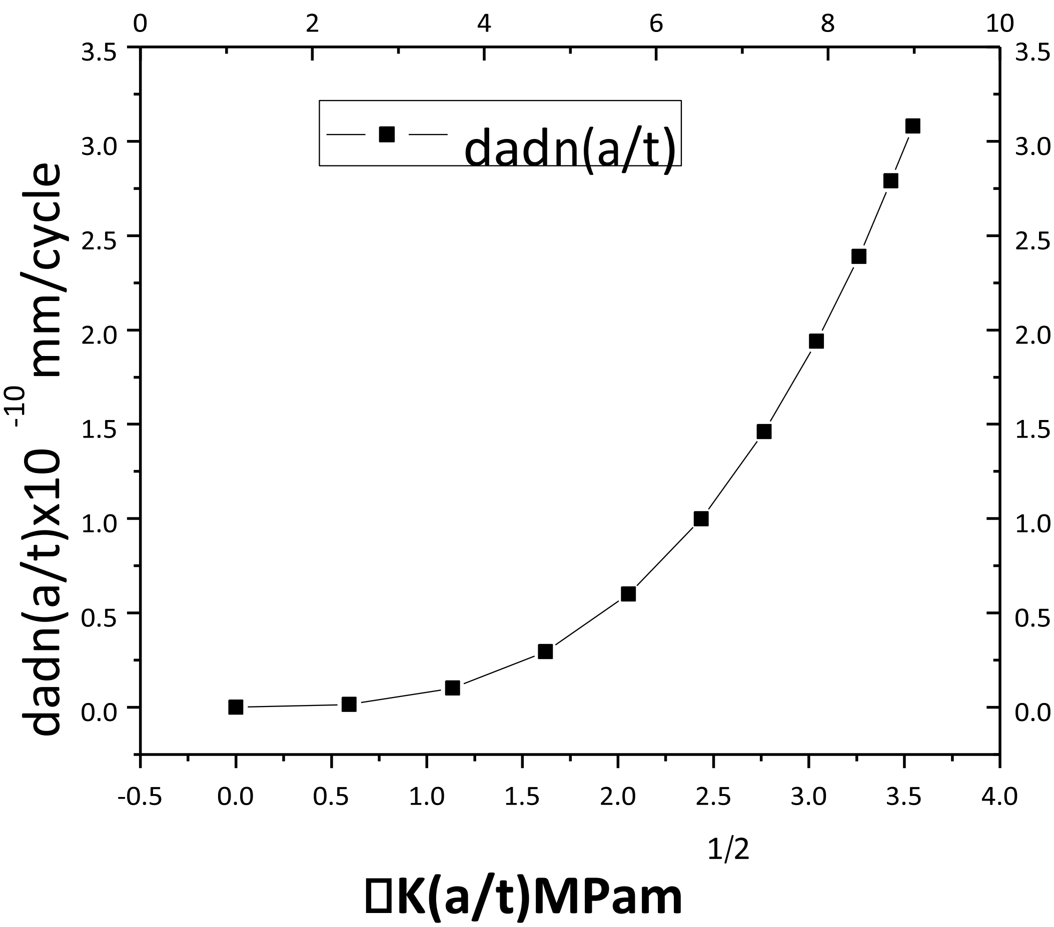

Figure 4. 2 Graphical Plot of fatigue Crack Growth Rate against Stress Intensity Factor Range

The Fatigue Crack Growth Rate is the slope, and it is found in the third region. Therefore, this graph shows that there will be no major crack growth in the first two regions.

4.4: Hole Radius to Pipe Thickness

The Hole Radius to Pipe Thickness is the ratio of the hole to the thickness of the pipe. The Stress Intensity Factor was predicted using ranges of different Numerical Analysis of hole radius to the thickness of pipe made by Neumann and Raju, and an assumed stress ratios (of bending to tension) to better understand the applied stress(es) a pipeline needs to withstand. Meanwhile, the Crack growth Rate was also studied.

r/t ratios	**Applied Stress Ratios (Sb/St)**	**Stress Intensity Factor**	**Stress Intensity Factor Range**
0.5	0.5	0.4432	6.6480
0.65	0.65	0.7490	6.3422
0.8	0.8	1.1346	5.9566
0.95	0.95	1.5999	5.4913
1.1	1.1	2.1451	4.9461
1.25	1.25	2.7700	4.3212
1.4	1.4	3.4747	3.6165
1.55	1.55	4.2592	2.8321
1.7	1.7	5.1234	1.9678
1.85	1.85	6.0674	1.0238

Table 4. 3 **Hole Radius to Pipe Thickness**

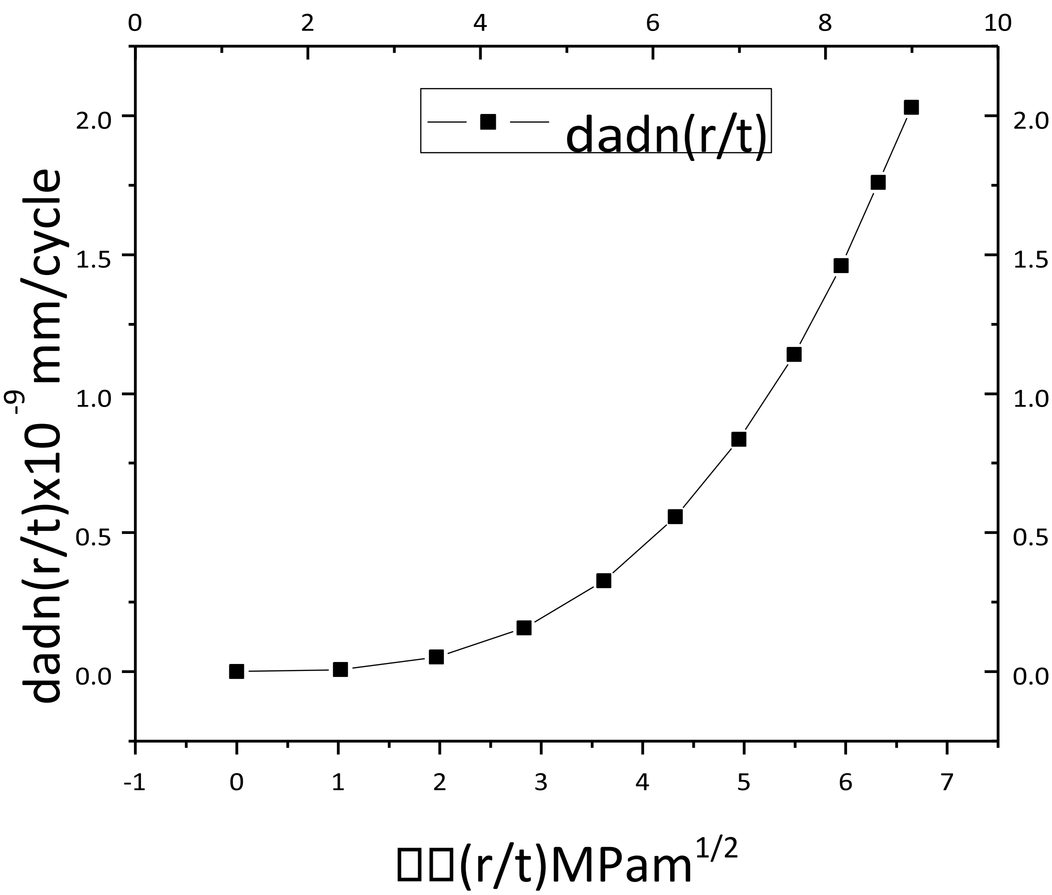

Figure 4. 3 Hole Radius to Pipe Thickness

This plot also stipulates that there is no major crack growth in the near threshold and Paris Regions. Crack is noticed in the third region when the slope of the Crack Growth Rate is found.

4.5.1: Stress Distribution

The Stresses applied on the pipeline showed that almost every parts of the pipeline had equally similar amount of stress distribution. The deformation scale factor was also seen to be low.

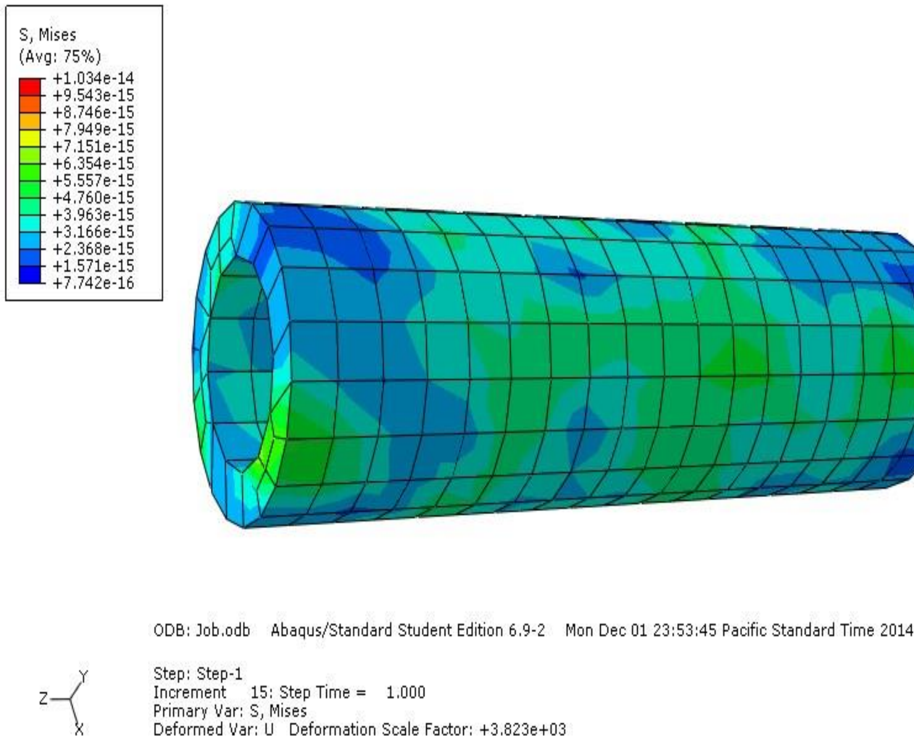

Figure 4. 4 Stress Distribution

4.5.2: Geometry

The pipe was divided into two halves. In tracking the crack as an edged crack, a xy plane was drawn to get to where the crack was inserted which was then treated as a rectangular structure.

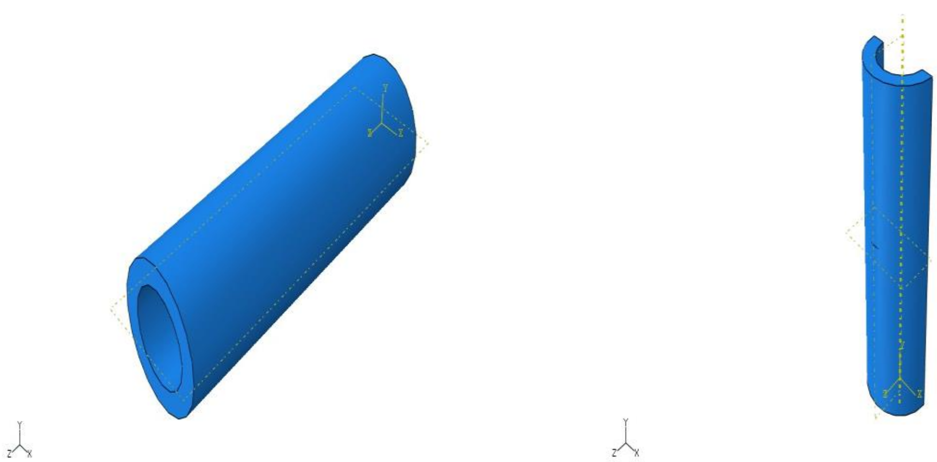

Figure 4. 5 Geometry of Pipe

4.5.3: Crack Growth Rate

In determining the Crack Growth Rate, three different crack lengths were considered to understand its behavior in terms of changing crack lengths. The flow rate of the fluid was 20MPa and the environment was corrosive, so that the understanding is made properly in regards to the behavior of crack growth rate in both corrosive and non-corrosive environments.

Crack length, c=0.7mm, Crack depth, a=0.20mm, Pipe thickness, t=0.25mm

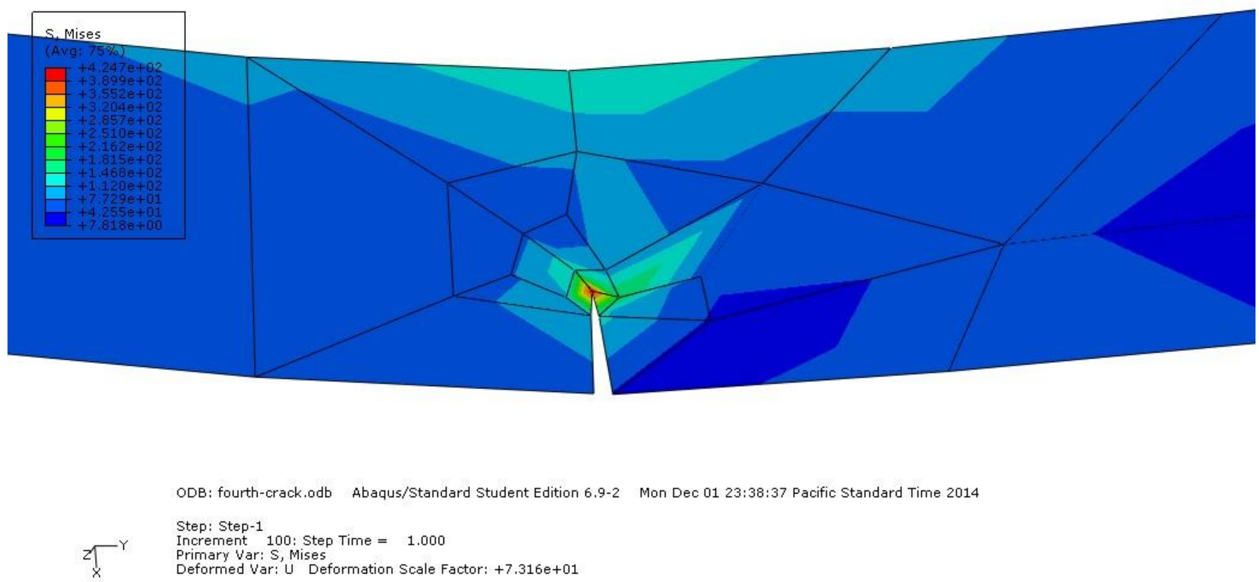

Figure 4. 6 Model of Crack Growth Rate on Pipe with Crack Length of 0.7 mm

This shows that the stresses on the pipe was not that enough to easily increase the crack growth rate

Crack length, c=0.6 mm, Crack depth, a=0.20 mm, Pipe thickness, t=0.25 mm

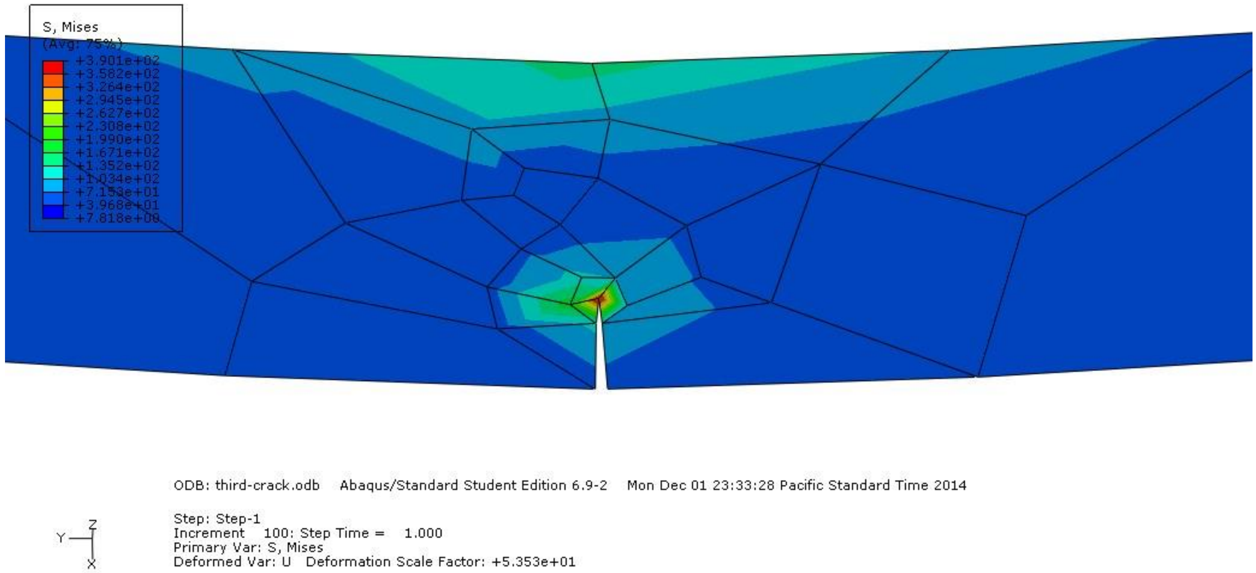

Figure 4. 7 Model of Crack Growth Rate on Pipe with Crack Length of 0.6 mm

Similarly, the structure will not easily get tire and start cracking due to low stresses.

Crack length, c=0.5mm, Crack depth, a=0.20mm, Pipe thickness, t=0.25mm

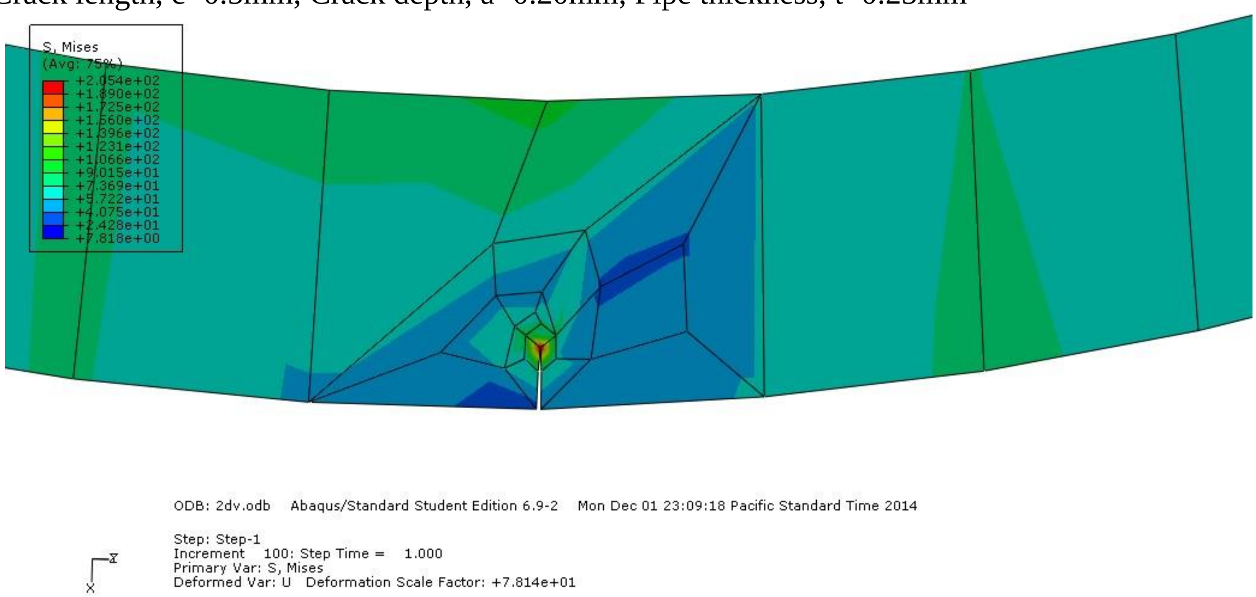

Figure 4. 8 Model of Crack Growth Rate on Pipe with Crack Length of 0.5 mm

As the length of the crack reduces, the applied stresses on the pipeline increase. This will cause the crack tip to be under suppression which gradually makes the material to fail.

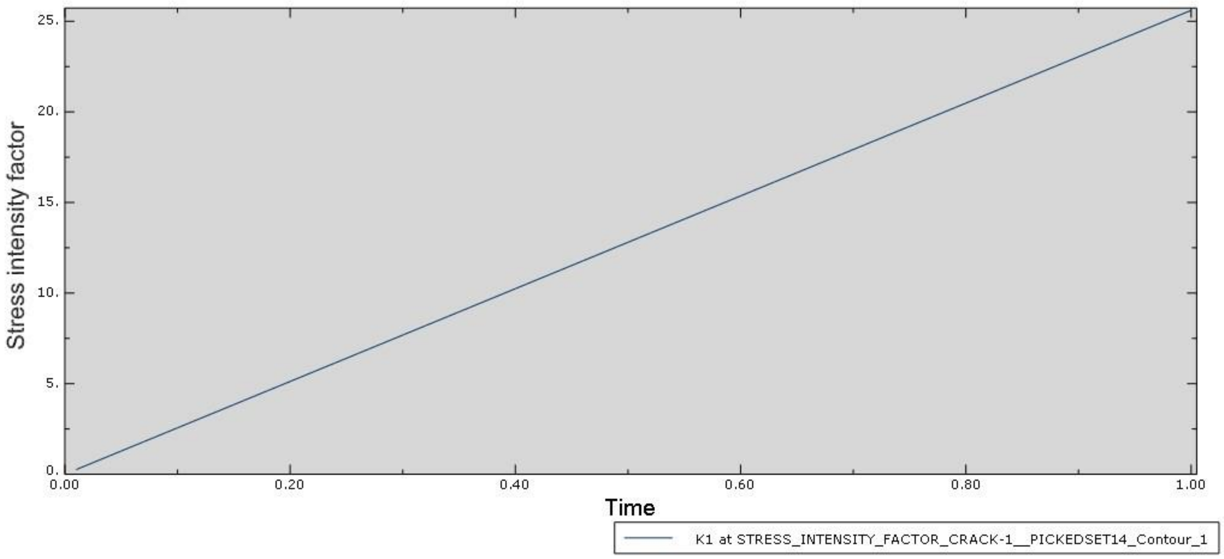

Figure 4. 9 Plot of Stress Intensity Factor against Time of safe Aspect Ratios

This plot shows that the driving force of the crack will increase as the pipe spends maximum number of time in service. It is also greater than the released strain energy on the pipe.

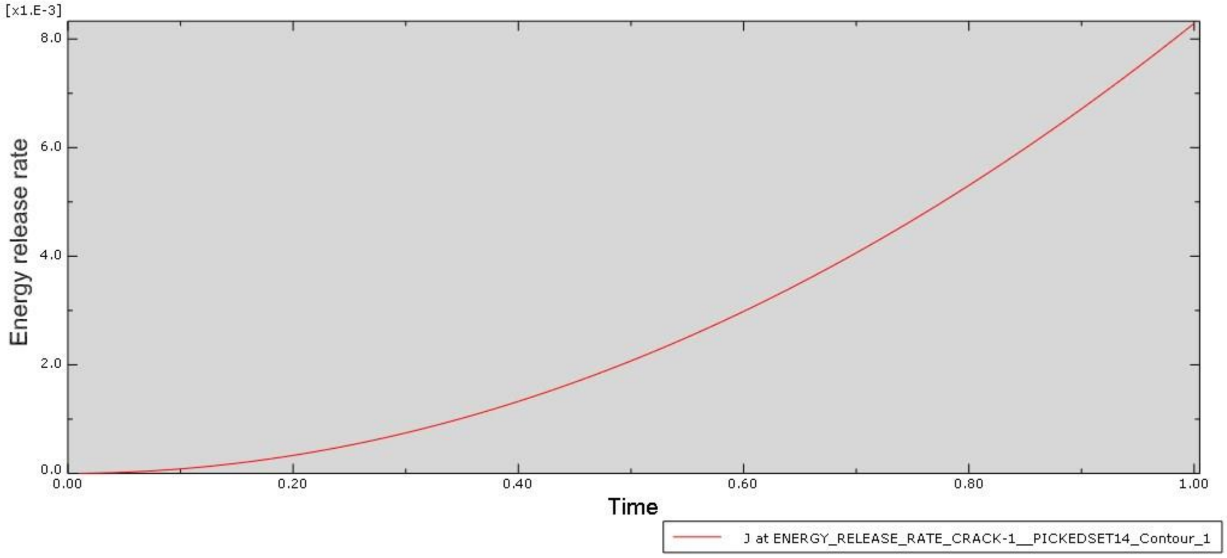

Figure 4. 10 Plot of Strain Energy Released Rate against time of safe Aspect Ratios

The behavior of the Energy Released Rate with time is similar to those of the Crack Growth Rate. It also indicates that with respect to time, the strain is lower on the pipe as compared to the crack driving force, which simply means that the pipeline will not easily get tire.

CHAPTER FIVE: Conclusion and Recommendations for future work

5.1: Implication of the Results

1) The Strain Rate on the pipe is low due to nearly equal distribution of the applied loads.

2) The Crack Growth Rate is very slow, which starts initiating close to the region three of the Fatigue Crack Growth Rate.

3) The Fracture Toughness of the pipeline is greater than the driving force of cracks.

4) Between the Aspect Ratios of 0.2 to 0.5, the pipeline is safe when the stress ratios of 0.8 to 1.1 are applied due to bending and tension.

5.2: Conclusion

This paper focuses on the evaluation of stresses that a pipeline needs to withstand before cracking using Fracture Mechanics approach. The Paris Law, Stress Intensity Factor, Stress Intensity Factor Range and XFEM modeling were used to analyze how the stresses are distributed in/on the pipeline before it gets tire; as well as its effect on the Crack Growth Rate per time in an aggressive environment. The loading conditions were bending and tension. X65 graded pipeline steel with Poisson ratio, v=0.33, Young's Modulus, E=206e3MPa, materials constants C=6.9e-12 and m=3 were considered.

The Fracture Toughness, which is a unique property that describes the ability of the pipe to resist fracturing, was higher than the Stress Intensity Factor after the insertion of crack. It is one of the very important properties of a material for the application of many designs. Therefore, the predictions showed a good estimation.

5.3: Recommendations for Future Work

It is thereby recommended that the method used for the testing of the pipeline before been fit for service be improved; since most welding defects that lead to cracks are not easily noticed when the pipeline is under test. Improvements need to also be made on the coatings because; offshore pipelines are highly susceptible to corrosion. The above estimations should be used to predict the life span of the pipeline with respect to Erosion-assisted Environmentally-assisted fatigue Crack Growth. There is also a need of finding a relationship between Weight Loss Measurement and Fatigue Crack Growth Rate of a material.

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