RELIABILITY AND RISK-BASED ASSESSMENT OF OFFSHORE JACKET STRUCTURES IN THE NIGER DELTA, NIGERIA

BY

OMOTOSO, MATTHEW FOLORUNSO

M.Sc. Civil & Industrial Engineering,

Vinnitsa Polytechnic Institute, Vinnitsa Ukraine, 1987

Matric N0: 069042032

A THESIS SUBMITTED TO THE SCHOOL OF POST GRADUATE STUDIES IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

DOCTOR OF PHILOSOPHY (Ph.D) IN THE DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING OF THE UNIVERSITY OF LAGOS

FEBRUARY 2014

SCHOOL OF POSTGRADUATE STUDIES
UNIVERSITY OF LAGOS

CERTIFICATION

This is to certify that the Thesis:

RELIABILITY AND RISK-BASED ASSESSMENT OF OFFSHORE JACKET STRUCTURES IN THE NIGER-DELTA, NIGERIA

Submitted to the
School of Postgraduate Studies
University of Lagos

For the award of the degree of

DOCTOR OF PHILOSOPHY (Ph.D.)

is a record of original research carried out

By:

OMOTOSO, MATTHEW FOLORUNSO
In the Department of CIVIL AND ENVIRONMENTAL ENGINEERING

OMOTOSO MATTHEW		14/02/2014
AUTHOR'S NAME	**SIGNATURE**	**DATE**
PROF. M.A. SALAU		14/2/2014
1ST SUPERVISOR'S NAME	**SIGNATURE**	**DATE**
PROF DAVID ESEZOBOR		14.02.2014
2ND SUPERVISOR'S NAME	**SIGNATURE**	**DATE**
DR. O.S. ASAOLU		14/02/2014
1ST INTERNAL EXAMINER	**SIGNATURE**	**DATE**
DR E.E. IKPONMWOSA		14/2/2014
2ND INTERNAL EXAMINER	**SIGNATURE**	**DATE**
Prof Y A Jimoh		14/02/2014
EXTERNAL EXAMINER	**SIGNATURE**	**DATE**
Dr. T.A. Fashanu		14/02/2014
SPGS REPRESENTATIVE	**SIGNATURE**	**DATE**

Dedication

This Dissertation is dedicated to:

My mother and my late father,
My senior sister and my late uncle
My wife and my children,
My teachers

ACKNOWLEDGMENTS

Glory be to God Almighty for giving me the strength, wisdom and knowledge to successfully undertake my PhD research work. My appreciation goes to my dynamic and able supervisors, Professor M.A Salau and Professor D.E. Esezobor for their professional supervision and guidance during the course of my study.

I recognize Professor. G. I. Lawal of University of Lagos and Mr. Niyi Fowowe of Foundarock Engineering Limited for their wonderful assistance in providing me relevant information regarding University of Lagos post graduate program. I express my profound gratitude to Dr. Essien Etok of ExxonMobil for his guidance in ensuring that my research findings were adequately presented in a straightforward and distinct manner.

I would like to express my gratitude to Mr. Olakunle Fasakin of DeltaAfrik Engineering Limited for his assistance with computing during my research work. My appreciation also goes to Dr. Benson Onyebueke of Shell Nigerian Exploration & Production Company for his useful and informative technical discussions. I thank my educators and colleagues in the Civil and Environmental Engineering Department, University of Lagos for their cooperation at all time. The love and support of the secretarial staff are also appreciated.

I am very grateful to my mother and late father who were not only my perfect medium to this world, but wonderful parent who guided me to be a winner. I must express my profound gratitude to my late big uncle and early life coach, Pius Olaniyan who continued the good work where my late father stopped.

I sincerely wish to thank my dear wife, Mrs. Bosede Omotoso and my wonderful children, Bukky, Kayode and Olaoluwa for their patience, encouragement and cooperation throughout the period of my study. The research work is dedicated to my fantastic family members and associates. Nevertheless this gesture is not sufficient to pay for your steady compassion and encouragement. In conclusion, I thank all who made this study a complete success.

Matthew Folorunso, Omotoso
February 2014

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

ABSTRACT

In Nigeria, a large number of jacket platforms installed in the Niger Delta have been operating beyond design life of 25 years due to the exorbitant cost of replacement with new ones. These Jacket structures often undergo corrosion and fatigue damages due to hostile offshore conditions and accidental release of corrosive agents from crude oil production activities. Therefore, there is a growing need to closely monitor the structures to protect unexpected failures. Applications of appropriate assessment methods for corrosion and fatigue hazard mitigation measures can assist to check mate or prevent the jacket structure premature failures. The available basic design techniques and the standards in the petroleum industry standards for the new structures are somehow inappropriate for the assessment of the existing jacket structures. The ambiguity in the characteristics of corrosion and fatigue hazard has made the deterministic approach unsuitable for the risk-based assessment of jacket structures. The above mentioned reasons have made it imperative to search for a new structural assessment technique for the jacket structures.

This study established the appropriate relationship between chloride accumulation and diffusion process within the offshore jacket structures. Marine steel structure corrosion damage model was developed for corrosion damage monitoring and mitigation. The study also evaluated the existing jacket platform integrity in the Niger Delta with special reference to the jacket structure system reliability and operational safety. Relevant engineering standards for offshore structures, new design and assessment with special reference to API RP 2A WSD which are widely

used in the petroleum industry were appraised. Several jacket component damage scenarios were evaluated and simulated with due consideration to corrosion and fatigue hazard. Reliability method for the assessment of corroded jacket structures was developed. A ratio between reliability of an intact and a corrosion damaged jacket structure known as reliability factor (RF) was also derived to establish when the jacket platform with associated corroded jacket structure would be due for abandonment.

The study revealed that jacket structure reliability (Rsj) and RF for three jacket structures investigated in the study are 85.8% and 1.166 respectively. It demonstrated that components with localized corrosion and fatigue damage exhibited an unacceptable risk level that urgently required revamp works.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

An offshore jacket platform is described as a man-made "island" built to allow offshore crude oil production through conventional above-water techniques. Around 65% of Nigerian offshore crude oil production is via jacket platform with associated subsea pipelines and manifolds (Department of Petroleum Resources, 2011). The submerged part of offshore platform known as jacket structures is constantly exposed to salty sea water that hasten the structure corrosion damages. This work was intended for studies and appraisal of several factors that affect integrity of offshore jacket platform, so that prediction can be made with regards to jacket structure reliability.

Jacket structure is subjected to member diameter and thickness reduction as a result of corrosion losses, which significantly affects offshore jacket platform global strength. The action of ocean wave and strong winds against jacket platform also leads to the development of fatigue cracks on the jacket structure joints. Therefore, corrosion and fatigue risks demand detailed study and investigation on how the hazard affects offshore jacket platform with special reference to jacket structures.

The safety of jacket structure is generally assumed to be achieved by design according to the established standards and procedures in order to prevent a

catastrophic collapse which may be caused by component deterioration and associated risks. But there is a general recognition across the construction industry that assessment method for existing structures is quite different from the new design process. The compliance with existing rules and regulations may contribute to the safety of the jacket structure's safety in the design stage. But may not be appropriate for the assessment of ageing and corroded jacket structures.

Jacket structures may have been deteriorated to an undisclosed degree through decades of existence in deep sea water. Adequate safety of the structures can be achieved through assessment and appropriate revamp works. It is essential therefore to develop a scheme that presents a minimum of workloads required to be completed before the proper future safety of jacket structures can be guaranteed with regards to corrosion, fatigue and related threats.

1.2 Statement of the Problem

Large numbers of existing offshore jacket platforms for the crude oil production in the Niger Delta in Nigeria have been designed for a life span of 25 years as specified by API RP 2A WSD. The exorbitant cost of replacement of the jacket platform with new structures has made the majority of the operators in the oil sector to exploit the platform beyond the design life.

The age distribution for jacket platform installations in the Niger Delta shows that relatively large number of the platform age is greater than the design life of 25 years as shown in Figure 1.1. The likelihood of failure with time in service for civil

engineering structures increases during the late life which is often associated with degradation of construction materials and onset time dependent failure mechanisms. Jacket structure safety against environmental loads and operation stresses, which was acceptable in the design life, may not be appropriate for the same structure in later lifetime.

The investigation of Sharp, (1992) on damaged offshore structures installed in the North Sea for a period up to 1987 is shown in Figure 1.2 to support the above declarations.

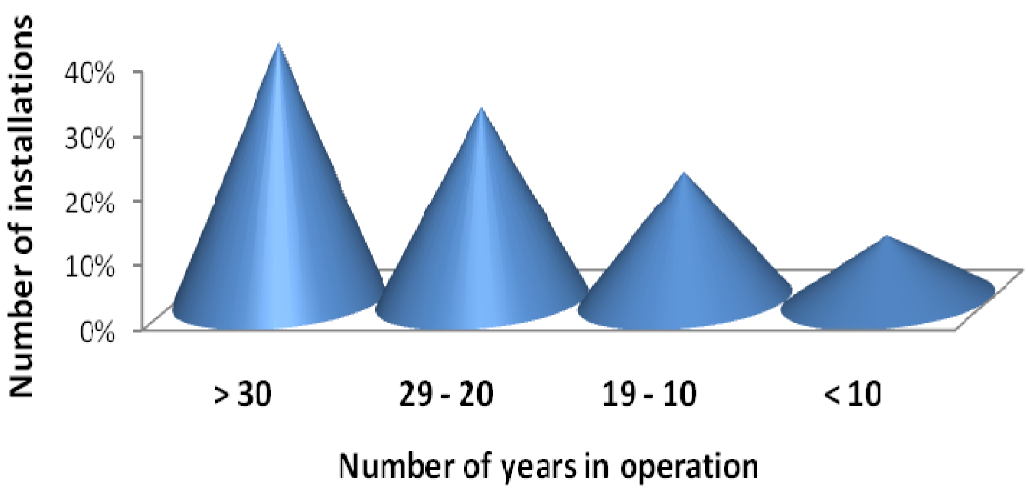


Figure 1.1- Age Distribution of Jacket Platforms in Offshore Niger Delta (DPR and IOC)

Steel structures located in an offshore environment are subjected to corrosion degradation due to oxygenated and salty seawater. The section of an unprotected specimen generally has the highest corrosion rates around the splash zones. Therefore, legs, framing members and boat landing areas of jacket structures suffer more corrosion damages than any other parts of the structures.

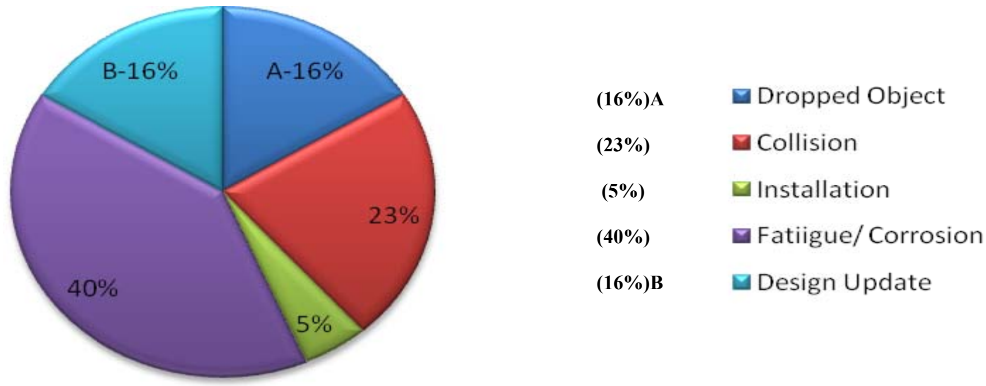


Figure1.2- Offshore Jacket Platforms Damages
(Sharp, 1992)

However, the available basic design methods in the current standards used for new structures may not be suitable for the assessment of existing jacket structures with regards to corrosion damages, while regular structural reliability evaluation of jacket structure is significant to prevent the structures from sudden collapse. The above phenomena formed the foundation of this research work which can be summarized as:

i. **Complexity of corrosion processes and limited information on corroded offshore jacket structures.**

ii. **Limited life span of offshore jacket structure due to environmental pollution (Accidental release of ions from oil production activities).**

iii. **Non availability of defining method for jacket structures reliability estimation of corrosion losses.**

iv. **Uncertainty in the characteristics of corrosion and fatigue hazard, which makes deterministic approach less suitable for the risk-based assessment of jacket structures.**

1.3 Justification of the Study

Offshore jacket platforms are aging and failing, safety assessment of the structure has been of increasing interest and urgently require new structural assessment techniques (Gerhard Ersdal, 2005; Moan, 2000). Several assessment methods have been proposed for jacket structure assessment, but no defined reliability evaluation method for corrosion damages (Aghakouchak and Stiemer, 2001). API RP 2A WSD, 2000 standard emphasized that sufficient data should be obtained concerning investigated offshore jacket platform to provide comprehensive engineering appraisal of the structure's integrity. However, the standard does not adequately cover jacket platform probability of failure during operating lifecycle. Also, assessment guidelines in the standard were based only on life safety and failure consequences with little consideration for risk-based assessment for damaged components. Deliberation on jacket structure reliability as a result of corrosion losses was not covered in API RP 2A WSD and other relevant standards used for jacket platform assessment in the petroleum industry.

The basic assumption in the study is that the appropriate structural safety is not restricted by the incidence of member corrosion losses alone, other than the structure has an acceptable reliability value. The research work evaluates the minimum workloads that required to be completed for jacket structure safety during operation life cycle. Assessment of particular hazard that intimidate jacket structural safety shall be determined.

The study has developed a scheme that presents a minimum work load to be completed in order to guarantee jacket structure safety.

i. **Specific hazard evaluation that threatens jacket structural safety has been determined and resolved.**
ii. **Provision of economic advantages of structural reliability technique over existing manual and structural analysis computer software (SACS) methods.**
iii. **Frontier of knowledge for the determination of the structural reliability and material risk-based assessment of offshore jacket structures is established.**

1.4 Aim and Objectives of the Study

Aim: To establish a structure reliability technique for the offshore jacket structure assessment.

Specific objectives:

i. **To investigate chlorine accumulation and diffusion process within an offshore jacket structure.**
ii. **To analyse jacket structure corrosion losses in an offshore environment.**
iii. **To develop reliability assessment method for offshore jacket structures.**
iv. **To perform a risk-based assessment with regards to corrosion and fatigue hazard.**

1.5 Research Questions

In line with the aim and objectives of this study, the following research questions are enumerated:

i. **What is the trend of jacket member corrosion losses in various tidal zones?**

ii. **What are the effects of environmental pollution on the reliability of the jacket structure?**

iii. **What is the possible method of evaluating the jacket structures reliability with respect to corrosion losses?**

iv. **What levels of risk are associated with corrosion and fatigue on jacket structures in an offshore environment?**

1.6 Scope and Limitation of the Study

Based on the research background and the statement of the problem, the study scope is as specified below:

i. **The study determines the appropriate work load that guarantees existing jacket structural safety in the Niger Delta, Nigeria. However, the procedure is also applicable to jacket structures in any other part of the world.**

ii. **The acceptance criteria for jacket structural safety indicators against collapse was investigated based on jacket components corrosion losses, which were derived from site survey data using ultrasonic measurement equipment. Specific hazard evaluation that threaten jacket structural safety was researched and resolved with special reference to corrosion and fatigue hazard being the most prevalent offshore environment risk.**

iii. **Piles may degrade due to fatigue and corrosion, however it is difficult to inspect piles of an offshore jacket structure. Hence, pile related failures has not been included in this study, and the conclusion is based on this limitation.**

1.7 Definition of Operational Terms

Abrasion Scars: The damage of a steel structural member due to scratches.

Advection: The transport mechanism of a substance**.**

Bare Metal: Metal without coating application.

Cathodic Protection: A method used to protect an object from corrosion by making it a cathode.

Coating Life Span: This is a life expectancy of a coating material.

Complete Failure: Total item failure that occurred, as a result of deviation from the specific limits.

Concentration Gradient: Differences in solute concentration.

Conductor: A tubular member that transport crude oil from the ground to the surface.

Corrosion Allowance: Provision of addition material thickness during the design stage to take care of corrosion damages and losses.

Corrosion Fatigue: Component degradation due to cyclic tensile stress and corrosion environment.

Degradation Failure: Failure which occurs gradually and partially.

Failure Mechanism: The cause of the failure, whether physical, chemical or gaseous.

Failure Mode: The means by which or how a failure occurred.

Failure Probability: The probability that an item will fail over a given period of time.

Fatigue Life: The duration required (year) for a joint failure as a result of cyclic loading.

Flooded Member: Corrosion damaged jacket tubular member filled with sea water**.**

Frequency: The number of occurrences.

Jacket Structures: The submerge sections of offshore jacket platform.

Joint Fatigue Profile: The fatigued-joint distribution along jacket structures tidal zones.

Life Extension: Jacket structures operating life beyond design life (i.e. > 25 years).

Marine Growth: The growth of algae, slime and seaweed on marine structure surface.

Mud line: The point of intersection of seawater and bottom soil.

Operating Lifecycle: The sum of jacket platform design life and life extension.

Probability of Failure: The probability that equipment will fail.

Probability: The likelihood of an occurrence of an event.

Qualitative Probability: Probability of event occurrence represented in the superlative degree.

Quantitative Probability: Probability of event occurrence represented in percentage.

Reliability Factor: Ratio between intact jacket structure system reliability and corroded jacket structure system reliability.

Reliability: the probability that an item will perform its intended function for a specific period of time under certain condition.

Required Function: The function or combination of functions, of an item, considered necessary to provide services.

Risk: The probability of an incident and its consequences.

Scenario Consequences: The penalty of a particular damage state.

Splash Zone: The area above the spring high tide line of coastline.

Sudden Failure: Failure that could not be anticipated by prior examination.

Topside: Part of offshore platform located above sea water level.

Unity Check: Ratio of actual stress with allowable stress.

Wear Out Failure: Failure resulting from deterioration from use of the system.

Wellhead Platform: Platform built on the top of oil production well.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 General

Marine environments are severe corrosive agent for mild and low alloy steel structures. For economic reasons, such steels remained the preferred materials for many engineering structures such as offshore jacket platform and ship hulls. However, statistics show that about 40% of jacket structural failures are attributed to corrosion, and fatigue (Emi, Yuasa and Kumano, 1993). There have been a number of offshore jacket platform failures and environmental disasters attributed to poor structural assessment and maintenance as a result of corrosion and fatigue (Sharp, 1992; Dillion, 2006).

Probabilistic concepts are currently accepted explicitly for limit state design. Thus, no structure can be absolutely certified safe. The distinction between a 'safe' and an 'unsafe' design is in the degree of risk considered acceptable, not in the hallucination that such risk can be completely eliminated. The acceptable probabilities of various limit states have not yet been defined or quantified, but the acceptance of probabilistic concepts marks an important step forward in design which required further research. The probability of failure of a structure is heterogeneous and offshore jacket platform follow the same failure representation. Gerhard Ersdal (2005) carried out studies on offshore jacket structure safety due to extreme environmental loads but, limited work have been done on jacket structural

safety and reliability as regards to member corrosion losses. This study established correlation between corrosion and fatigue hazard using Structural Analysis Computer System (SACS). The work also examined component damage scenarios with regard to corrosion and fatigue hazard using risk-based assessment method. The outcome of this effort guaranteed effective mitigation method against corrosion and fatigue hazard. Similarly, It is impossible to protect every component of the structure to the extent they become impervious to corrosion and fatigue attacks, and therefore necessary from an assessment perspective to identify the high risk scenarios of various hazards with proposed mitigation measures (Damir and Hinko, 2005; Pereira, 2004).

Corrosion is a function of many variables and uncertain in nature as regards to offshore jacket structures (Guedes and Garbator, 1999). A purely theoretical model of the likely loss of material on the actual corrosion mechanism is extremely difficult due to the complexity of the problem (Melchers, 1999). Modeling of the durability of marine steel structures with regards to corrosion damage required quantitative understanding of pollution activities and corrosion agents diffusion processes around the structures (Youping Liu, 1998). Equations for diffusion processes generally exist, but the majority of the models discussed in the literature has been developed for specific environment with a constant chlorine concentration (Melchers, 2003). The appropriate diffusion equation is therefore required for offshore jacket structures environs, dominated by ocean waves, current and increase in chlorine concentration as a result of oil production activities. Jacket member corrosion losses lead to structural resistance reduction, which may result

into entire platform structural failure. The reliability calculations based on limit state have been presented for ship structures with generic form of limit state function for structural member corrosion loss is represented in Equation 2.1 as proposed by Yong Bai (2003). However, similar work has not been carried out for corroded jacket structures.

$$g_C = d - d_{crit} - d_{UC} \qquad \textbf{(2.1)}$$

The depth d_{UC} of the uniform corrosion which is applied for the reason that uniform corrosion normally has less influence on the structural resistance, d_{crit} is the critical member thickness loss at which failure occurs. The existing engineering design codes often use simplified formulation for structural capacity estimation for easy applications instead of the exact equations that may be complex. However, more precise equation with updates eradicates conservatives in simplified formula when used for the evaluation of existing jacket structures. High uncertainty requires a large safety margin, and reduced uncertainty also lower safety margin. A number of procedures permit lower acceptance criteria to be used during evaluation of existing structures compared to the new design as prescribed in the working stress standard (API RP 2A WSD, 2000).

2.2 Assessment Procedures in accordance with API RP 2A Standard

In the petroleum industry worldwide, selection of jacket platform for monitoring, survey and assessment are carried out according to the recommendations of API RP 2A WSD (API 2000). The publications deal with recommended practice for planning, designing and constructing fixed offshore platforms. The document

essentially address problems of a general nature with respect to particular circumstances and regulations that may be reviewed as need arise. API 2000 special note stated that the standard is not undertaking to meet the duties of employers and manufacturers concerning health and safety risks. It is the responsibility of the platform owners to ensure their facility safety. Also, the facility operator should work in partinership with structural engineer to determine jacket platform integrity and capability to withstand the functional loads.

General industry practices recognize that older, existing structures may not meet current design standards. However, many of jacket platforms that are in an acceptable condition may be structurally adequate using a risk-based assessment criteria that considers jacket platform function and the consequence of failure. API 2000 stated that the existing platform should undergo an assessment to demonstrate fitness for purpose if any of the following conditions noted exist: addition of personnel and facilities leading to increase of load on the jacket platform structures, inadequate deck height and the deviation of significant.

The damage found during inspections, such as corrosion and fatigue damage should be used to assess the fitness for purpose of a structure, particularly when significant damage is found on the primary structural components. Minor structural damage may be justified by appropriate structural analysis without performing a detailed assessment. However, the cumulative effects of damage must be documented and accounted in future detailed assessment.

The API 2000 standard assessment guidelines are divided into the subsequent sections describing assessment initiators: exposure categories, platform information, assessment process, analysis and mitigations. The jacket platform screening to determine, which of it that may be proceed to detailed analysis is performed by executing the first four components of the general assessment process illustrated in Figure 2.1. If a structure does not pass screening, there are two potential sequential analysis checks, which are design level analysis and ultimate strength analysis. It is generally more efficient to begin with a design level analysis, However, it is allowed to bypass the design level analysis and proceed directly with an ultimate strength analysis. Jacket platform comprehensive assessment process proposed in API 2000 is revealed in Figure 2.2.

API 2000 section 17.8 stated that jacket platform structure, which does not meet assessment requirements through screening, design level analysis, or ultimate strength analysis require mitigation actions. The mitigation actions may be inform of structural modifications and operational procedures that reduce loads and increase capacities. An alternative approach to jacket platform structure's intervention that may be appropriate in some circumstances to minimize the risk of structure failure is by imposing load restrictions, altering aspects of the use of the structure, and implementing monitoring and control regim. However, it is the responsibility of the platform operator in partnership with the relevant authority to make the final decision on structural intervention methods based on good engineering judgement with due consideration to crude oil production regime.

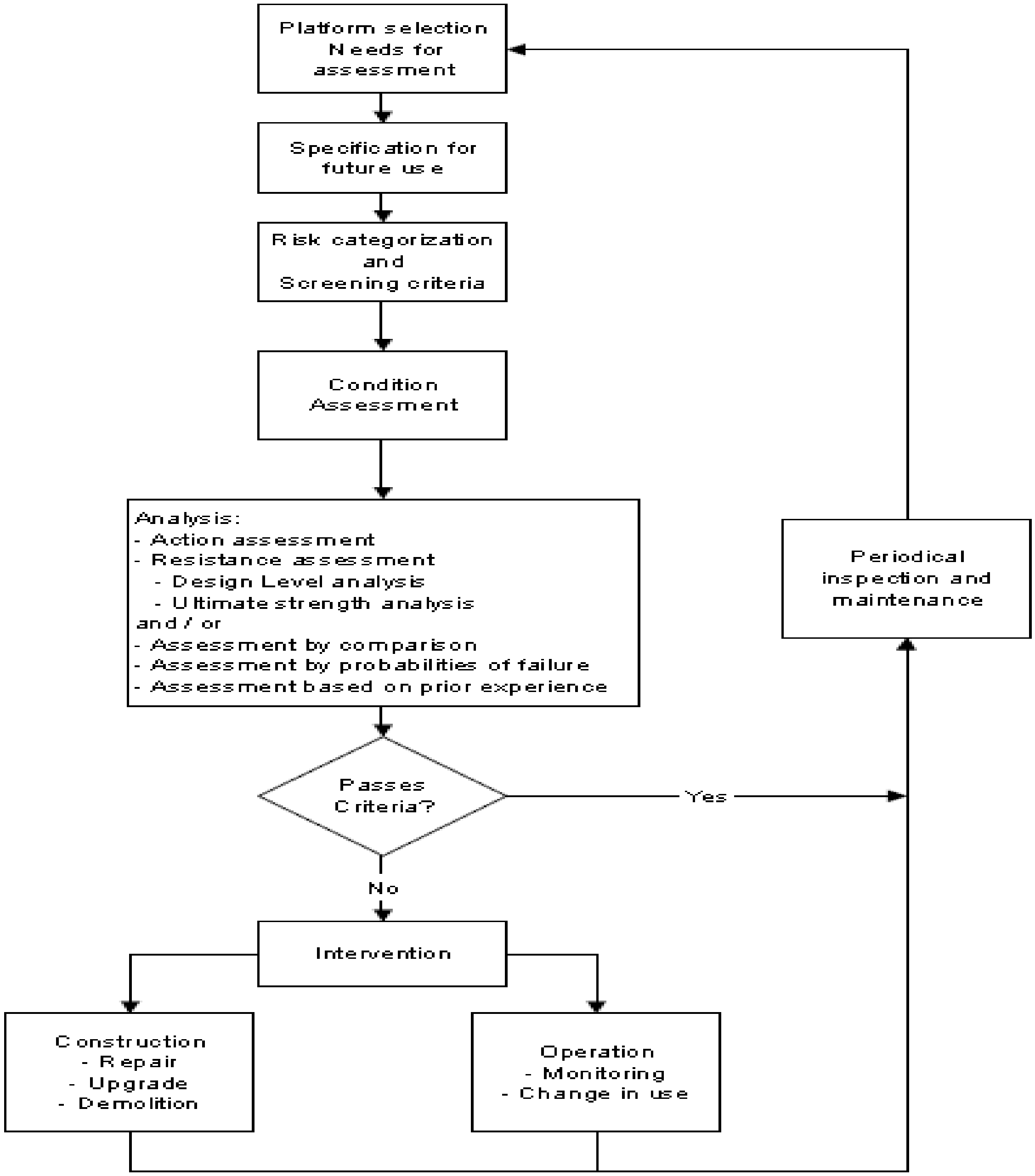
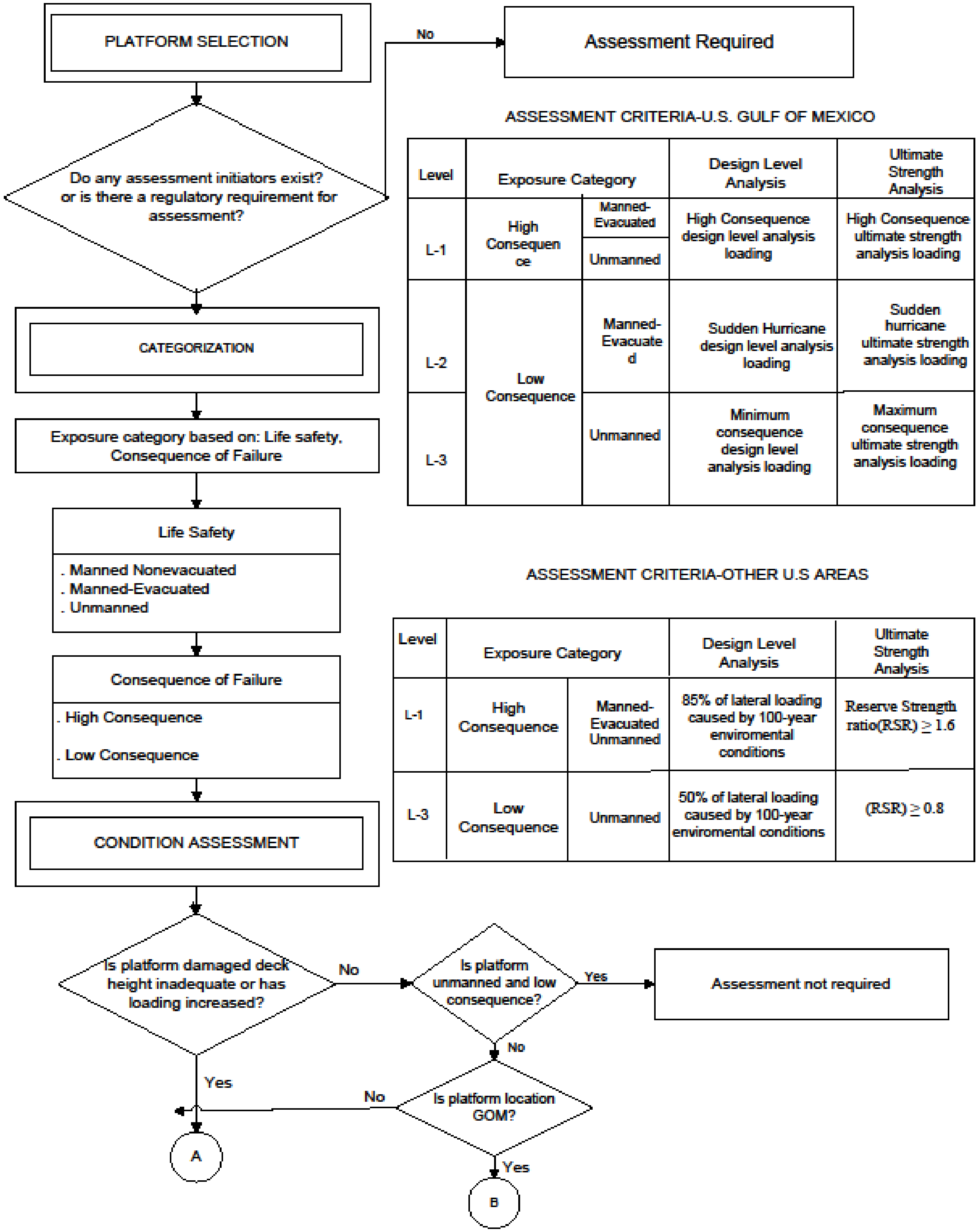


Figure 2.1, General Assessment Procedure (API 2000)



ASSESSMENT CRITERIA-U.S. GULF OF MEXICO

Level	Exposure Category		Design Level Analysis	Ultimate Strength Analysis
L-1	High Consequence	Manned-Evacuated Unmanned	High Consequence design level analysis loading	High Consequence ultimate strength analysis loading
L-2	Low Consequence	Manned-Evacuated	Sudden Hurricane design level analysis loading	Sudden hurricane ultimate strength analysis loading
L-3		Unmanned	Minimum consequence design level analysis loading	Maximum consequence ultimate strength analysis loading

ASSESSMENT CRITERIA-OTHER U.S AREAS

Level	Exposure Category		Design Level Analysis	Ultimate Strength Analysis
L-1	High Consequence	Manned-Evacuated Unmanned	85% of lateral loading caused by 100-year environmental conditions	Reserve Strength ratio(RSR) ≥ 1.6
L-3	Low Consequence	Unmanned	50% of lateral loading caused by 100-year enviromental conditions	(RSR) ≥ 0.8

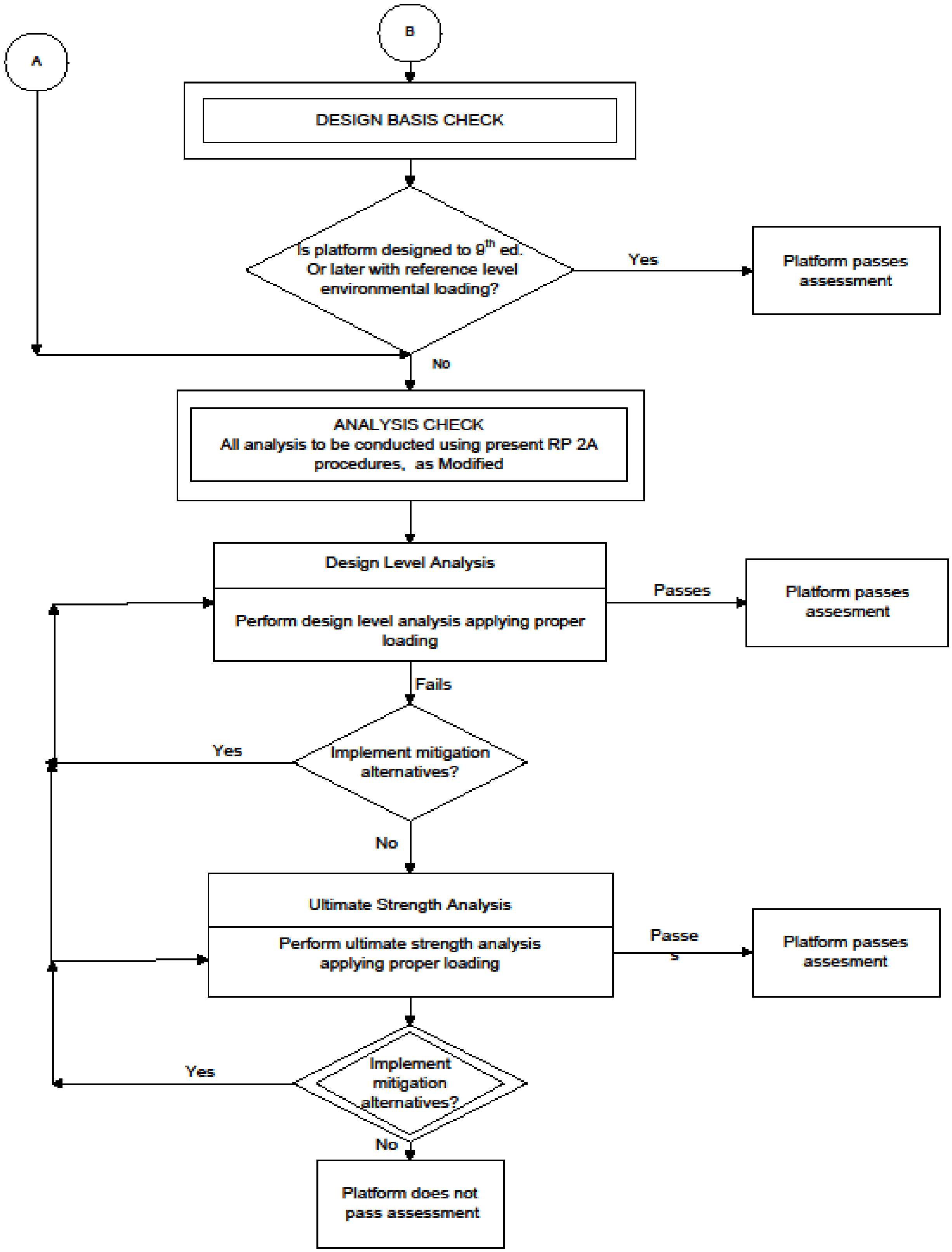


Figure 2.2 Platform Assessment Process Proposed in API RP 2A WSD (API 2000)

2.3 Discussion and Remarks on Reviewed Standard

The API RP 2A WSD is the most frequently applied standard for the structural design of offshore jacket platform in Nigeria and worldwide. The standard is of interest because is the most accessible document that takes assessment of existing jacket structures to a detailed level. Hoewver, the standard affirmed to be only applicable for the assessment of jacket platforms designed in accordance with 20th or earlier editions of the same API standard. But Structures designed after the 21st edition, should be assessed in accordance with the criteria originally used for the design. By this clause API 2000 cannot be used for assessment of all the existing jacket platforms since some of the platforms were built before the estabilishment of the standard. Therefore, this assertion is considered to be one of the API 200 limitions.

There are two possible analysis checks mentioned in API RP 2A WSD, design level analysis and ultimate strength analysis. However, the design level analysis procedures for assessment is similar to those used for new platform structural design in the area of safety factors application. But, lateral environmental load can be reduced to 85% of the 100-year condition for the high consequence jacket platforms, and to 50% for low consequence jacket platforms. The above review document is a relevant standard for jacket structure assessment, nevertheless the standard did not adequately covered jacket structure failure probability of the structure during operating life cycle. Also, the assessment guidelines in the standard are based only on life safety and failure consequences with little consideration for structural reliability and risk-based assessment of domineering offshore hazard.

2.4 Environmental Pollution and Corrosion Damage

Fick's second law predicts how diffusion causes the concentration to change with time, provided chloride ion concentration remain constant. However, the surroundings of offshore production jacket platforms are characterized with accidental discharge of ions that makes chlorine ion increases with time. The chloride accumulation was assumed to be increases linearly and this rate is not readily available in the surrounding of a marine structures (Youping Liu, 1998). However, this rate may be estimated if the age of the platform is known and the seawater chlorine ion is concentration revealed by seawater chemical analysis. The process of chloride induced corrosion of marine steel component is by diffusion of chlorides through the damaged coating. The chloride is build up overtime on steel surface to attain critical threshold that breaksdown the passive oxide layer on the steel surface for corrosion start. The replacement of corroded component may be made, however the cycle continues on the new component.

2.5 Existing Jacket Structures versus New Designs

Regarding the existing offshore jacket platform in this study, the focus will be on the structural safety during operating lifetime. The issue will be whether the safety established in the initial design stage is still appropriate during the jacket platform in service. The aim of structural inspection and assessment is to ensure safety of jacket platform, while the structural element which is not meeting the evaluation criteria may be strengthened. There are significant differences in the data about the existing jacket platform and the structure in the design stage. It is therefore

essential to account for these details while carrying out reliability assessment of existing structures. These differences are discussed in Kallaby et al (1994) and Moan and Vardal (2001), which are summarized in Figure 2.3.

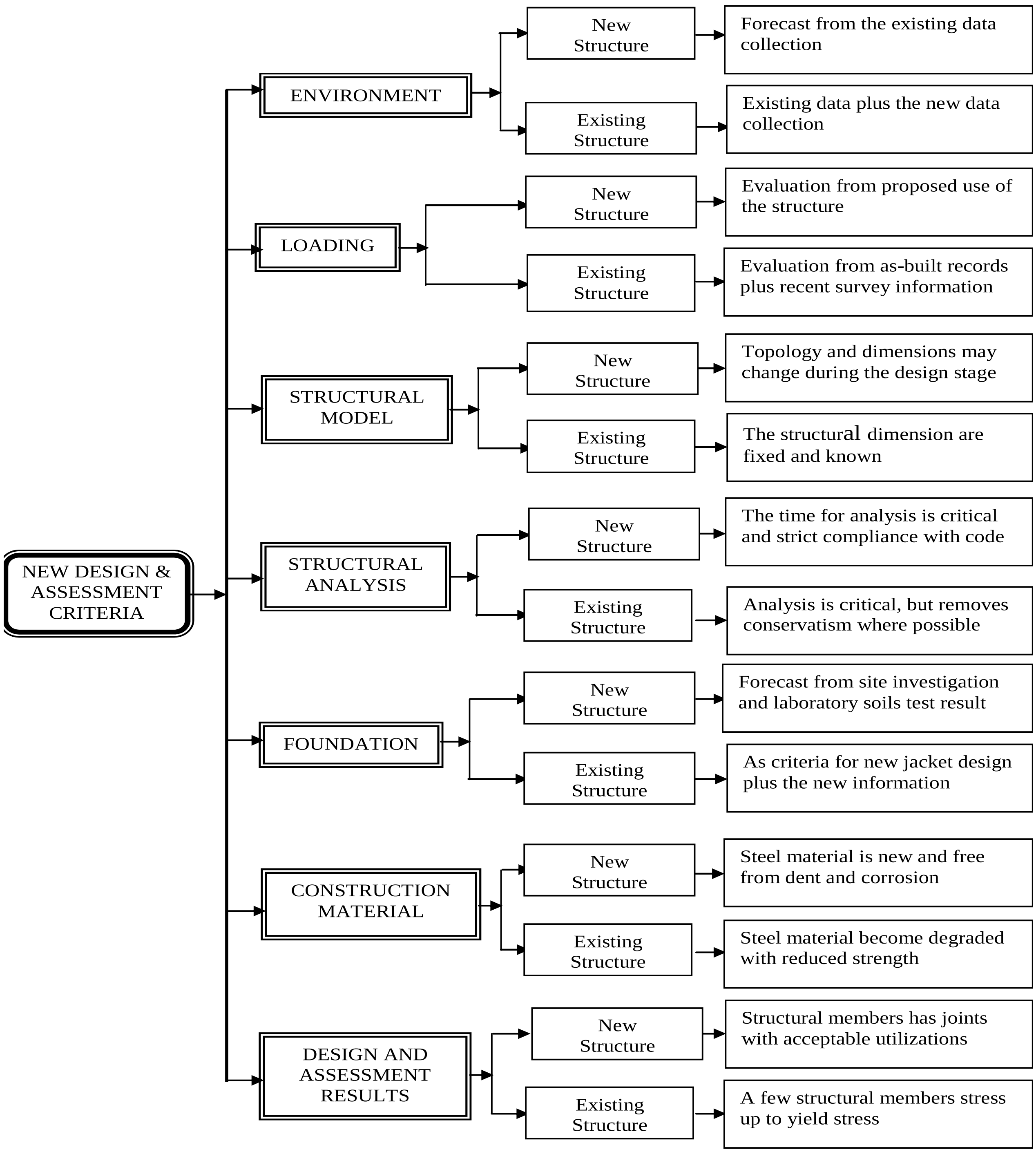


Figure 2.3 New Structural Designs Vs Structural Assessments

The model of a new jacket platform may have topology and dimensions altered as the engineering design works progress if so demanded by the asset managers until the detail design is completed and issued for construction. Equally, the existing jacket platform structures have dimensions fixed and changing of structural member sizes are forestalled. For adequately managed jacket platform structures, the available data are sufficient to enhance the structural analysis accuracy. High uncertainty requires a large safety margin, and reduced uncertainty also lower safety margin as it is described in API RP 2A WSD.

2.6 Jacket Structure Hazard Assessment

Jacket structure integrity assurance is to make sure that the structures meet required design purpose with great consideration for safety and reliability. It is a multi- disciplinary activity that comes together for this purpose, which includes inspection, material science, welding technology, structural analysis, and engineering safety. Hazard identification is significant for jacket structure failure prevention and the method can be divided into three major components, hazard identification, assessment and the maintenance program.

The key element of structural integrity assessment with regards to offshore jacket structures is presented in Figure 2.4. The diagnosing of jacket structure hazard is to provide an understanding of mechanisms that leads to the structure deterioration and potential failure that enable design engineers to arrive at appropriate structural assessment methods. Structural hazard identification span from inspection works

on site such as using ultrasonic tester (UT) , assessment activities off site and hazard resolution.

The method used for the determination of hazard potential is dependent on the hazard characteristics, frequency and the root causes. Since the design method used for new design is not appropriate for the existing jacket structure assessment, the basic criteria for choosing a jacket structure inspection and the assessment method depend on the technical capability to detect component defects and structural strength.

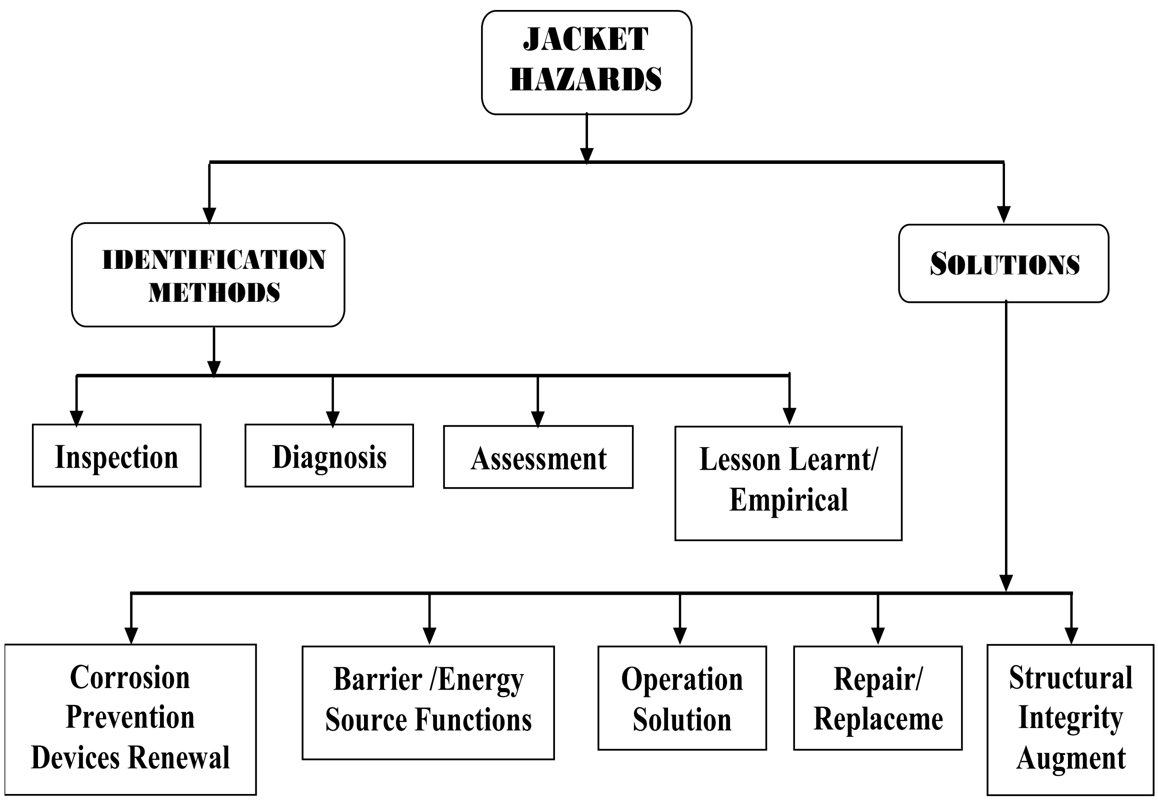


Figure 2.4 Jacket Structural Reliability Assessment Key Elements (Beden et al, 2009)

The widely applied solution method recommended for the jacket structure hazard in the literatures includes structural integrity augments, repair, replacement strategy, operational solution, corrosion mitigation and barrier/energy source functions (Beden et al, 2009). However, comparison methods based on the researcher past experience on the similar structures located around the same site can also be considered as documented in API 2000 standard.

CHAPTER THREE

3.0 METHODOLOGY

3.1 THEORETICAL FRAMEWORK

3.1.1 Offshore Structure Corrosion Damage

This Chapter provides brief discussion and summary of a theoretical framework that applied during the course of this study. The framework includes series and parallel reliability theories, fatigue development and risk-based assessments among others. The factors that lead to structural degradation and possible collapse are presented. The basic reliability theories, corrosion growth model and root Cause analysis are also presented.

In an ageing marine steel structure, of significance are defects related to corrosion and fatigue hazard. In a number of cases of damages to aquatic and land-based steel structures that have been reported, it is probable that corrosion and fatigue damage may have occurred in the structure's primary members. For a steel structure built in a marine environment, corrosion and fatigue are the most prevalent forms of deterioration mechanism, particularly when installed corrosion protection systems are malfunctioning. In this research work, other steel deterioration mechanisms like dents as a result of impact load will not be considered.

3.1.1.1 General Deterioration Models

Deterioration of jacket platform components is due to ageing effects and time dependent failure mechanisms. It manifests itself on a substantially continuous basis

and these effects are rarely superimposed on each other, Ciampoli (1999). Ciampoli recommended a model for the assessment of existing and future reliability of structural components that are presumed subject to deterioration due to the effects of aggressive agents such as the one in the offshore environment. Damage indicators modeled by a Markov process (Melchers, 2003) describes material deterioration and other several authors (Guedes Soares and Garbator 1999) described the effect of deterioration adopted Markov models. Under the Markov assumption, the time evolution of the effects of many degradation mechanisms follows an exponential law, characterised by uncertain parameters.

Material deterioration is concluded in Moan (2005) to be a reliability issue for a system subjected to a random sequence of aggressive events discrete in time. A Semi Markov model was adopted, in which the decay prediction depends on transition probabilities, on the holding time distributions and on the initial conditions with increasing or decreasing hazard rates.

The life times were effectively modeled by Weibull distributions (Marcello Ciampoli, 1999) system, with only one component degrades randomly over time. The main objective of the model is to indicate the deterioration level of the system at some time, t. The degradation of the system is between D^0 and D^{max}, where D^0 is the initial deterioration of a component at time t^0 and D^{max} is the maximum deterioration of the system. The system fails if its deterioration exceeds the maximum deterioration, D^{max}. The deterioration of the system evolves randomly over time.

3.1.1.2 General Corrosion

Corrosion is a major problem for steel structures and more predominant in offshore facilities such as jacket platform. Provided maintenance is adequate and corrosion protection devices are properly applied, the steel structure will continue to experience deterioration. Probabilistic model seems to be the most appropriate to describe a corrosion process, which is a function of many variables and uncertain in nature. The effect of corrosion can be modeled by a monotonic time varying thickness reduction, leading to an increased uncertainty in the probability density function of the remaining strength.

The corrosion rate is influenced by physical, chemical and biological factors, which are complex phenomena. C. Guedes Soares and Y. Garbatov (1999) have observed that the wastage thickness increases non-linearly in a period of 2 to 5 years of exposure, but afterwards it becomes relatively constant. This explanation concludes that after a period of initial non-linear corrosion, the oxidised material that is produced remains on the surface of the plate and prevents the continued contact of the plate surface with the corrosive environment, hence may act as inhibitors to corrosion.

However, in the presence of fatigue load and ocean waves, the process may cause the rupture of the oxidised structures therefore encouraging corrosion activities.The effect of corrosion is often represented by an uncertain but constant corrosion rate, which results in a linear decrease of plate thickness with time.

The general monograph on corrosion of steel provides the fundamental basis for this section and an extensive overview on the more practical aspect of corrosion can be found in C.P Dillion (1982).

The first approach to the complex corrosion problem is to consider the geometrical characteristics of corrosion defects, which facilitates a stochastic description of the defects. Corrosion phenomena can be distinguished by their geometrical characteristics without considering their driving mechanisms. In simplifying form, corrosion geometry is described in either uniform corrosion or localised corrosion and most corrosion deterioration problems encountered in the real world are a combination of these two forms. Consequently the total corrosion depth at any location *x* and time *t* can be described by the sum of the two types as expressed in the Equation 3.1

$$d_C(x,t) = d_{UC}(t) + d_{LC}(x,t) \qquad \textbf{(3.1)}$$

Where, $d_C(x,t)$ is the total depth of the corrosion at the location x at the time t, $d_{UC}(t)$ is the depth of the uniform corrosion and $d_{LC}(x,t)$ is the depth of the localised corrosion defect.

3.1.1.3 Corrosion Growth Model

Guedes Soares and Garbatov, (1998) proposed a nonlinear function of time that describes the growth of corrosion in three different phases. The model is more flexible alternative and also generally presents the model that includes an early phase with corrosion-protected surface. Corrosion rates depend on many factors including coating properties, dissolved oxygen, water temperature, maintenance

systems and practices. Therefore, the corrosion rate model should be appropriate based on the statistics of measurement data.

Practically, the time-variant corrosion rate model may be divided into three phases. The summary of the phenomenon is that in the first stage there is no corrosion because the protective coating of metal surface works properly. The second phase is initiated when the corrosion protection is damaged and the material is real in contact with corrosion agents, which decreases the structural component thickness. The third phase corresponds to a stop in corrosion process and corrosion rate becomes zero. The corroded material stays on member surface and protects it from contact with the corrosive environment which makes the corrosion process stops permanently. However the cleaning of member surface or any involuntary action that removed the surface material originates the new start of the non-linear corrosion growth process in Figure 3.1 and Figure3.2. This study suggested model in (Figure 3.1) which is represented mathematically in Equation 3.2.

$$d(t) = d_{\infty}\left(e - ^{\frac{t-\tau_c}{\tau_t}}\right), \quad t > \tau_c \qquad \textbf{(3.2)}$$

where, *d*∞ is the long-term thickness of the corrosion wastage, *d(t)* is the thickness of the corrosion wastage at time *t,* where τ_c is the coating lifetime, which is equal to the time interval between the painting of the surface and the time when its effectiveness is lost, and τ_t is the corrosion duration. The parameters *d*∞ , is steady corrosion rate.

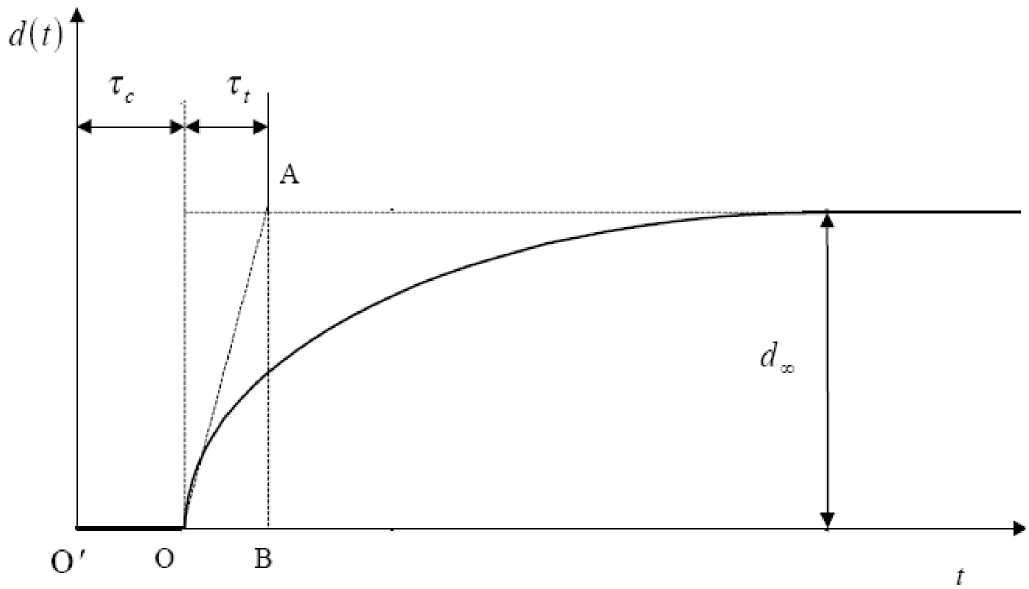


Fig. 3.1 Corrosion Wastage Vs Time Guede (1999a)

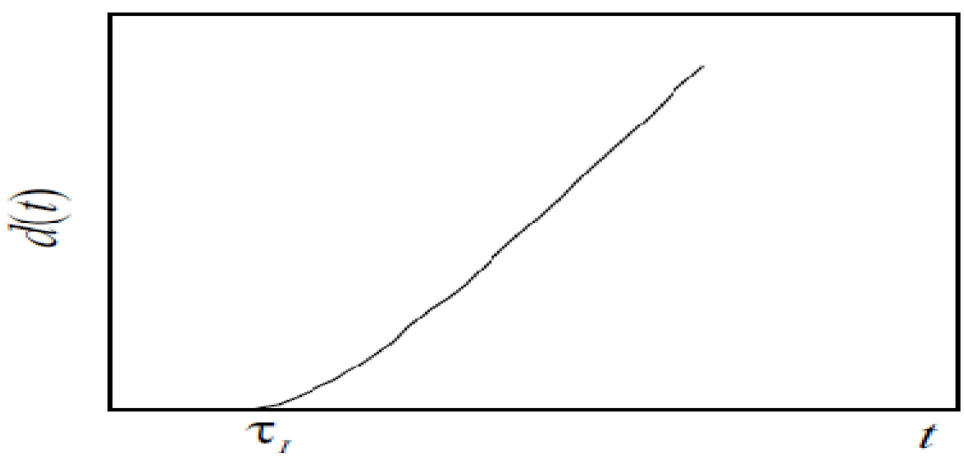


Figure 3.2 Corrosion Loss versus Time

This model furnishes that in many cases the governing factor is mainly the lifetime of the coating protection. By integrating Equation 3.2, the corrosion depth can be obtained from equation 3.3.

$$d(t) = d_{\infty}\left[t - (\tau_c + \tau_t) + \tau_t e^{\frac{t-\tau_c}{\tau_t}}\right] \quad \textbf{(3.3)}$$

where the parameters time t, τ_c and $d(t)$ should be fitted to inspection results. The coating lifetime τ_c may be assumed to be fitted by a Weibull distribution as shown in Equation 3.4 and $d\infty$ to be fitted by a normal distribution.

$$f(\tau_c) = \frac{\alpha}{\beta}\left(\frac{\tau_c}{\beta}\right)^{a-1} \exp\left[-\left(\frac{\tau_c}{\beta}\right)^{a}\right] \quad \textbf{(3.4)}$$

Figures 3.2 illustrate the corrosion depth reproduced by the present model based on the net measurement data of Yamamoto from bulk carriers. There exists some variability of the data along the regression curve.

3.1.1.4 Chloride Diffusion

Chloride ions are transported in solution through damage steel coating and coating holidays on structural members in various processes. These include diffusion (driven by the concentration gradient between various sections of the coating) and capillary action of water in coating damaged areas. Meijers (2003) developed a finite element analysis model that uses convection and conduction.

However, most models assume that the dominant process is diffusion for a reasonably well-constructed structure with reasonably good coating quality. Therefore, diffusion calculation is a reasonable approximation of the overall real process chlorine ion transportation. The diffusion process is modeled by solving the one dimensional equation for Fick's second law of diffusion.

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial X^2}\right) \quad \textbf{(3.5)}$$

where:

C **= salt ion concentration (%)**

T **= time (yr)**

D **= diffusion coefficient**

This Equation is usually solved using the error function solution:

$$C_{(x,t)} = C_0\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right] \quad (3.6)$$

where:

$C_{(x,\,t)}$ **= salt concentration at depth x at time t (%)**

C_o **= surface concentration (%)**

erf **= error function**

3.1.1.5 Chloride Vs Corrosion Damage

Chlorine ion is one of the agents that responsible for corrosion in a marine environment. Coated steel develops a passive oxide layer that is highly protective and corrosion grows at a very slow rate.

Seawater typically contains about 3.5% sodium chloride, although the salinity may be stronger in some areas with additional chlorine substance into the seawater. The rate of corrosion is controlled by the chloride content and oxygen availability. About 3.5% salt content of seawater produces the most corrosive chloride salt solution as shown in Figure 3.3.

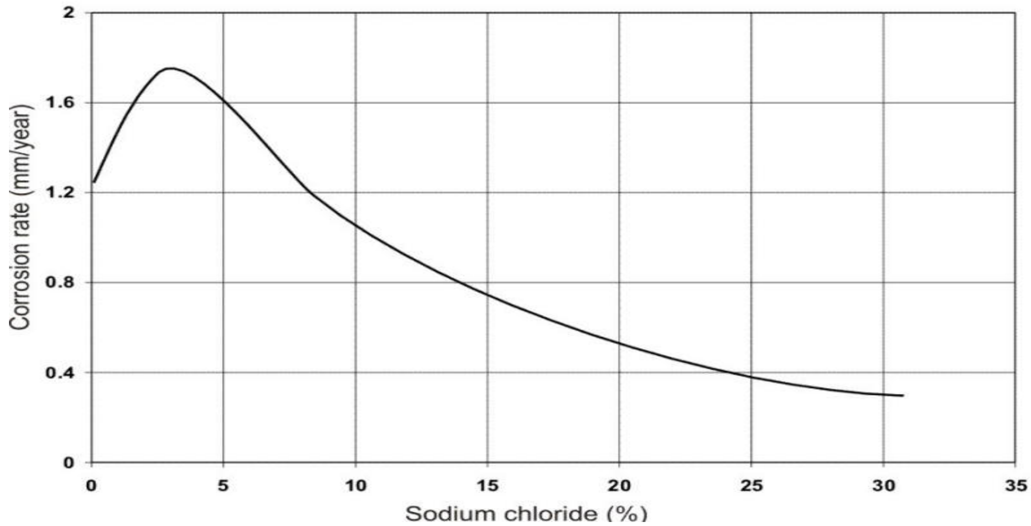


Figure 3.3 Corrosion of Steel (Pierre. R. Roberge (1999)

Petroleum production activities with discharge of waste water and other associated chloride substance into the seawater lead to increases of chloride ion concentration. Accidental discharge of drilling mud and flushing of pipeline hydro-testing water into the seawater also considerably increases the salt concentration in the neighbourhood of offshore platforms.

3.1.1.6 Corrosion Fatigue

Corrosion fatigue is simply two different failure mechanisms working together. One mechanism is corrosion and the other is mechanical. But oil and gas facilities are located in an aggressive offshore environment and therefore a combination of corrosion and fatigue have significant impact on them. While the corrosion defect grows, the stress concentration at the tip of the defect increases. The stress intensity range ΔK caused by cyclic loading, exceeds the threshold ΔK_{th} fatigue crack growth may be initiated and propagated to the final failure. In Beden et al (2009) the

transition from the corrosion controlled phase to the fatigue-controlled phase can be characterised by Equation 3.7.

$$\Delta K \geq \Delta K_{th} \;, \quad \left(\frac{da}{dt}\right)_{FM} \geq \left(\frac{da}{dt}\right)_{Pit} \qquad \textbf{(3.7)}$$

where ΔK- fatigue growth and ΔK_{th} represented corrosion growth in structure joint. The first condition is a prerequisite to the second, the process is thus assumed fatigue controlled, if the calculated fatigue crack growth is higher than the corrosion growth. The model can be simplified, based on the assumption of no interaction between the chemical (corrosion) and the mechanical (stress ranges) deterioration process. The modeling of corrosion fatigue follows to a large extent the fracture mechanics based crack growth models which shall be discussed in the subsequent sections.

3.1.1.7 Fatigue Failure

The fatigue life of a structural component is directly linked to the fatigue progression, which can be grouped into the following three major stages as demonstrated by investigation (Wohler 1893): crack initiation, crack propagation and finally fracture failure. Fatigue can be classified as high-cycle (low stress) fatigue or low-cycle (high stress). A fatigue is called "low-cycle fatigue" if the number of cycles to failure is less than 10^4. But the number of cycles in a high-cycle fatigue is usually several millions Yong Bai (2003). For the marine structures, the latter has been our concern.

To identify a fatigue limit state, it is required to know the mechanical behaviour of fatigue. Fatigue is the progression of damage accumulation of material initiated from yielding in the material by the sliding of atomic layers due to cyclic load. This sliding is caused by a combination of displacement and local stress concentrations (Sobczyk and Spencer, 1992). Once a crack is present in a material, it will tend to grow under the influence of cyclic loading. Consequently several microscopic cracks are formed and later joined to each other and result in major cracks.

The total time of three phases of crack initiation and growth constitute the complete lifetime of fatigue damage accumulation, as shown in Figure 3.4. Fatigue assessment of structural connections like tubular joints or plated connections is one of the most critical issues in the design of marine structures such as jacket platforms. The fatigue crack usually occurs on the free surface of the body at places of high stress concentrations (e.g. weld toes, surface imperfections, grinding boundaries). The crack may be initiated by fatigue, or may be pre-existing from manufacture, or may be caused by an impact or thermal shock.

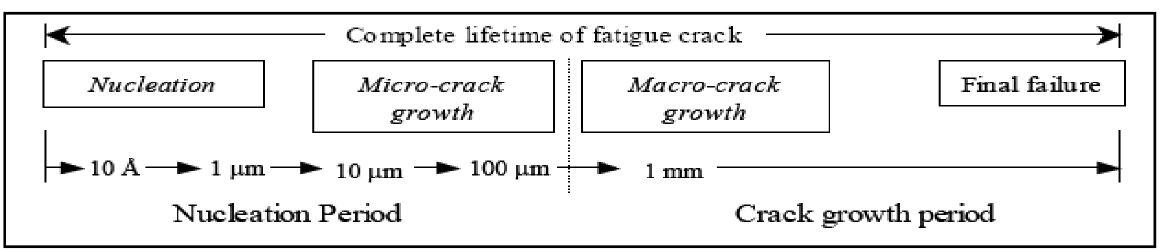


Figure 3.4 Crack Nucleation and propagation
(Sobczyk and Spencer, 1999)

Based on the material properties and the type of loading, the nucleation phase can be of importance in estimating the fatigue life. Collins (1993) concluded in the experimental observations that at high cycle fatigue, a significant proportion of the

usable fatigue life may be consumed by the crack initiation period. For a low-cycle fatigue, crack starts to develop in the early cycles. In the same principles, structures such as offshore jacket platforms where flaws are unavoidable due to the fabrication process.

3.1.1.8 Uncertainties in Corrosion Modeling

The quantitative corrosion models applied by engineers are normally developed for design purposes and represent a kind of worst case scenario model without clarification of essential uncertainties. Until the models published in Melchers (2003), engineers are not conscious to quantify the uncertainties involved in the corrosion prediction for practical operation purposes. The model of corrosion uncertainties is crucial to the development of a risk-based approach to corrosion control. Lack of enthusiasm for corrosion engineers to account for the uncertainties in regard to their models constitutes a major shortcoming in corrosion modeling.

However, Postlethwaite et al. (1992) provided a rough estimate of uncertainty related to the corrosion perdition by means of the Dewaards-Millams equation in the form of a multiplicative factor. For the reason that the original corrosion models does not differentiate between different possible forms of corrosion, therefore the work provided a different model of uncertainty for pitting and other types of corrosion.

Furthermore, the model does not give any information about the spatial variability. They assumed that the calculated corrosion rate is the maximum time-average corrosion rate at any location of the structure. The fact that the maximum corrosion

depth is increasing with size were neglected. The assumption of a constant time-averaged corrosion rate may be suitable for engineering design purposes. However it can lead to misinterpretation of inspection results when changes in the operating conditions are not considered. Therefore, in this research work all these factors are disregarded in the presentation of corrosion reliability models.

3.1.1.9 Structural Reliability Concept

Today, the concept of structural reliability design has taken a more prominent position than the traditional deterministic design in the more advanced form. In the traditional design methods, parameters are used in deterministic values without uncertainties. Whereas in reality, these values are not unique values but rather have probability distributions that reflect many uncertainties. For offshore jacket structures, several uncertainties are obvious such as fluctuations of loads, variability of material properties and thickness. The above mentioned parameters and other uncertainties make reliability methods to be more appropriate for existing offshore platform assessment as it is applied in this study. Reliability calculations based on limit state for tubular member can be expressed in a simple and generic form of limit state function as:

$$g_C = d - d_{crit} - d_{UC} \tag{3.8}$$

The depth (d_{UC}) of the uniform corrosion which is applied for the reason that uniform corrosion in general has no negative effects on structural resistance. (d_{crit}) is equal to critical member thickness corrosion loss at which failure occurs. From an engineering viewpoint, a stiffened cross section thickness tubular member is

considered ineffective when corrosion induced thickness reduction exceeds 25% of original thickness.

3.1.1.10 Risk-based Assessment

Risk-based assessment is a tool for the management of safety, health and environmental protection. This is a collection of several activities performed to provide support for decision-making. This section shows the basic procedures for the risk assessment. More information on this topic can be found from ISO/CD 19902, (2000). Risk Estimation and Evaluation Flow Chart by Yong Bai is presented in Figure 3.5

The source of a potential risk for typical civil structures is the deviation from the intended conditions such as insufficient structural strength due to fatigue or corrosion degradation parameters out of acceptable range. The flow chart in Figure 3.5 summarily explains how risk-based assessment is performed and recommendations are proposed to mitigate or eliminate the risks. As a result of several possible scenarios regarding structural component damages due to corrosion and fatigue hazard, jacket structures required risk-based assessment. The outcome of assessment scenarios shall be revealed on Risk Assessment Matrix (RAM) with associated risk levels. RAM is an expression of risk assessment with several hazard and scenario analysis that provide support to establish every scenario risk level. The technique has proven to be suitable for management of hazard, safety and environmental protection.

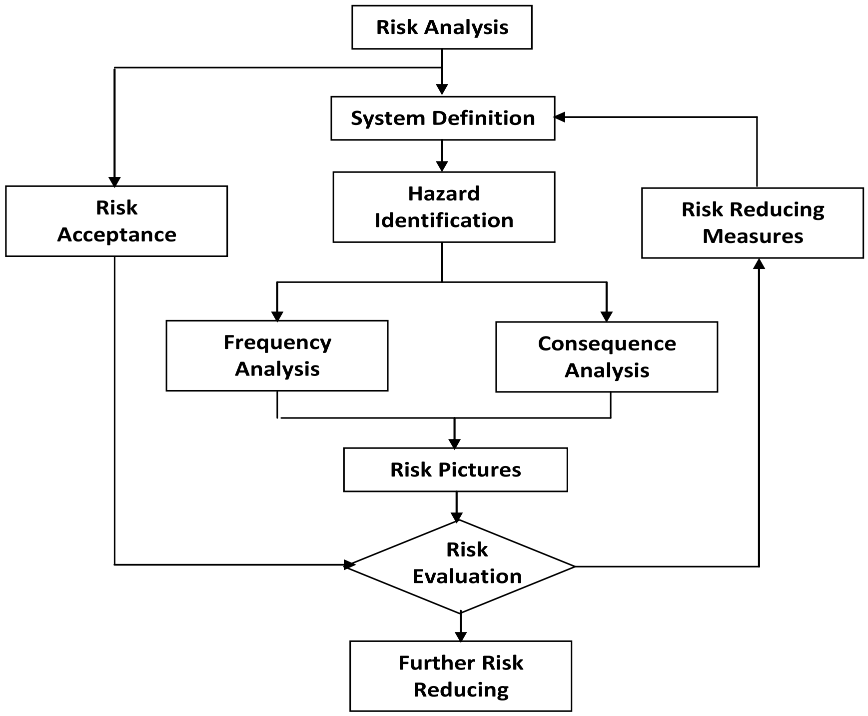


Figure 3.5 Risk Estimation and Evaluation Flow Chart (Yong Bai, 2003)

However, to properly carry out a risk-based assessment, there should be scenario development via event tree that gives details of the scenarios and probability factors as presented in (Figure 3.6). The consequence for departure from an intended condition of structures may lead to safety impact and financial consequences. The measure of consequences is referred to as severity. Fortunately enough, more severe events are less likely to occur than minor events and understanding the factors that differentiate a small event from a larger one to shape our safeguards. It may also be expressed as a number of incidents per period of time. The completion of risk-based assessment in this study will be of assistance for the establishment of structural component degradation that is at higher risk of failure such as when offshore jacket

continues operation without efficient corrosion and fatigue hazard mitigation measures.

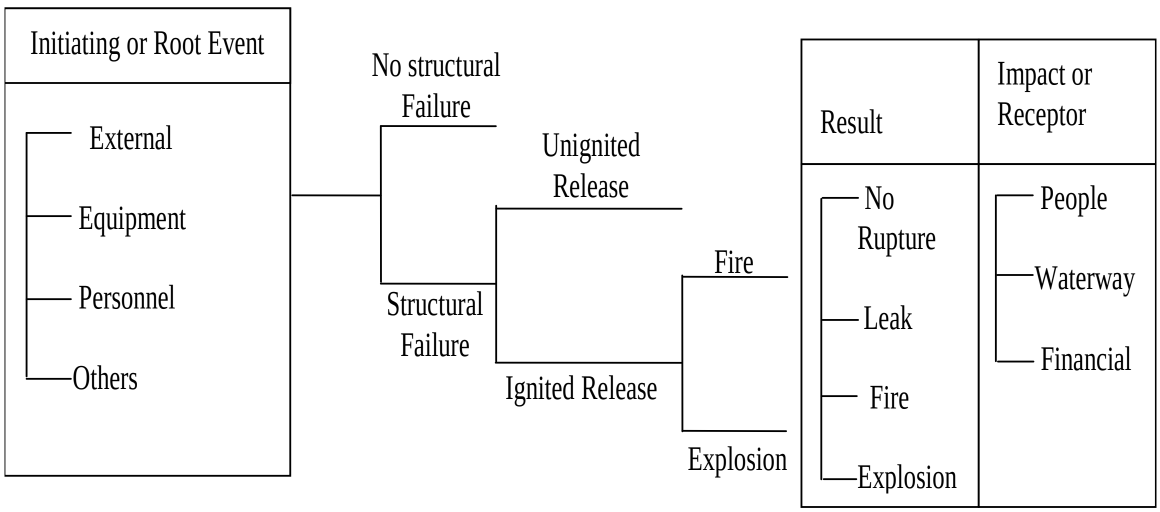


Figure 3.6 Event Trees (Dagmar 1999)

3.2 PROCEDURE AND TECHNIQUES

3.2.1 Field Analysis

Ultrasonic devices or Pulse-echo technique method is predominantly used to conduct surveillance on components to know the current corrosion wastage, flaws and ultimately the current member thickness. The device uses ultrasonic energy generated by transducers that change high-energy frequency signal into high frequency mechanical energy. A liquid couplant to the metal wall transmits the sound wave generated by a transducer and ultrasonic sound travels through the wall until reaching member thickness discontinuity as illustrated in Figure 3.7.

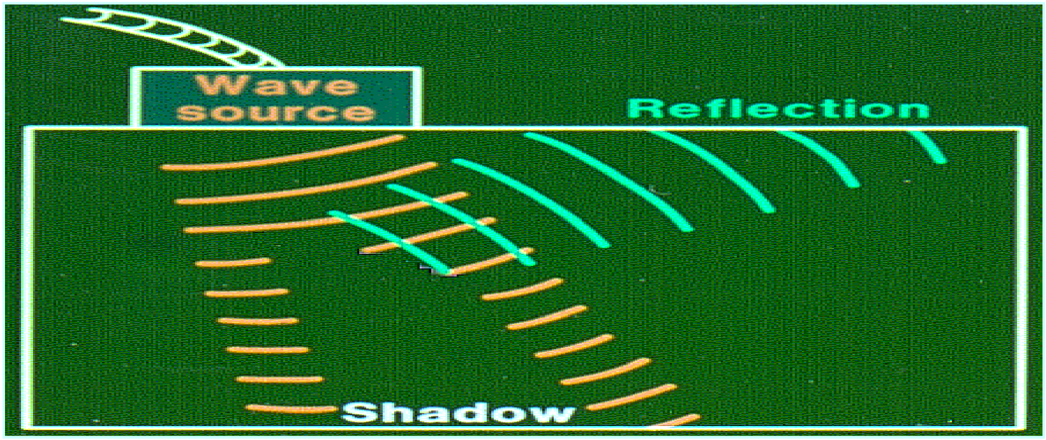


Figure 3.7 Detection and Reflection of Ultrasonic Beam

The echo sound waves is received and transformed into electrical impulses by the transducer. The device measures the time between the impulse and reflection thereby the member current thickness can be calibrated, read and recorded on a data sheet. For a jacket structural member with appreciable length, the UT test is performed on three spots along the member length. The spot with the minimum thickness is adopted as a member current thickness. The schematic diagram of the three jacket platforms investigated in the study is illustrated in Figure 3.8. The data collected with the found anomalies criteria are also summarized in Table 3.1.

The information given in the table includes, cathodic protection systems, damage condition and marine growth among others.. The result of inspection shows that anodes in the splash zone depleted faster than other ones installed in the lower tidal zones. This occurrence may be accounted for by high tide and continuous contact with highly aerated and warm seawater which promote corrosion process.

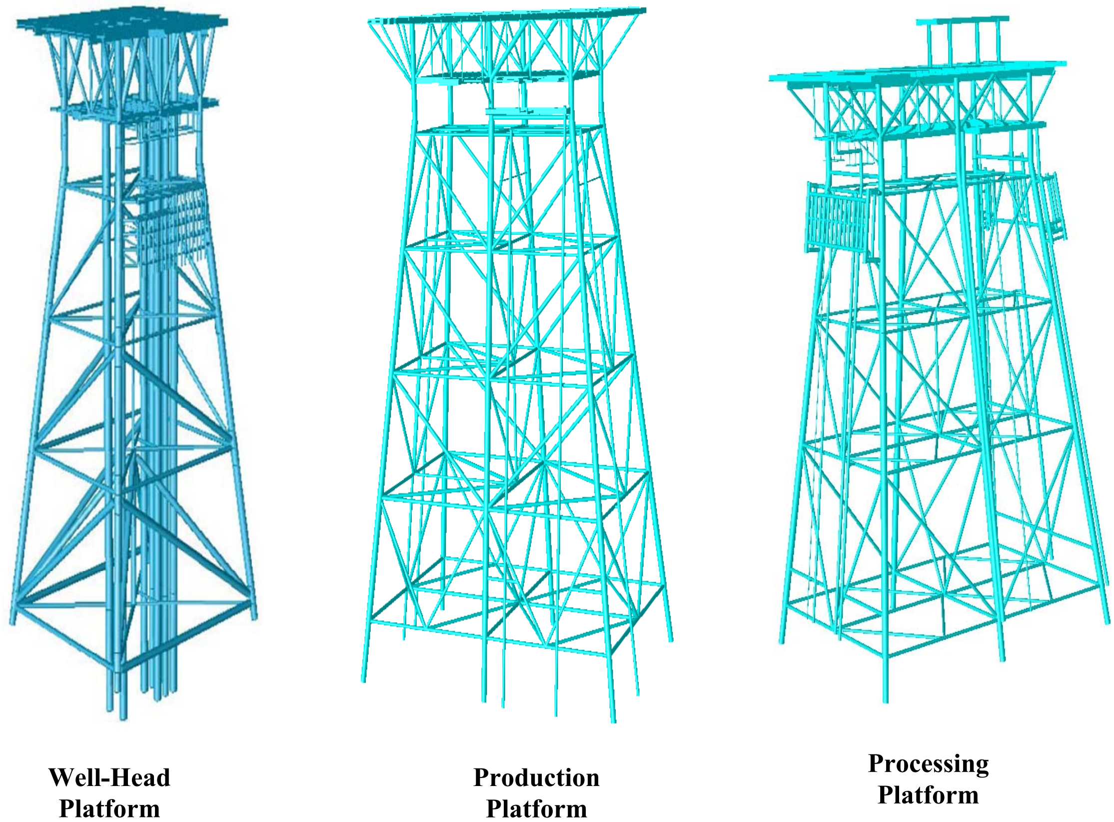


Figure 3.8 Jacket 3D Model

During the jacket structures inspection, components were found to be covered with uniform corrosion with the members various thickness as reported in Table 3.1. The cathodic protection systems generally remain effective as the appropriate operational and maintenance procedures are employed. Extensive corrosion damage has not been found except the general isolated to known vulnerable details such as spider deck, gratings, conductor bays and appurtenance connections. The data collected during the jacket structure inspection demonstrates that fatigue damages may develop in underwater welds and joint, therefore lowering structural system strength. Consequently, the jacket structure is susceptive to high risk of failure

when subjected to corrosion and fatigue hazard concurrently. The elevations and sections of the jacket structures used as a case study in the thesis are illustrated in Figure 3.9 – 3.16 with the position of sacrificial anodes along the length of the jacket.

Table 3.1 Jacket structure Data and Anomaly Criteria of Non Conformity

JACKET STRUCTURES	WELLHEAD PLATFORM	PRODUCTION PLATFORM	PROCESSING PLATFORM
Length (m)	44	55	57.7
Leg Number (Qty)	4	6	6
Water Depth (m)	32	43	49
Structure Age (yr)	24	31	36
Vintage	Early-RP2A	Early-RP2A	Early-RP2A
Platform Type	Wellhead	Production	Production
Conductor Quantity	12	None	None
Coating Damage	Bare metal	Bare metal	Bare metal
Marine Growth (mm)	79	82	85
CP Devices	Impressed current	Impressed current	Impressed current
Anodes Conditions (%)	≥ 40%	≥ 45%	≥ 50%
Max Member Thickness Loss (%)	17.32	16.74	18.25
Min Member Thickness Loss (%)	4.31	4.85	7.47
Abrasion Scars	Damage	Damage	Damage
Weld Defects	Joints undercut with weld loss and cracks	Joints undercut with weld loss	Joints undercut with weld loss and cracks
Flooded Member (Qty)	1	None	2
Member Damage	Buckled & dented	Buckled & dented	Buckled & dented
Jacket Bottom Condition	Scour	Build-up	Scour

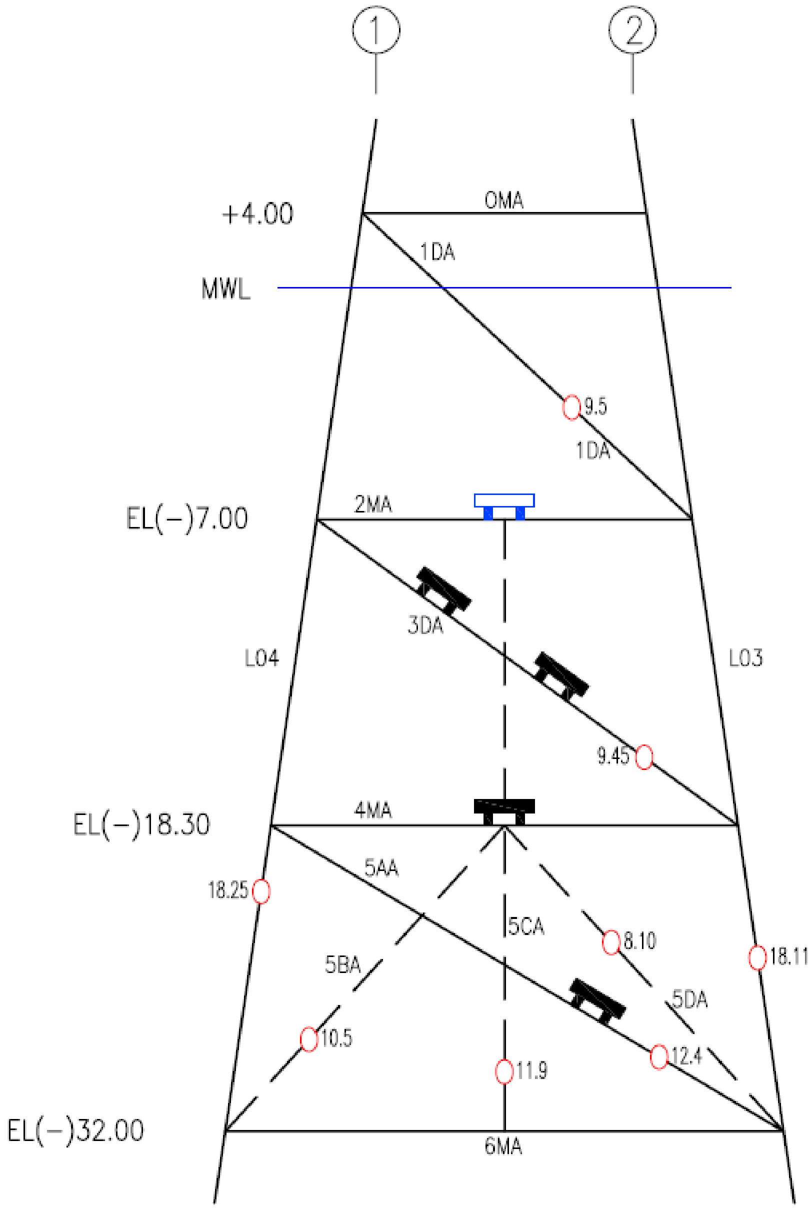


Figure 3.9 Elevation of Jacket at Row-A East Face Viewed from Outside

Sacrificial Anodes Conditions

 = GRADE 'A'   50% - 79% of Original

 = GRADE 'B'   Less than 50% of Original

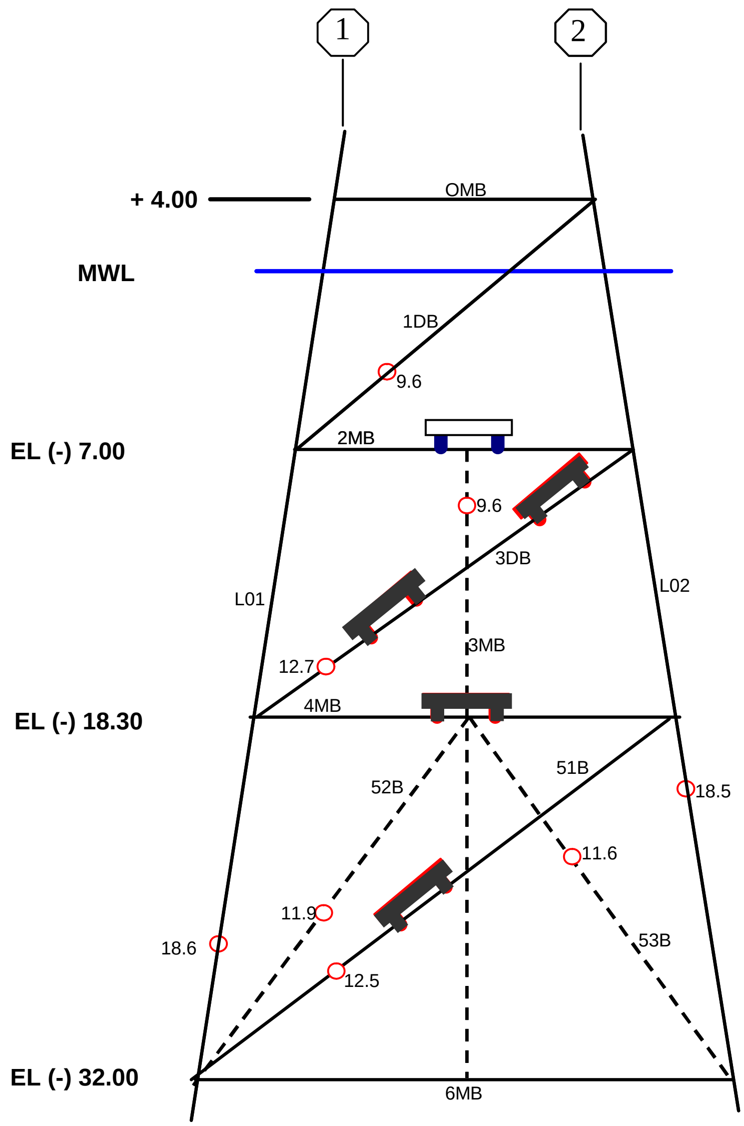


Figure 3.10 Elevation of Jacket at Row-B West Face Viewed from Outside

Sacrificial Anodes Conditions

= GRADE 'A'   50% - 79% of Original

= GRADE 'B'   Less than 50% of Original

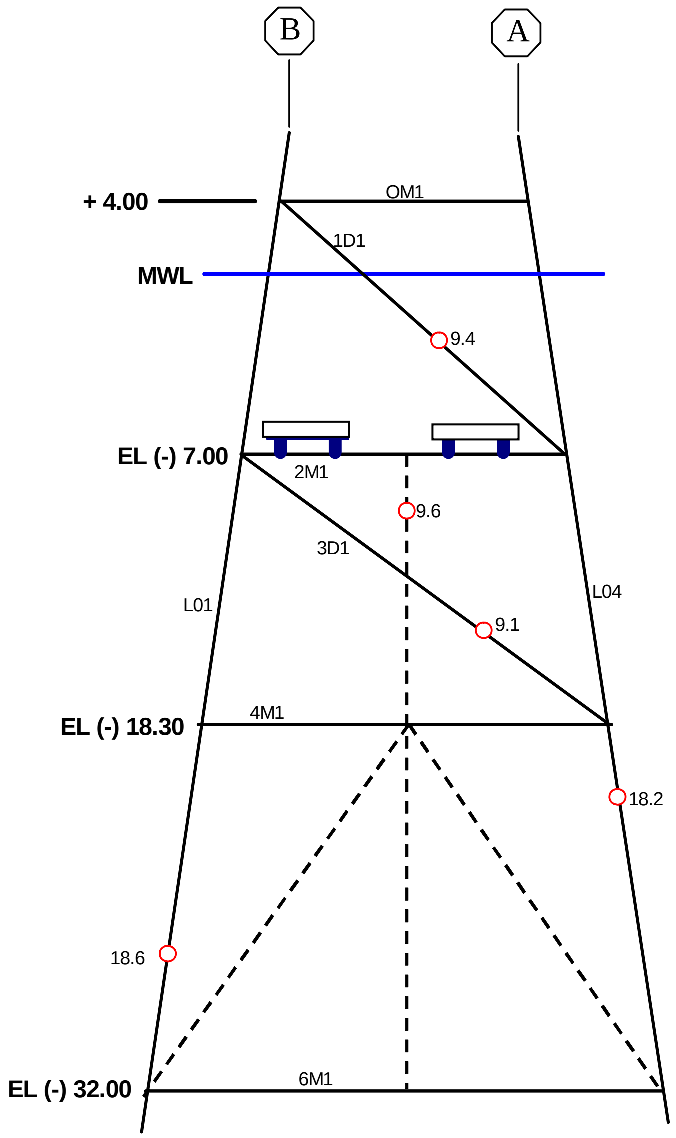


Figure 3.11 Elevation of Jacket at Row - 1
South Face Viewed from Outside

Sacrificial Anodes Conditions

= GRADE 'A' 50% - 79% of Original

= GRADE 'B' Less than 50% of Original

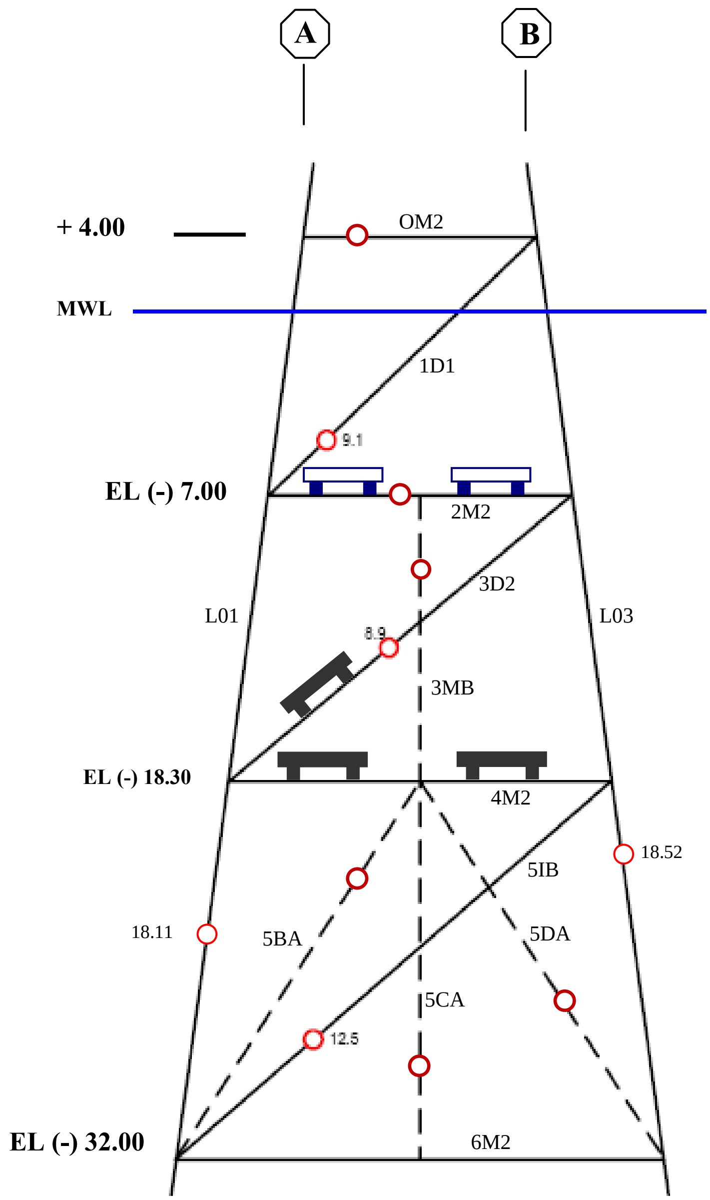
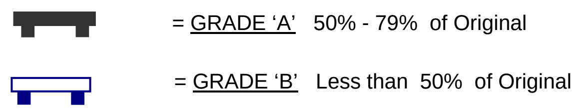


Figure 3.12 Elevation of Jacket at Row-2
North Face Viewed from Outside

Sacrificial Anodes Conditions



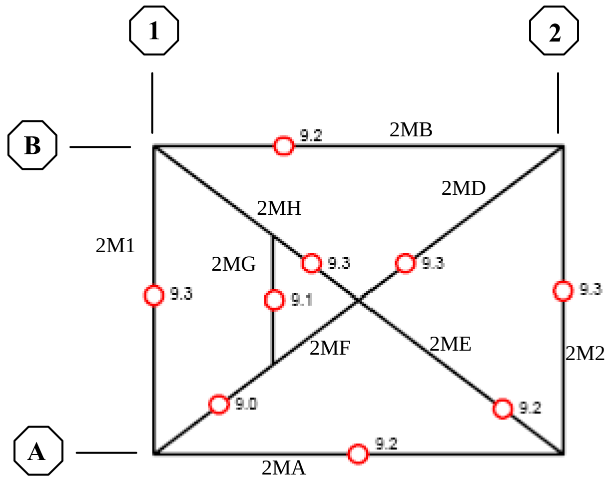


Figure 3.13, Plan at Level (–) 7.00

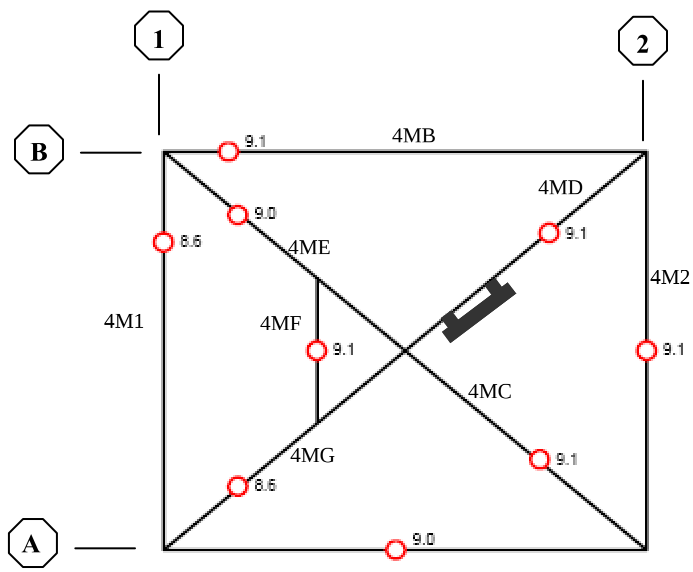


Figure 3.14 Plan at Level (–) 18.30

Sacrificial Anodes Conditions

 = GRADE 'A' 50% - 79% of Original

 = GRADE 'B' Less than 50% of Original

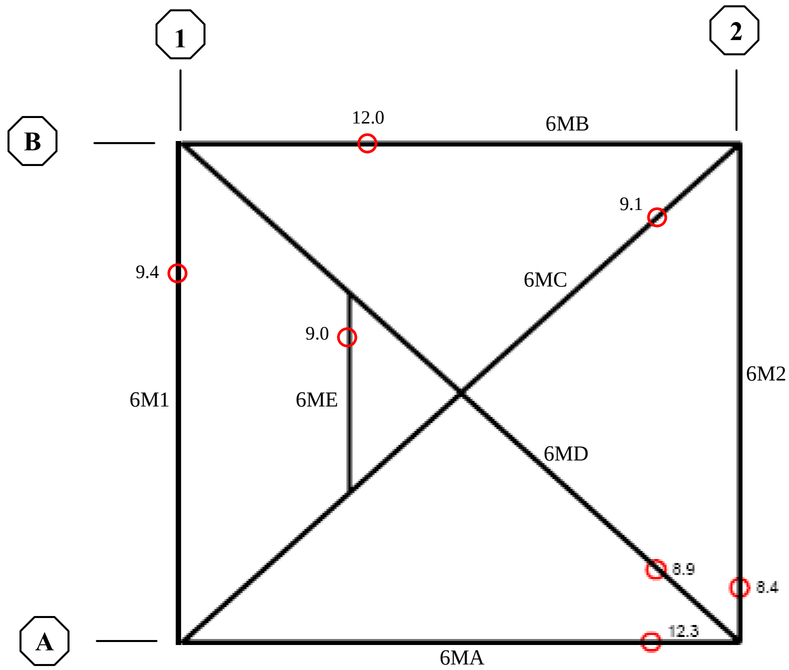


Figure 3.15, Plan at Level (–) 32.00

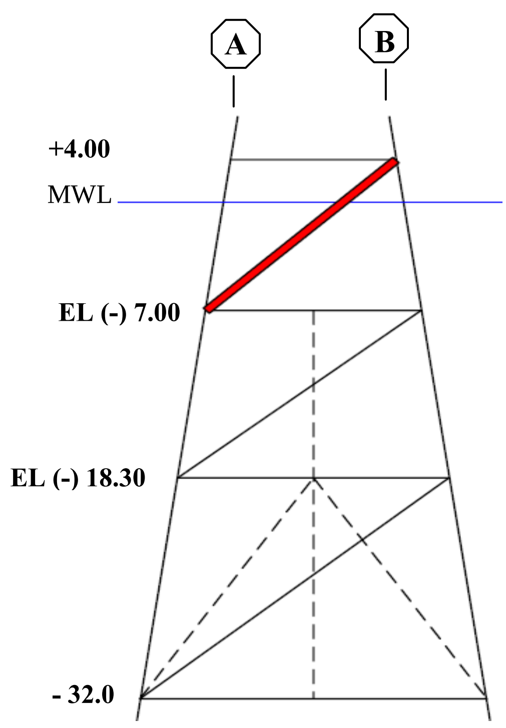


Figure 3.16 Elevation of Jacket at Row-2
Showing the Flooded Member

3.2.2 Diffusion Process

This section reviews the current state-of-the-art modeling for marine steel civil structures chloride-induced corrosion. Investigating the effect of ocean wave and chloride accumulation in the neighborhood of jacket platform. The work provides an estimation method for chlorine-ion concentration rate in the surrounding of jacket platform based on seawater velocity and chloride accumulation rates

3.2.2.1 Basis of Model

Modeling durability of marine steel structures as a result of corrosion damage requires quantitative understanding of the structure environment and steel component physical deterioration processes. Equations for each part of these processes are available. However, several models that are available in the literature have been developed in a particular environment which was not suitable for offshore crude oil production platforms associated with accidental ion discharge. This work provides extension to Ficks' second law of diffusion to account for ocean wave and chloride accumulation in the neighbourhood of jacket platform as a result of crude oil production activities.

The process of chloride-induced corrosion of a coated marine steel component is by diffusion of chloride through the damaged coating while the chloride builds up with time on the steel component surface. Once the chloride attains critical threshold, the passive oxide layer on the steel breaks down and corrosion starts. The replacement of corroded component may be made, where the cycle continues on the new component.

The process of modeling requires the following details:

- **calculating the chloride accumulation rate in the surroundings of offshore platforms.**
- **Determining the effect of ocean wave on chlorine ion concentration.**
- **Establishing a period at which steel components begin experiencing corrosion losses as it is common to offshore jacket components.**

3.2.2.2 Chloride-ions Diffusion Process

Chloride ion is transported in solution through the damaged steel coating into the surface of steel members in several ways which includes diffusion. However, most models assume that the dominant process is diffused for a reasonably well-constructed structure with good coating quality. Diffusion calculation is a reasonable approximation of the overall real process for chlorine ion transportation. The diffusion process is modeled by solving one dimensional equation for Fick's second law of diffusion.

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2}\right) \qquad (3.9)$$

C - salt ion concentration (mol/m^3)

t - time (s)

D - diffusion coefficient (m^2/s)

x – is the position (length) (m)

Equation 3.10 can be derived from Fick's First law and the mass balance.

$$\frac{\partial C}{\partial t} = D\frac{\partial}{\partial x}J = \frac{\partial}{\partial x}\left(D\frac{\partial}{\partial x}C\right) \tag{3.10}$$

If the diffusion coefficient D is constant we can exchange the orders of the differentiating and multiplying by the constant:

$$\frac{\partial}{\partial x}\left(D\frac{\partial}{\partial x}C\right) = D\frac{\partial}{\partial x}\frac{\partial}{\partial x}C = D\frac{\partial^2 C}{\partial x^2} \tag{3.11}$$

In the case of diffusion in two or more dimensions Fick's Second Law becomes:

$$\frac{\partial C}{\partial t} = D\nabla^2 \mathrm{C} \tag{3.12}$$

In a condition in which concentration does not change from time, the above equation becomes zero which is Laplace's equation. This Equation is usually solved using the error function solution:

$$C_{(x,t)} = C_0\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right] \tag{3.13}$$

$C_{(x,t)}$ **- salt concentration at depth x at time t (%)**

C_o **- surface concentration (%)**

erf **- error function**

∇ **- use for two or more dimensions**

3.2.2.3 Chloride - ions Concentration

The Fick's second law of diffusion discussed in the previous sections specified that chloride ion concentration (C_0) should remain constant during the diffusion process. However, the surroundings of offshore production platforms are characterized by accidental discharge of ions which makes chlorine ion increases with time. The rate of chloride accumulation (*m*) is not readily available. However this value can be

calculated using Equation 3.14. Also, the platform age should be known and the chlorine ion concentration in the platform neighborhood through seawater chemical analysis.

Fick's second law predicts how diffusion causes the concentration to change with time. To account for the increasing C_0, it was assumed that C_0 increases linearly and satisfying Equation 3.14.

$$C_O = mt \tag{3.14}$$

where m is the rate of chloride accumulation (mol/m^3/yr) and t is the age of the facility (yr). The solution to Fick's second law is updated in Equation 3.15 to account for the increase in chlorine ion concentration.

$$C_{(x,t)} = \int_0^t m\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right] dt \tag{3.15}$$

3.2.2.4 Advection Term and Diffusion Equation

As it was established in Equation (3.15), chlorine ion concentration *($C_{x.t}$)* increases with the platform age and the chloride rate of accumulation. However, this equation may require further modification as a result of ocean waves and current that constantly causes water to move away from neighbourhood of the platform. As seawater moves, the concentration of the solute in seawater is affected by both physical processes and diffusion processes that make it necessary to introduce the advection term (Freeze and Cherry, 1979) to account for the phenomenon as expressed in equation (3.16).

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2}\right) - v\left(\frac{\partial C}{\partial x}\right) \tag{3.16}$$

To provide solutions for the last part of the equation (3.16), analytical solutions were presented for one-dimensional advection equation with variable coefficient in longitudinal finite initially solute free domain similar to Atul Kumar et al (2009).

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left[D(x,t)\frac{\partial C}{\partial x} - v(x,t)C\right] \quad \textbf{(3.17)}$$

where C represents the solute concentration at position x along the longitudinal direction at time t, D is the solute diffusion and u is medium's flow velocity. The temporary dependent solute diffusion of a uniform input concentration of a continuous nature in an initially solute free finite domain was considered as:

$$D(x,t) = D_o f(mt) \quad \text{and} \quad v(x,t) = v_o \quad \textbf{(3.18)}$$

where m is a coefficient whose dimension is the inverse of that of the time variable; Thus *f(mt)* is an expression in non-dimensional variable *(mt)*. The expressions of *f(mt)* are chosen such that *f(mt)* = 1 for *m* = 0 or *t* = 0. The former case represents the uniform solute diffusion and the latter case represents the initial diffusion. The coefficient D_o and v_o in the equation (3.18) may be defined as initial diffusion coefficient and uniform flow velocity, respectively. Thus the partial differential equation (3.17) along with initial condition and boundary conditions may be written as:

$$\frac{\partial C}{\partial x} = D_x f(mt)\frac{\partial^2 C}{\partial x^2} - v_o\frac{\partial C}{\partial x} \quad \textbf{(3.19)}$$

$$C(x,t) = 0, \quad 0 \le x \le L, \ t = 0 \quad \textbf{(3.20)}$$

$$C(x,t) = C_0, \ x = 0, t > 0 \quad \textbf{(3.21)}$$

$$\frac{\partial C(x,t)}{\partial x} = 0, \ x = L, \ \ t \ge 0 \quad \textbf{(3.22)}$$

where the input condition is assumed at the origin and a second type or flux type homogeneous condition is assumed at the other end *x* = *L*, of the domain. C_o is a reference concentration.

Using the Laplace transform technique conveniently, a new independent variable in terms of its transformation was introduced.

$$X = \int \frac{dx}{f(mt)} \quad or \quad \frac{dX}{dx} = \frac{1}{f(mt)} \tag{3.23}$$

As *mt* is a non - dimensional term, the dimension of *X* will be that *x* is referred to as a new space variable, a moving co-ordinate, though it is different from those considered in the references cited at the outset of the first section. The initial and boundary value problem in new space variable may be expressed as:

$$f(mt)\frac{\partial C}{\partial t} = D_o\frac{\partial^2 C}{\partial x^2} - v_o\frac{\partial C}{\partial x} \tag{3.24}$$

$$C(X,t) = 0, \quad 0 \le x \le X_0$$

$$t = 0, \quad X_0 = \frac{L}{f(mt)} \tag{3.25}$$

$$C(x,t) = C_0, \; X = 0, \quad t > 0 \tag{3.26}$$

$$\frac{\partial C(X,t)}{\partial X} = 0, \; X = X_0, \; X = X_0, \; t \ge 0 \tag{3.27}$$

To get rid of the time dependent, the coefficient of transformation used by Crank, (1975) can be introduced.

$$T = \int \frac{dx}{f(mt)} \tag{3.28}$$

The dimension of T will be that of the variable *t* so it is referred to as a new time varying. Also, it should be ensured while choosing *f(mt)* that T = 0, t = 0, the nature of the initial condition does not change in the new time domain. The initial and boundary value problem (equation 3.24 – 3.27) may be expressed therefore, in new time variable as:

$$\frac{\partial C}{\partial T} = D_0 \frac{\partial^2 C}{\partial X^2} - v_0 \frac{\partial C}{\partial X} \tag{3.29}$$

$$C(X,T) = 0, \quad 0 \leq X \leq X_0$$

$$T = 0, \quad X_0 = \frac{L}{f(mt)} \tag{3.30}$$

$$C(X,T) = C_0, \quad X = 0, \ T > 0 \tag{3.31}$$

$$\frac{\partial C(X,T)}{\partial X} = 0, \quad X = X_0, \ T > 0 \tag{3.32}$$

Using the Laplace transform technique, the desired analytical solution may be expressed as:

$$C(X,T) = C_0 A(X,T) \tag{3.33}$$

where:

$$C(X,T) = \frac{1}{2} erf\left(\frac{X - v_{0T}}{2\sqrt{DT}}\right) + \frac{1}{2} exp\left(\frac{v_{0X}}{D_0}\right) erf\left(\frac{X + v_{0T}}{2\sqrt{DT}}\right) + \frac{1}{2}\left[2 + \frac{v_0(2X_0 - X)}{D_0} + \frac{Tv_0^2}{D_0}\right] \times$$
$$exp\left(\frac{v_{0X_0}}{D_0}\right) erf\left(\frac{(2X_0 - X) + V_0T}{2\sqrt{D_0T}}\right) - \sqrt{\frac{v_0^2 T}{\pi D_0}} \ exp\left[\frac{2v_{0X_0}}{D_0} - \frac{(2X_0 - X + v_0T)2}{4D_0T}\right] \tag{3.34}$$

$X = x/f(mt)$, $X_0 = L/f(mt)$, and T may be obtained from the transformation (equation 3.28).

However, in this study, the first part of the equation (3.34) and effect of longitudinal dispersion as illustrated by a simple column experiment for a step-function input,

concentration profile described by Freeze and Cherry (1979) was adopted. This is expressed in equation (3.35).

$$\frac{C_O}{C_1} = \frac{1}{2} erf\left(\frac{x - vt}{2\sqrt{Dt}}\right) \qquad (3.35)$$

This initial problem in equation (3.16) may be expressed in simplified form as shown in equation (3.36), where erf is expressed as a complementary error function, continuous supply of tracer at a concentration C_0 over time t_0, and outflow with tracer at a concentration C_1 after time t.

$$C_{(x,t)} = \int_0^t m\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right] dt - \frac{1}{2} erf\left(\frac{x - vt}{2\sqrt{Dt}}\right) dt \qquad (3.36)$$

3.2.2.5 Time to Corrosion Damage

The period required for the steel structures in marine environments to experience corrosion damage is equal to the time needed for the chlorine ion to diffuse down to the steel component surface, accumulate in concentration in excess of the corrosion threshold and the time for corrosion to occur and generate enough rust material to fall off from the steel component surfaces. The rate of marine steel component corrosion losses is directly proportional to the amount of rust generated and with the later falling off from the member surfaces. The rate of production of rust is determined using Equation of Youping Liu (1998) as shown in Equation (3.37).

$$\Delta S_{crit}^2 = 2\int_0^t 2.59 * 10^{-6} \left(\frac{1}{\alpha}\right) \pi D i_{corr}(t) dt \qquad (3.37)$$

where:

α= molecular weight of steel or corrosion products (mg)

$i_{corr}(t)$ = rate of corrosion as a function of time (mm/yr)

t = time (yr)

ΔS_{crit} = critical volume of corrosion product required to fall off (mm^3)

The time required to generate the volume of rust is obtained by solving Equation (3.37). This model was validated in the laboratory and the model is inappropriate once corrosion initiates since the corrosion rate will vary with time. Andrade and Gonzalez (1982) have suggested measuring the corrosion rate several times using the average of the measured corrosion rates. This method is frequently used in the petroleum industry for offshore civil structure assessment such as jacket platform structures. The period required for steel components to experience corrosion losses can be represented mathematically as described in Equation 3.38 and 3.39 for coated and uncoated marine steel structures respectively.

$$T_d = T_i + t_p \tag{3.38}$$

$$T_{d1} = \tau + T_i + t_p \tag{3.39}$$

where T_d – time for corrosion losses, T_i – time for chlorine ion accumulation in excess of corrosion threshold, t_p – time for corrosion occurrence and rust material falling off, τ - coating life span and T_{d1} - time for corrosion losses for coating component.

3.2.3 Jacket Fatigue Life Profile

This section is concerned with corrosion damage and investigation of joint fatigue life diminution trend. The jacket platform case study was modeled using SACS with due considerations to material deformation and non–linearity in geometry. The

analysis did not account for dynamic loading, which is peculiar to slender deep water platforms such as compliance structures. However, since this study is largely an evaluation of joint fatigue life parameter this simplification was found satisfactory.

The computer model was based on the use of SACS suites of software version 5.2 (Engineering Dynamic Inc.). A SACS model was built for the platform using existing engineering drawings and current member thickness. The jacket platform model is represented correctly by member cross sectional properties, joint eccentricities and end fixities. The 3D structural model consists of an integrated model of sub-structures (jacket) and superstructure (topsides), having a detailed representation of primary members, risers and conductors, together with a simplified representation of the elements causing hydrodynamic effects, such as anodes, marine growth, boat bumpers and other appurtenances as shown in Figures 3.17 and 3.18.

The riser model and pile-soil interaction was developed and incorporate into SACS model. The platform was designed for the combinations of dead load, live load, riser loads and environmental loads. The Marine growth profile used for the design is as per the environmental data collected during the inspection. The platform legs and the other structural members that are subject to corrosion are modeled as a structural member with reduced diameter and thicknesses to reflect the decayed states.

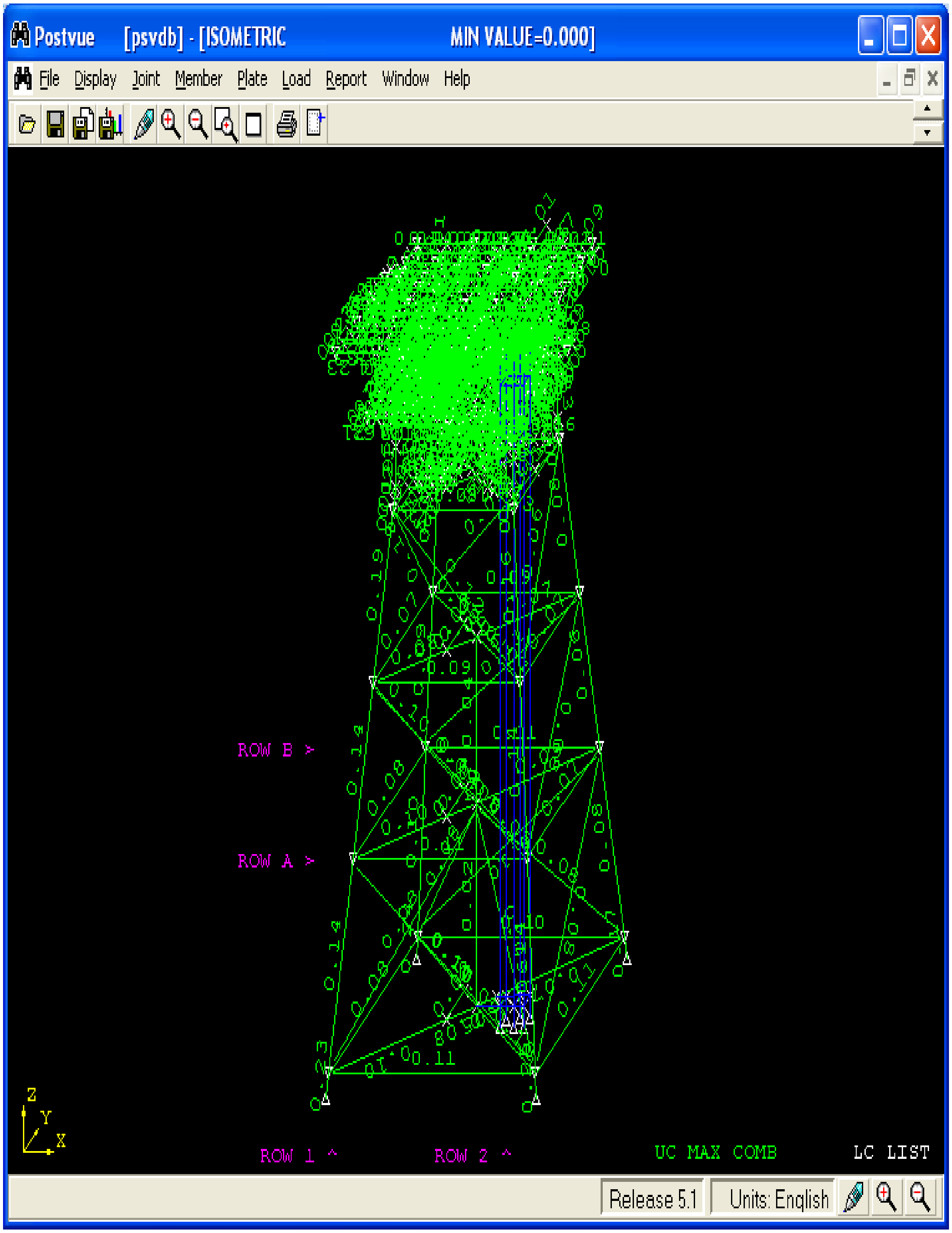


Figure 3.17 Platform SACS Model

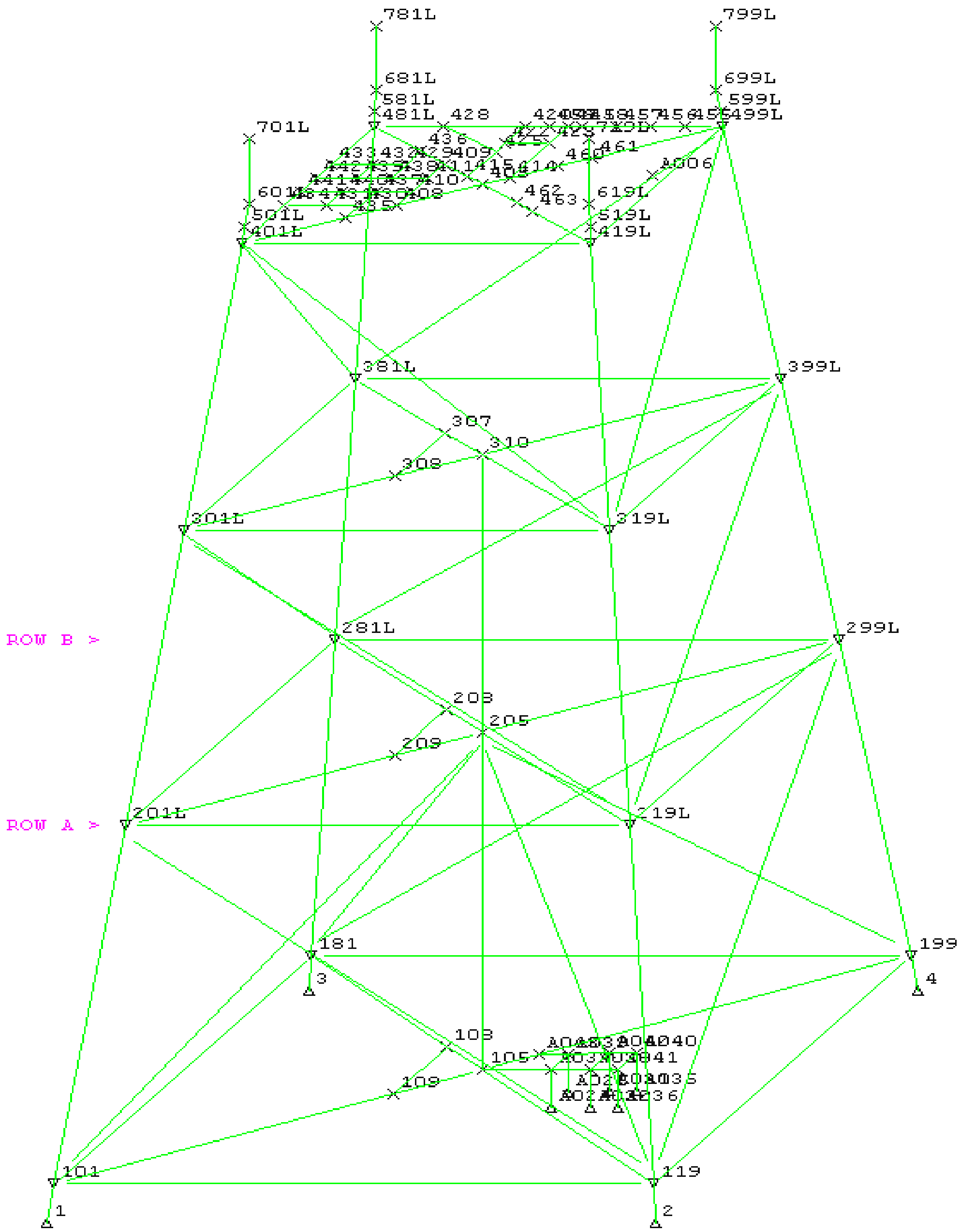


Figure 3.18 Substructure Nodes and Joints

The fatigue life damage and corresponding fatigue lives are generated using the fatigue modules. The member force spread transfer functions, response spectra and damage are computed.

The fatigue life of the jacket joints is reviewed to capture the number of joints with fatigue life less than 90 years as expected for the jacket structure with a life span of 30 years and safety factor of 3.0. The jacket structure is divided into four distinct tidal zones as follows:

(1) Boat landing;

(2) High tide zone;

(3) Medium tide zone;

(4) Low tide zone.

Joints with fatigue life less than 90 years located at each of the tidal zones mentioned above is recorded and presented in the Chapter 4 of the thesis.

3.2.4 Jacket Structure Reliability Assessment

The primary objective of this section is to present jacket structure reliability assessment technique with regards to member corrosion losses. Jacket members have been noted for time varying thickness reduction due to corrosion wastage that often lead to undesirable effects on structural global strength. Jacket structure that is exposed to seawater with many corrosion agents frequently leads to member corrosion damages. There are several corrosion agents in the seawater and it varies according to the site and location. However, despite the application of barrier

coatings and cathodic protection, corrosion process is barely mitigated but not totally prevented.

The traditional manual calculation method used to assess corroded structural member is by estimating the member net area after corrosion losses and verifying with applied load, and ensuring that member stress is not greater than allowable. Nowadays, the use of computer software is popular such as SACS, however the method only revealed the structural integrity of the members in the form of unit check (UC), but do not indicate jacket structure system structural reliability. This vital parameter (system structural reliability) is vital for making appropriate decision concerning the existing jacket structure overall fitness for purpose. The methods employ to achieve this are series and parallel reliability theories. The structural reliability technique offers an appropriate assessment procedure for existing jacket structure particularly when the platform is proposed for life extension. The manual calculation method for member capacity check and structural reliability method are presented in the subsequent sections.

3.2.4.1 Structural Member Capacity Check

Corrosion leads to reduction of structural member resistance and perhaps partial or total structural system failure. The manual check of a corroded tubular member for residual strength assessment can be carried out using the following procedures.

For a tubular member such as a structural element of a jacket platform, the initial area of the member is (A_1), the corrosion loss area is (A_2) and net area (A_o) is equal

to the steel cross section area available to resist load stresses that depend on the remaining member thickness after corrosion losses. The area *(A_o)* of a corroded tubular member is usually calculated manually by engineers using Equations (3.40)-(3.43)

$$A_1 = \frac{\pi D^2}{4}\left(1-\xi^2\right), \qquad \xi = \frac{d}{D} \tag{3.40}$$

$$A_2 = \pi D \Delta t \tag{3.41}$$

$$A_o = \frac{\pi D^2}{4}\left(1-\xi^2\right) - \pi D \Delta t \tag{3.42}$$

$$\frac{P_{load}}{A_o} \le \sigma \tag{3.43}$$

where (d) is member internal diameter (mm), (D) is external member diameter (mm), (D) represent the initial member thickness (mm), Δt corrosion loss thickness (mm), and σ is allowable steel stress kN/mm^2.

3.2.4.2 Reliability Model

The time-varying reliability and corresponding reliability factor are functions of time required for the member corrosion losses. The time-varying reliability is determined by Equation (3.44) – (3.46).

$$R(t) = 1 - P_f(t) \tag{3.44}$$

$$R(t) = T - P_f(\Delta t) \tag{3.45}$$

$$R(t) = 1 - \frac{\Delta t}{T} \tag{3.46}$$

where:

$R(t)$ **- system reliability,**

$P_f(t)$ **- probability of system failure**

T **– initial member thickness**

Δt - member corrosion losses (thickness)

Equation (3.45) can be rewritten in term of member original thickness and time variant corrosion member corrosion losses as shown in Equation (3.46).

3.2.4.3 Series Reliability

Series reliability model states that the items or components of a system are connected in some form of fashion, one after the other (Figure 4.3). Accordingly, if one component preceding a component fails, then the entire system fails (Nicholas Summerville 2004). A typical example of such system in the field of engineering is a product pipeline or offshore jacket structure support legs. When a segment of a pipeline punctured due to corrosion or accidental damages, the entire pipeline systems will not perform the intended functions and eventually will fail. For a system with four components as in Figure 3.19, the system reliability is the combination of the success probabilities of these four components.

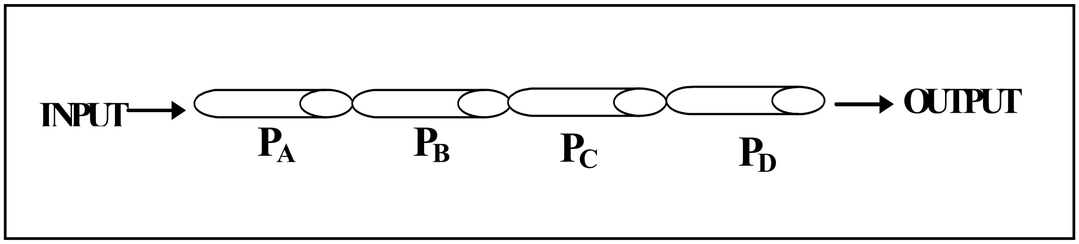


Figure 3.19 Schematic of Series Reliability Diagram

In this case all the components are essential for the successful operation of the system. Therefore the system reliability is the probability that all the components will function correctly. The system reliability calculation is represented in the Equation (3.47).

$$R(s)(t) = R(p_A).R(p_B).R(p_C).R(p_D) \qquad \textbf{(3.47)}$$

The system above is a series network where the system is non-redundant. Component P_A, P_B, P_C, and P_D must work for system success and only one pipe need to failing for the entire system to fail. If R_A, R_B, R_C and R_D represent the reliability or probability of successful operation of components *A, B, C, D, and QA, QB, QC, QD* represents the probability of failure of *A, B, C,* and *D*, the success of the system *(S)* can be represented in terms of Boolean logic as:

$$S = A \cap B \cap C \cap D \qquad \textbf{(3.48)}$$

The reliability or probability of success of the systems is:

$$RS = R_A.R_B.R_C.R_D \qquad \textbf{(3.49)}$$

For "n" components, the series can be universally written as:

$$R_S = R_1.R_2.R_3.R_4 - - - - R_n \qquad \textbf{(3.50)}$$

The characteristics of series systems are that the greater the number of the components, the lower the system reliability. The least reliable component in the system determines the overall reliability of the system.

3.2.4.4 Parallel Reliability

The parallel reliability system is a system that is designed with redundant components. This is often adopted when reliability of some of the items in the system is insufficient, or when reliability of a system tend to low as the time progresses due to material degradation as it is applied to offshore jacket platforms built in corrosive environment. Parallel systems can either be active parallel or stand-by parallel. In an active parallel system, the whole components are active at all times. For a Stand-by Parallel System, some of the components will be standing-by in a ready state, but will not be engaged until the first parts fails.

Active parallel systems, where component A and B are active at all time is illustrated in Figure 3.20. A good example of this type of this system is the bracing members of offshore jacket structures with active redundant members.

The jacket system is believed to be operating at all time under one of the following conditions:

(1) A and *B* are both functional.

(2) Item *A* is functional and B has failed.

(3) Item *B* is functional and *A* has failed.

But if *A* & *B* fail, then the system is considered to be a failure.

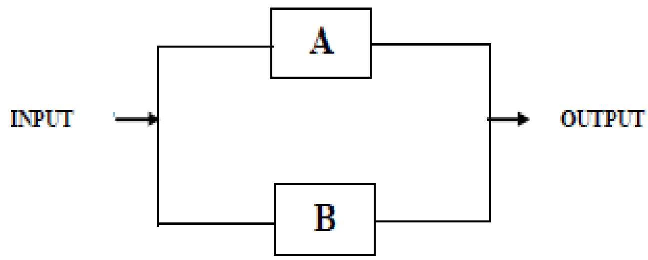


Figure 3.20 Active Parallel System Diagram

The calculation for the reliability of the system that is active parallel is represented in Equation 3.51

$$R(s) = R(a) + R(b) - R(a).R(b) \tag{3.51}$$

where R(s) is the reliability of the system and R(a) and R(b) is the reliabilities of the components of the system. For the Stand–by parallel, the system is fully redundant. Either A or B or combination A and B in the working condition will make the system successful. All components must fail for the system to fail. Example of this system is not so common in the structural engineering field. However, it may be applicable to a relationship between group bracing of jacket structures. The failure of Stand-by Parallel can be represented in Boolean Logic as:

$$F = A \cap B \tag{3.52}$$

The probability of the system failure is given by either:

$$P_S = P_A.P_B \tag{3.53}$$

$$P_S = 1 - \{(1 - R_A).(1 - R_B)\} \tag{3.54}$$

where, P_A, P_B are the failure probility of item A and B respectively.

3.2.4.5 Jacket Structure Reliability Flow Chart

Jacket structure reliability flow chart illustrated in Figure 3.21 was used in this study to carry out a structural assessment of a jacket structure as a result of member corrosion losses.

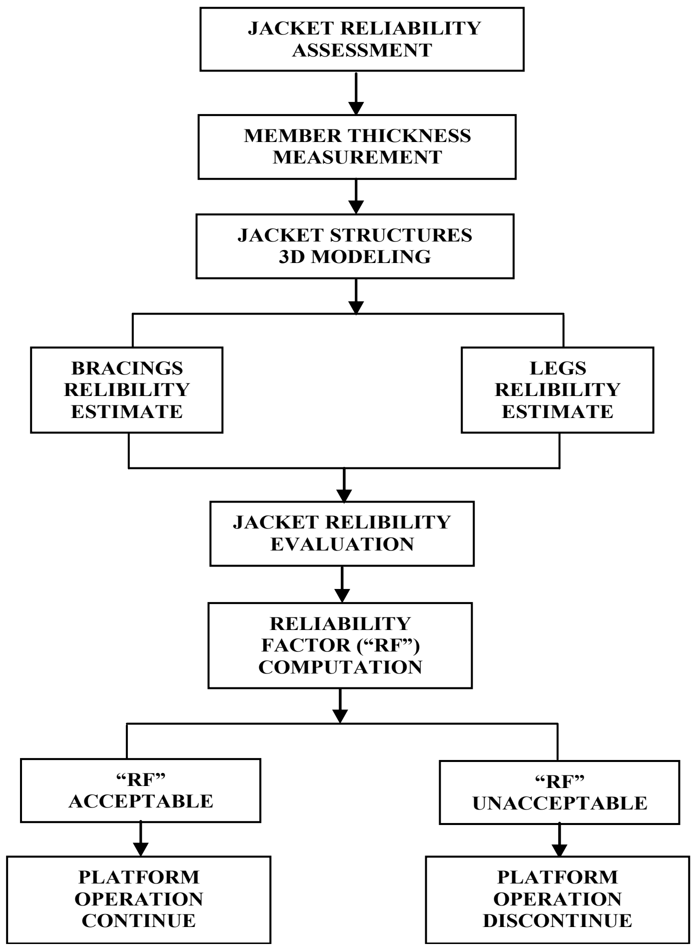


Figure 3.21 Jacket Structure Reliability Flow Chart

3.2.4.6 Jacket Structure Reliability Estimation

Different proportions of member thickness losses due to corrosion damaged were obtained from the structural member surveying which are presented in Tables 4.1. The hub of this section is to put forward a clear-cut and accurate reliability estimation approaches for jacket structure assessment to forestall unexpected platform failures. Thus, in regards to jacket platform design, several bracings groups are introduced at different level of the structure deliberately to distribute the applied loads and compensate for insufficiency that may be arise due to any bracing failures.

For the jacket structures shown in Figure 3.22, the bracing groups represented as A, B, C, D, E, F, and most of the bracing members are active, while some may be redundant or use below 100% capacity. The jacket bracing member system is believed to be operating at all time under one of the following modes:

1. **Some bracing members in the group failed and others are functional.**
2. **All bracing groups (A, B, C, D, E, and F) are functional.**
3. **All bracing group (A, B, C, D, E, and F) fail, then the system is considered a failure.**

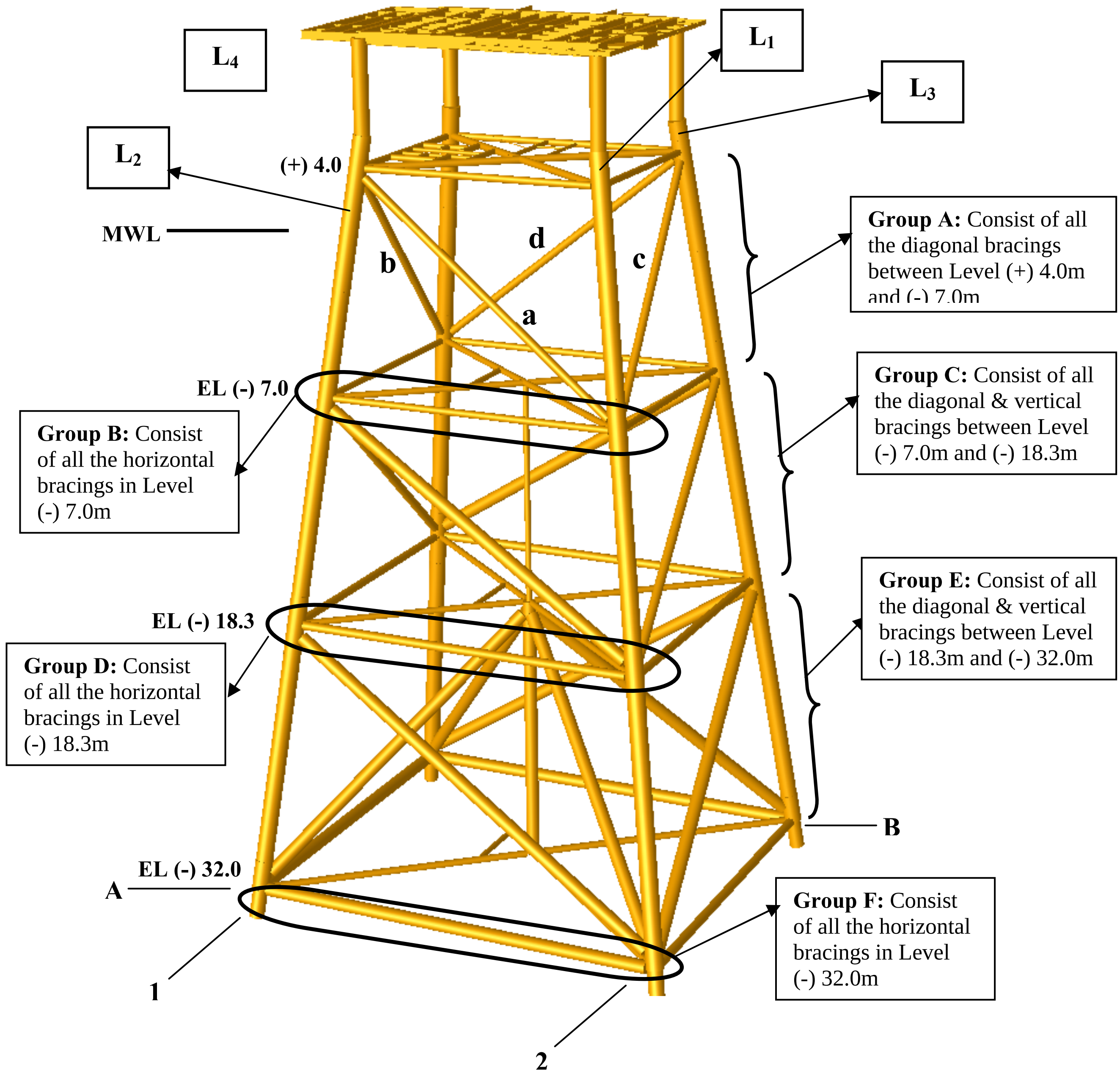


Figure 3.22 Jacket Structure Diagram

3.2.4.7 Jacket Structure Bracing Reliability

The bracing members of a jacket structure vary in sizes, location and arrangements. The member in bracing group A, B, C, D, E, F, is positioned horizontally, diagonally or vertically. The study assumed that all the bracing members located at the same

level and arrange in similar manners work together as a group. Therefore, the bracing members in every group work together and operating in an active parallel reliability system principle. While, all the bracing group is active at all times and assumed to be operating under any of the following conditions.

1. **All the bracing groups are functional.**
2. **Some members are operating and a few members have failed.**

If and only if, all the bracing members at any of the group A, B, C, D, E, F failed then the group is considered to be completely failed (Reliability = 0) and the loads earlier carried by the failed group will be transferred to other bracing group in the jacket structures. Jacket structures in Figure 3.22 show group-A bracings, which is arranged in parallel mode. Group-A bracing reliability is expressed in Equation 3.55.

$$R_A = 1 - [(P_a + P_b + P_c + P_{d.} - P_a.P_b.P_c.P_d)] \qquad \textbf{(3.55)}$$

R_A is the reliability of the bracing group "A" and P_a, P_b, P_c, P_d is the failure probabilities of the bracing members or member thickness corrosion loss. Accordingly, the reliability of other bracing groups B, C, D, E, and F could also be calculated.

3.2.4.8 Jacket Structure Group Bracing Reliability

Reliability for jacket group bracing system is in stand-by parallel manner. The reliability or probability of successful operations for bracing groups A, B, C, D, E, and F are written as $R_A, R_B, R_{C,} R_{D,} R_{E,} R_F$ and the probabilities of failure or average reduction of member thickness due to corrosion by $P_a, P_b, P_{c,} P_{d,} P_{e,} P_f$ respectively.

The system failure is represented symbolically as F_f, which can be presented in Boolean Logic as in Equation 3.56.

$$F_f = A \cap B \cap C \cap D \cap E \cap F \qquad \textbf{(3.56)}$$

The probability of failure of the group bracing system can be represented in Equation (3.57).

$$P_{SG} = P_A.P_B.P_C.P_D.P_E.P_F \qquad \textbf{(3.57)}$$

The reliability of the group bracing system is given in Equation (3.58) and (3.59)

$$P_{SG} = 1 - \{(1 - R_A).(1 - R_B).(1 - R_C).(1 - R_D).(1 - R_E).(1 - R_F)\} \qquad \textbf{(3.58)}$$

$$R_{SG} = 1 - P_A.P_B.P_C.P_D.P_F \qquad \textbf{(3.59)}$$

$P_A = 1 - R_A$, $P_B = 1 - R_B$ - - - -$P_F = 1 - R_F$ which is group bracing failure probabilities.

3.2.4.9 Jacket Structure Leg Reliability

The reliability of jacket platform legs is the product of all the leg reliability since the entire legs are essential to the successful operation of the platform. Accordingly, the four legged jacket system reliability calculation due to corrosion losses (R_{SL}) is presented in Equation (3.60).

$$R_{SL} = R_1.R_2.R_3.R_4 \qquad \textbf{(3.60)}$$

where:

$R_1.R_2.R_3.R_4$ **- corresponding reliability of each jacket platform four legs.**

3.2.4.10 Jacket Structure System Reliability

A typical jacket structure consists of legs and bracings as shown in Figure 3.23. The bracings are grouped (A, B, C, D, E, F) according to how they work collectively to resist the external loads. Based on the principle of parallel and series reliability theories, the jacket structure system reliability network reduction is illustrated in Figure 3.22 R_A, R_B, R_C, R_D, R_E and R_F represent group bracing that are arranged in a parallel manner L_1, L_2, L_3 and L_4 represent jacket four legs that are arranged in series mode.

Jacket structural system reliability is the product of bracing reliability and reliability of the jacket legs. The jacket structural system reliability (R_{JS}) is represented mathematically by Equation (3.61).

$$R_{JS} = R_{SL} . R_{SG} \quad \textbf{(3.61)}$$

Where, R_{SL} is the jacket legs reliability and R_{SG} is the bracing group (A, B, C, D, E, F) reliabilities. Reliability factor (RF) is established between an intact and assessed structural system reliability to determining the reduction rate of jacket platform integrity. The proposed factor is represented mathematically in Equation (3.62).

$$RF = \frac{1}{R_n} \quad \textbf{(3.62)}$$

where:

R_n – structural system reliability of assessed jacket structures

With reference to the above principles, reliability estimation of a jacket structure is carried out in this study based on the leftover member thickness over 23 years the structure has been built and operated in the Niger Delta.

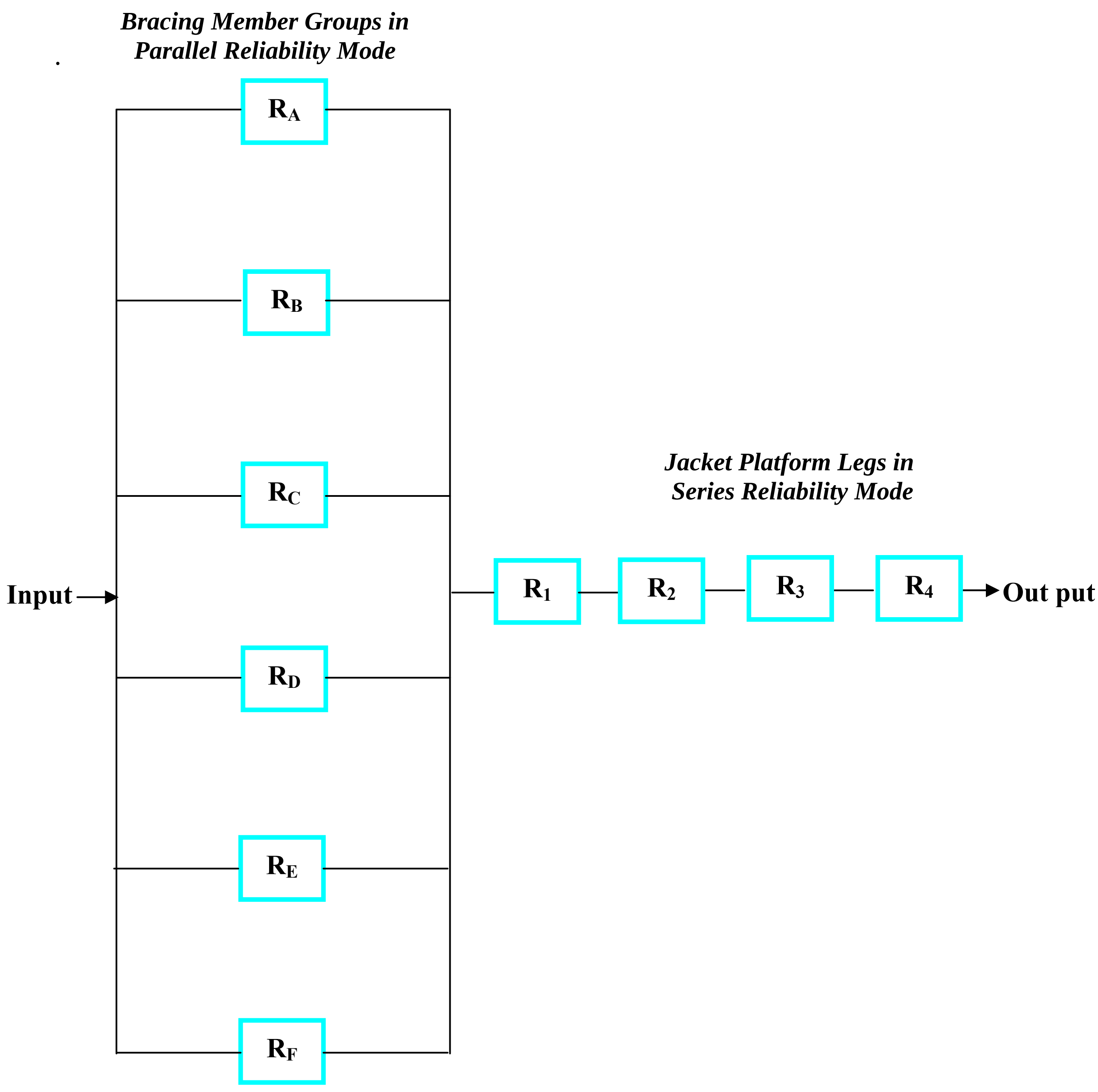


Figure 3.23 Jacket Structure Reliability Schematic Diagram

3.2.4.11 Comparative Analysis of Different Assessment Methods

Multi Attribute Analysis

A multi attribute analysis is a decision support method used to appraise the consequences with respect to different attributes. In contrast to cost benefit analysis, there is no attempt to transform all the different consequences into monetary or other comparable units. A multi- attribute value function is expressed mathematically in Equation (3.63) by Bedford and Cooke (2001).

$$v(x_1, x_2, x_3 \ldots\ldots x_r) = \sum_{i=1}^{r} w_i . v_i (x_i) \qquad \textbf{(3.63)}$$

where *w_i* is a weighting factor of the *i*th attribute, *x_i* is the *i*th attribute and *$v(x_i)$* is the marginal value functions.

Cost Benefit Analysis

Cost–benefit analysis (CBA) is a systematic process for calculating and comparing benefits and costs of a project or decision. CBA involves comparing the total expected cost of each option against the total expected benefits. In CBA, benefits and costs are expressed in monetary terms, and adjust for the time value of money, so that all flows of benefits and flows of project costs over time are expressed on a common basis in terms of their "net present value." Cost–benefit analysis function as applied in this study is expressed mathematically in Equation (3.64).

$$E[C] = \sum_{i=1}^{n} v_1 , v_2, v_3 \ldots\ldots v_n \qquad \textbf{(3.64)}$$

where *E[C]* is the total cost of the project or decision and $v_1 \ldots \ldots v_n$, are the cost of the various attributes in monetary term in (Naira).

3.2.5 Risk-based Assessment

The purpose of this section is to carry out a risk-based assessment with regards to fatigue and corrosion hazard as it is applied to offshore jacket platform structures. Jacket platforms of high consequence of failure are the structure subjected to corrosion and fatigue damage with potential impact on safety and economic losses. In the course of the study, several jacket damage scenarios were established and simulated. The risk level regarding every scenario was plotted on Risk Assessment Matrix (RAM) table to ascertain the most precarious conditions. RAM is a suitable expression of risk when several hazards and scenarios are concerned.

The risk analysis technique employed in the study is a tool for the management of hazard, safety, health and environmental protection. This is also a collection of several activities performed to provide support for decision-making such as marine structures inspection and maintenance programs. The intentions of risk screening process are to identify the high risk areas in the systems and determine critical damage mechanisms that require detailed evaluation. The risk screening process is also engaged to classify various scenarios based on failure probabilities and consequences.

Risk means exposure to hazard and risk level is determined by the severity of the consequences and the probability of an incident occurring. A general expression of risk "R" is described in Equation (3.65).

$$\boldsymbol{R = \sum f(p, C)} \quad \textbf{(3.65)}$$

where, p and C denote Frequency and Consequence of incident respectively.

3.2.5.1 Risk Analysis Framework

The risk-based assessment of offshore jacket structure that are vulnerable to fatigue and corrosion hazard was conducted using the flow chart in (Figure 3.5) as proposed by Bai (2003). The flow chart in summary says that the risk scenarios are to be identified, after which the risk levels is assessed and recommendations are made to mitigate or eliminate the risks. The risk ranking results will form the basis for the selection of scenarios which shall be subject to periodic inspection and maintenance.

The risk assessment process developed in this research work involved group discussion and consultation with senior colleagues. Hazard and issue details were discussed with regard to scenario probability, failure consequences and mitigations. Upon successful completion of mitigation measures, the risk levels are expected to reduce. However, implementation of prevention measure will be the measure for totally eliminating the risk. In the hierarchy of risk control, absolute elimination of exposure to risk is the best solution.

3.2.5.2 Risk Analysis Condition

The criteria for jacket platform hazard probability and damage potential are presented in Table 3.2 and Table 3.3 which shall be applied throughout this study. Table 3.4 illustrates the risk assessment matrix. The matrix is divided into three major regions, namely, unacceptable risk (A & B), acceptable risk (E) and the region between acceptable and unacceptable is medium (C & D).

Table 3.2 **Hazard Probability for Offshore Facilities (Damir & Hinko, 2005)**

Probability Category	Definition	Interpretation
A	Possibility of repeated incidents	Jacket structures with current conditions that indicate repeated future occurrences are possible
B	Possibility of isolated incidents	Jacket structures with current conditions indicate several future occurrences are
C	Possibility of occurring sometime	Jacket structures with current conditions indicate occasional future occurrences are possible
D	Not likely to occur	Jacket structures with current conditions indicate future occurrences are not likely to occur
E	Practically impossible	Jacket structures with current conditions indicate future occurrences are practically impossible

Table 3.3 Damage Potential for Offshore Facilities (Dagmar, 1998)

Consequence Category	Health/ Safety	Public disruption	Financial impact	Environmental impact
I	Fatalities or serious health impact on public	Evacuation of the whole personnel from the platform and continuing national or international attention	Corporate	Potential widespread, long term, significant adverse effects.
II	Permanently disabling injury and serious lost time	Evacuation of the whole personnel from the platform and continuing Regional attention	Business	Potential localised, medium term, significant adverse effects
III	Minor lost time injury with medical aid	Evacuation of some personnel and one time Regional attention	Field	Potential short term, minor adverse effects
IV	First aid	No evacuations, minor inconveniences to a few personnel	Others	Confined to lease or close proximity

Table 3.4 Risk Assessment Matrix (Yong Bai, 2003)

RISK ASSESSMENT MATRIX					
CONSEQUENCES	PROBABILITY				
	A	B	C	D	E
I					
II					
III					
IV					

High Risk *Medium Risk* *Low Risk*

The possible jacket structure damage scenarios and initiators are indicated in Table 3.5. The scenarios are expansively analyzed and classified accordingly in the RAM table. Accidents often occur as a result of several possible minor failures which create an unexpected weak mode in the structural systems as it is applied to jacket structures. Possible damaged scenarios as a result of corrosion and fatigue hazards documented during the site inspection of offshore jacket platform and group discussion are listed below:

- **Member uniform corrosion**
- **Member localised corrosion**
- **Joint uniform corrosion**
- **Little joint fatigue (Nucleation period)**
- **Medium fatigue (Fatigue growth period)**
- **No fatigue**

Table 3.5 Corrosion and Fatigue Hazard Scenarios

Scenario	Description
Scenario – 1	Joint and Member Uniform Corrosion + Little Fatigue
Scenario – 2	Joint and Member Uniform Corrosion + No Fatigue
Scenario – 3	Joint Localised Corrosion + Little Fatigue
Scenario – 4	Member Localised Corrosion + Little Fatigue
Scenario – 5	Member Localised Corrosion + Medium Fatigue
Scenario – 6	Member Localised Corrosion + No Fatigue
Scenario – 7	Joint Localised Corrosion + Medium Fatigue
Scenario – 8	Joint Localised Corrosion + No Fatigue
Scenario – 9	No Impact

(a) Little fatigue – Nucleation Period (c) Localised Corrosion – Pitting corrosion
(b) Medium fatigue – Fatigue Growth Period (d) Uniform Corrosion – General corrosion

3.2.5.3 Risk Analysis Estimation

The risk analysis of a damaged steel component as a result of corrosion and fatigue hazard was performed using the listed risk assessment tools.

- **Event Tree Scenarios**
- **Scenarios Outcome**
- **Scenarios Consequences**
- **Qualitative Probability**
- **Quantitative Probability**

Also, probability factors based on existing jacket structure's damage conditions and safeguards as per the researcher opinion is presented in Table 3.6.

Table 3.6 Probability Factors

S/N	PROBABILITY FACTORS
1	Corrosion Failure
2	The operator noticed corroded component before failure
3	Operator surveillance
4	Redundancy structural members prevent failure
5	Combination of corrosion and fatigue hazard

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 JACKET MEMBER EXISTING THICKNESS

The jacket structures used as a case study was built 23 years ago in the Niger Delta, NIgeria. The non-destructive Ultrasonic Tester (UT) equipment was employed to establish the member thickness. The member UT measurement results are presented in Table 4.1. The result showed that the member corrosion losses range from 0% to 17% of the original thickness and the average corrosion losses for every member was 4.5% of the original thickness.

Table 4.1 Jacket Member Wall Thicknesses

Location	Member		As-built Thickness (mm) 1985	UT Thickness (mm) 2008	Thickness Reduction (%) 2008
	ID	Type and Elevation			
Row A	1DA	Horizontal Bracing EL (-) 1.5m	9.525	9.501	0.262
	3DA	Horizontal Bracing EL (-) 1.5m	9.525	9.45	0.787
	5DA	Diagonal Brace EL (-) 4.0m to (-) 7.0m	9.525	8.1	14.961
	5BA	Diagonal Brace EL (-) 7.0m to (-) 18.3m	12.7	10.5	17.323
	5AA	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	12.40	2.362
	5CA	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	11.90	6.299
	1DA	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	12.4	2.36
	3DA	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	11.9	6.30
Row B	1DB	Diagonal Brace EL (-) 4.0m to (-) 7.0m	9.525	9.6*	-
	3DB	Diagonal Brace EL (-) 7.0m to (-) 18.3m	12.7	12.7	0.00
	3MB	Diagonal Brace EL (-) 7.0m to (-) 18.3m	9.525	9.6*	-
	53B	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	11.6	8.66
	52B	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	11.9	6.30
	51B	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	12.5	1.575

Row 1	1D1	Diagonal Brace EL (-) 4.0m to (-) 7.0m	9.525	9.4	1.31
	3D1	Diagonal Brace EL (-) 7.0m to (-) 18.3m	9.525	9.1	4.46
Row 2	1D2	Diagonal Brace EL (-) 4.0m to (-) 7.0m	9.525	9.1	4.46
	3D2	Diagonal Brace EL (-) 18.3m to (-) 32.0m	9.525	8.9	6.56
	5B2	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	12.5	1.57
Plan @ (-) 7.0m	2MB	Horizontal Brace EL (-) 7.0m	9.525	9.2	3.412
	2MD	Diagonal Member EL (-) 7.0m	9.525	9.3	2.36
	2M2	Horizontal Brace EL (-) 7.0m	9.525	9.3	2.36
	2MH	Diagonal Brace EL (-) 7.0m	9.525	9.3	2.36
	2ME	Diagonal Brace EL (-) 7.0m	9.525	9.2	3.41
	2MA	Horizontal Brace EL (-) 7.0m	9.525	9.2	3.41
	2MF	Diagonal Brace EL (-) 7.0m	9.525	9.0	5.51
	2M1	Horizontal Brace EL (-) 7.0m	9.525	9.3	2.36
	2MG	Horizontal Brace EL (-) 7.0m	9.271	9.1	1.84
Plan @ (-) 18.3m	4MD	Diagonal Brace EL (-) 18.3m	9.525	9.1	4.46
	4ME	Diagonal Brace EL (-) 18.3m	9.525	9.0	5.512
	4MC	Diagonal Brace EL (-) 18.3m	9.525	9.1	4.46
	4MG	Diagonal Brace EL (-) 18.3m	9.525	8.6	9.71
	4M2	Horizontal Brace EL (-) 18.3m	9.525	9.1	5.512
	4MA	Horizontal Brace EL (-) 18.3m	9.525	9.0	9.711
	4M1	Horizontal Brace EL (-) 18.3m	9.525	8.6	4.462
	4MB	Horizontal Brace EL (-) 18.3m	9.525	9.1	1.844
	4MF	Horizontal Brace EL (-) 18.3m	9.271	9.1	1.84
Plan @ (-) 32.0m	6M2	Horizontal Brace EL (-) 32.0m	9.525	8.400	11.811
	6MA	Horizontal Brace EL (-) 32.0m	12.700	12.300	3.150
	6MD	Horizontal Brace EL (-) 32.0m	9.525	8.900	6.562
	6MC	Horizontal Brace EL (-) 32.0m	9.525	9.1	4.462
	6ME	Horizontal Brace EL (-) 32.0m	9.525	9.0	5.512
	6M1	Horizontal Brace EL (-) 32.0m	9.525	9.4	1.312
	6MB	Horizontal Brace EL (-) 32.0m	12.700	12.300	3.150
Jacket Legs	4MD	Jacket Leg – 1	19.1	18.11	5.18
	4ME	Jacket Leg – 2	19.1	18.25	4.45
	4MC	Jacket Leg – 3	19.1	18.52	3.04
	4MG	Jacket Leg – 4	19.1	18.65	2.36

4.2 Corrosion Losses and Fatigue Damage

The facts with anomalies criteria collected during the jacket structure site survey are well documented in Table 3.1 of the thesis. These data include member corrosion damage status, marine growth and degree of anodes depletion among others. The site survey data revealed that, anodes installed in the splash zone depleted faster than those in the low tidal zones as a result of accelerated corrosion process.

The jacket member corrosion losses in the splash zone, medium tidal zone and low tidal zone are revealed in Figures 4.1, 4.2, and 4.3 respectively. These graphs are constructed based on the members UT measurement results for the jacket members over the years. The graphs revealed that more corrosion losses were recorded in the splash zones due to the presence of more corrosion agents, such as oxygenated seawater, warm water and continuous removal of rusting material from jacket member surfaces by ocean waves and current.

The combination of jacket member corrosion losses in the three tidal zones is illustrated in Figure 4.4. The diagram disclosed that the splash zone graph is steeper than the other graphs as a result of an accelerated corrosion process in the zone. This phenomenon is also accounted for the high tide and continuous jacket member contact with aerated warm seawater that significantly supports corrosion growth.

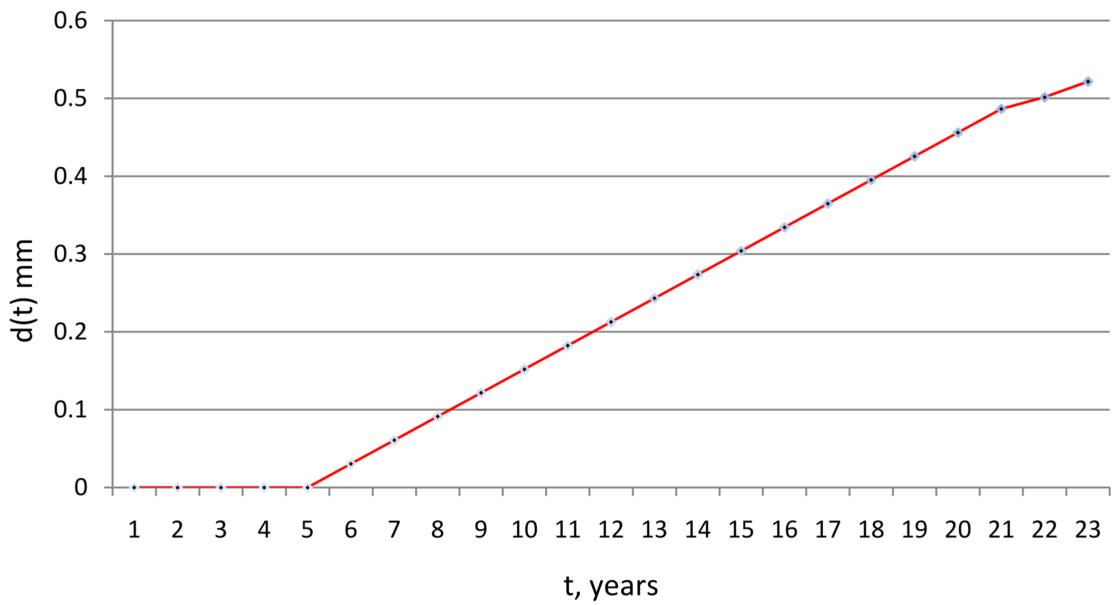


Figure 4.1 Member Corrosion Loss (High Tidal Zone)

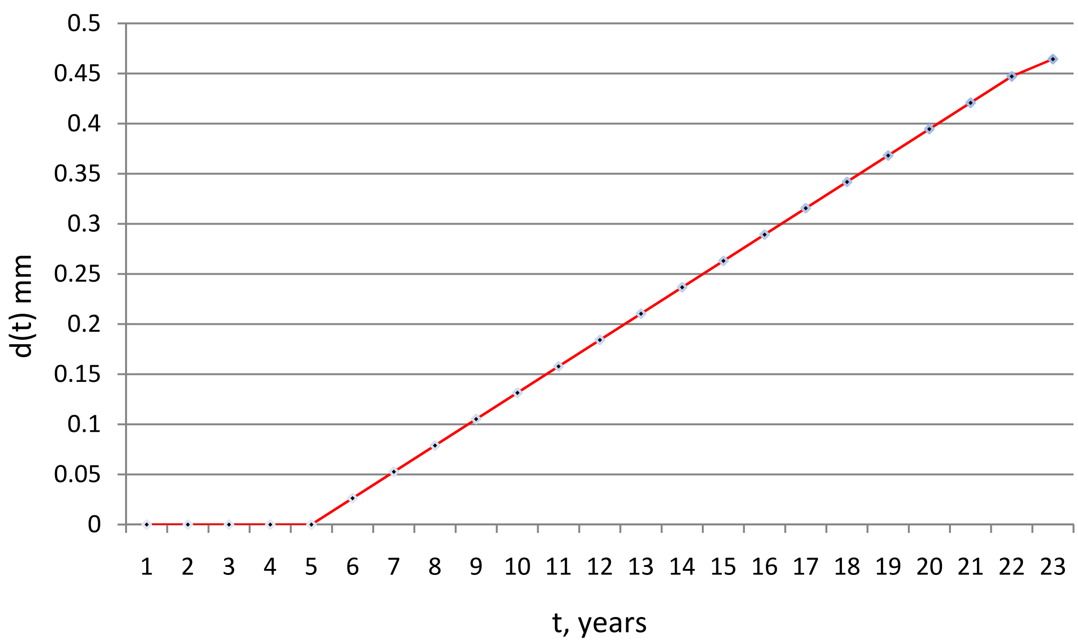


Figure 4.2 Member Corrosion Loss (Medium Tidal Zone)

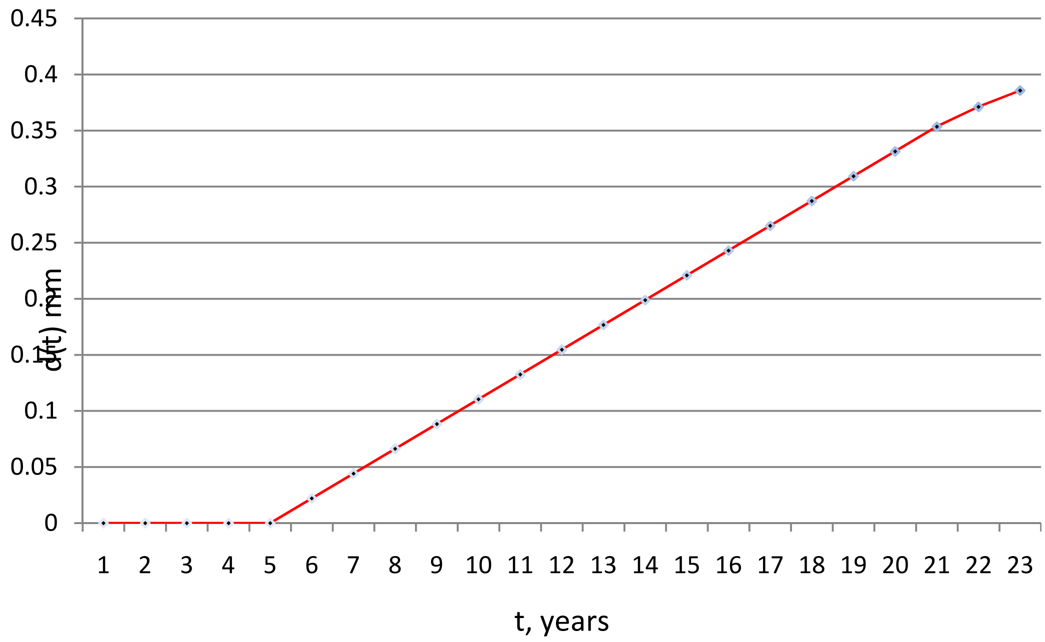


Figure 4.3 Member Corrosion Loss (Lower Tidal Zone)

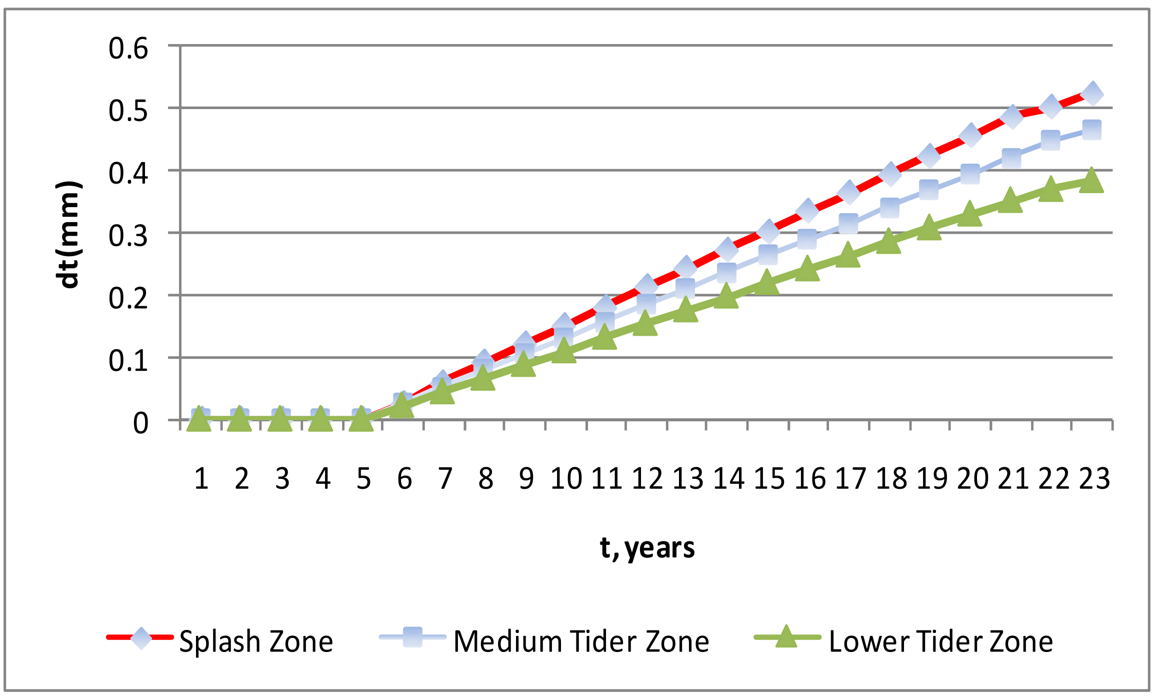


Figure 4.4 Jacket Structure Corrosion Losses versus Time

During the course of this study, the outcome of the jacket structure survey revealed that the structural damage is limited to general isolated parts, which include spider deck, gratings, tertiary members, conductor bays and appurtenance connections. Pitting corrosion in member and joint was found to be responsible for the water flooding of the jacket tubular members. The data collected from the jacket inspection revealed that jackets component may be corroded with fatigue cracks simultaneously leading to the reduction of the platform structural strength. Therefore, it is appropriate to develop a continuous process of in-service jacket structural integrity management that will include continual routing periodic underwater inspection as regards to corrosion and fatigue damage.

Another primary goal of the study is to establish corrosion damage effect on the jacket joint fatigue life and the ability of the jacket structure to remain in-service for continued operation. The procedure used for the jacket structure fatigue life assessment is based on the methodology presented in API RP 2A 2000, which is widely used in the petroleum industry. The effect of wave loading and structure response is explicitly accounted for during the structural analysis using SACS computer software in the course of the study.

The structural analysis of the jacket was carried out using member existing diameter and thickness that reflected the corroded state of the structure for the calculation of the jacket joint fatigue life. The fatigue damage was established for all the primary and secondary joints using a spectral fatigue approach.

The target design life of 30 years was proposed for the jacket platform with factor of safety of 3.0 that provided the minimum of 90 years fatigue life for all the joints. Therefore, joint with fatigue life less than 90 years in each tidal zone are documented and presented in Table 4.2.

Table 4.2 Joint Fatigue Life

S/N	**Joint Elevation**	**Tidal Zone**	**Quantity of joint with Fatigue Life less than 90yrs**
1	(+3)	Boat Landing Area	7
2	(+3) to (-4)	High Tide Zone (Splash Zone)	18
3	(-4) to (-18.3)	Medium Tide Zone	11
4	(-18.3) to (-32)	Low Tide Zone	8

The jacket fatigue profile diagram in Figure 4.5 indicates that the number of joints with fatigue life less than 90 years is a function of corrosion rate at each tidal zone. There are more joints with less fatigue life in the splash zone than any of the other tidal zones. The result of this study further supports the mitigation measure suggested in this study that additional thickness of steel for corrosion allowance (sacrificial steel) be provided for jacket platform structural member in the splash zone to compensate for the accelerating corrosion losses of the jacket components located in the splash zone.

A known corrosion allowance is of the order of 3-12mm depending on design specifications and applicable codes. However, minimum of 3mm is recommended to

the structural members seated in the splash zone for a well protected jacket structure in the Niger Delta. A well protected structure means jacket structures incorporated with the appropriate design and maintained cathodic protection systems.

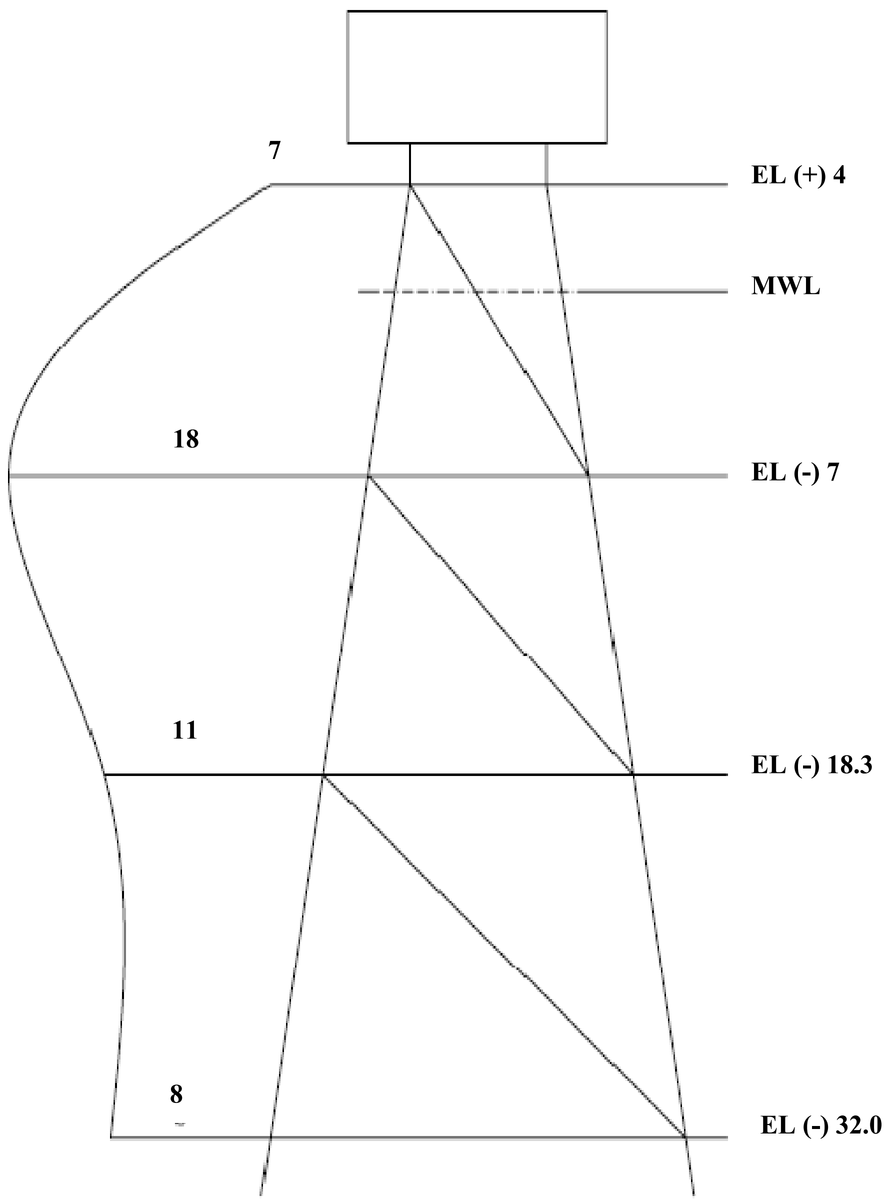


Figure 4.5 Jacket Structure Fatigue Life Profile

The outcome of this study offers a unique opportunity to determine the effectiveness of existing structural design standards and if so required to develop recommendations for changes. The study provided an opportunity to evaluate the available design process for a jacket structure with regards to corrosion and fatigue damage relationship.

4.3 CHLORINE ION ACCUMULATION AND DIFFUSION

The work revealed that chlorine ion concentration in the surrounding of jacket platform is higher than the open seawater as a result of crude oil production activities in the Niger Delta. The model demonstrates that the period required for a jacket platform structure built in the marine environment to experience corrosion damaged depends on the chlorine ion concentration on the structure surfaces.

The Metocean data and the estimated chlorine-ion concentration around the production platform are shown in Tables 4.3 – 4.5 (Santala, 2002).

Table 4.3 Niger Delta Metocean Data (Santala .M. J, 2002)

Metocean Directions (0^{o})	Waves Period (s)	Wave Velocity (m/s)	Wave Length (m)
20	14	0.31	4.34
65	13	0.57	7.41
110	5	0.57	2.85
155	5	0.31	1.55
200	5	0.41	2.05
245	5	0.57	2.85
290	5	0.57	2.85
335	13.5	0.36	4.86

Table 4.4 Age of Facility and Metocean Data

Facilities Description	Facility Age (yr)	Wave Velocity (m/s)	Chlorine ion Concentration (mol/m^3)
Off loading Buoy	12	0.41	3.80
Wellhead platform	13	0.41	3.58
Processing Platform	10.5	0.41	3.51
Living Quarters Platform	20	0.41	3.62
Production Platform	21	0.41	3.51

Table 4.5 Estimated Chlorine-ion Concentration around Production Platform

Metocean Directions (0^o)	Platform Age (yr)	Average Wave Velocity (m)	Chlorine-ion Concentration (mol/m^3)	Average Chloride Accumulation ($mol/m^3/yr$)
20	21	0.41	3.51	1.8
65	21	0.57	3.49	1.8
110	21	0.57	3.49	1.8
155	21	0.31	3.52	1.8
200	21	0.41	3.51	1.8
245	21	0.57	3.49	1.8
290	21	0.57	3.49	1.8
335	21	0.36	3.51	1.8
Average	21	0.47	3.50	1.8

The Fick's second law of diffusion was extended in the study to account for the continuous accumulation of chloride around offshore production jacket platforms. The seawater typically contained chloride in certain proportion and the field data revealed that the percentage of seawater chloride in the vicinity of production platforms is higher than open sea water accumulation. The percentage of chloride content in the seawater also varies according to the velocity of water movement along the metocean directions in the vicinity of the platform as shown in Figure 4.6. The chlorine-ion concentration is higher in the area with lower seawater velocity

than the region of higher seawater velocity. This phenomenon revealed that ocean wave and water current are continuously carring away chloride from the platform vicinity as they are generated from crude oil production activities.

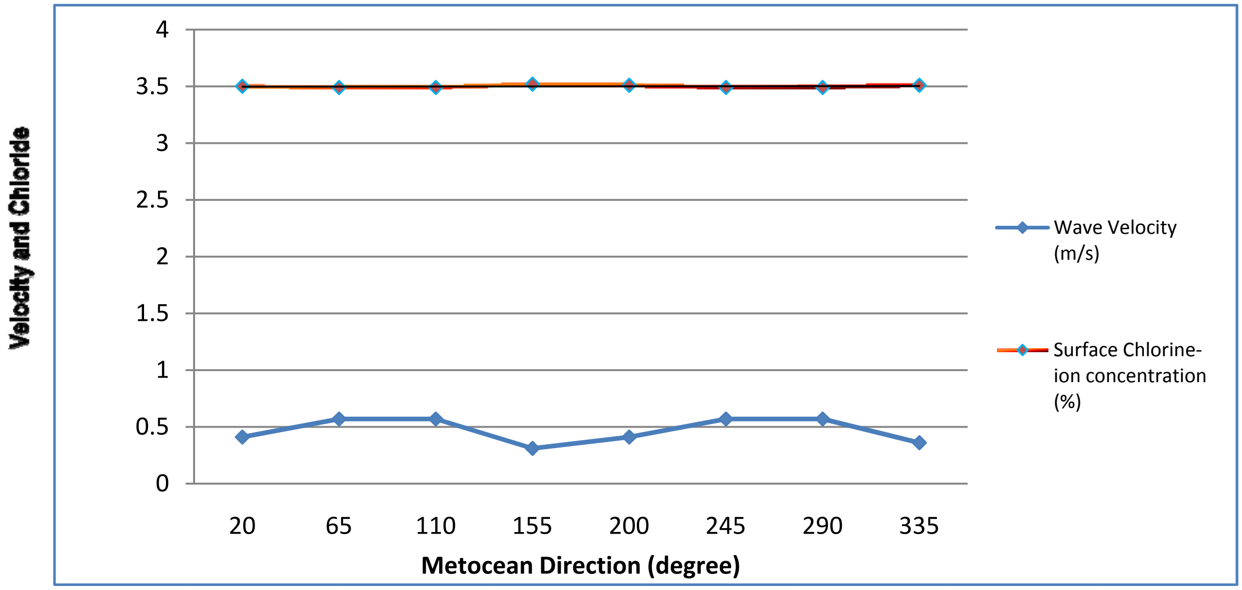


Figure 4.6 Graph Showing Effect of Chlorine-ion Vs Ocean Wave Velocity

The study revealed that the average salinity in an open seawater in the Niger Delta is 3.5% and the salinity of the seawater around production jacket platform is 3.8%. By applying the extended Fick's second Law of diffusion in Equation 3.34, the rate of chloride accumulation in the vicinity of the platform is established to be 1.8g/Liter/yr based on the average seawater velocity of 0.41m/s. This study has revealed the relationship between chlorine-ion concentration and chloride accumulation within jacket structures with an accurate index representation.

When the rate of water movement (v) around offshore jacket platform increases, the chlorine-ion concentration decreases and vice visa, Similarly, when chlorine accumulation rate increases, chlorine-ion concentration also increases and the other way round. However, there will be no condition in which the chlorine-ion concentration around the offshore jacket platform will be less than open seawater chlorine-ion concentration.

The rate of chlorine ion concentration (C_o) increases from initial seawater chlorine-ion concentration of 3.5%, as chloride accumulation increases in the vicinity of the platform as shown in Figure 4.7. The chlorine-ion concentration decrease as ocean wave and seawater current velocity increases as also revealed in Figure 4.8. The relationship between chloride accumulation, chlorine-ion concentration and seawater velocity is illustrated in Figure 4.9.

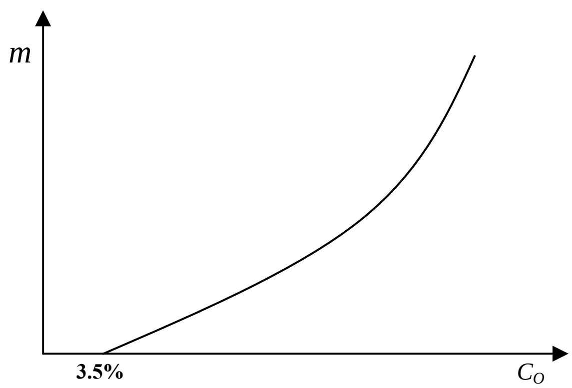


Figure 4.7 Indicate Chloride Accumulation (m) Vs Chlorine-ion Concentration (C_o)

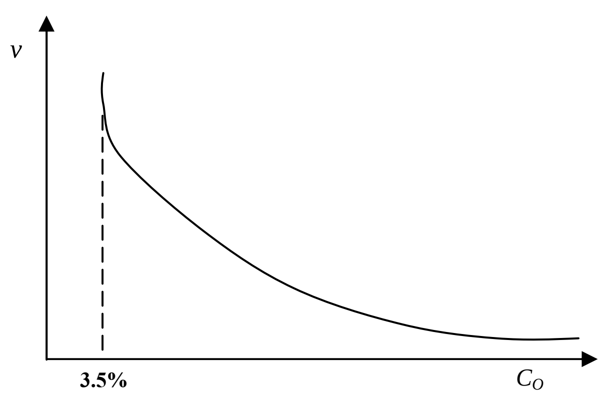


Figure 4.8 Indicate Seawater Velocity (v)Vs Seawater Chlorine-ion Concentration (C_o)

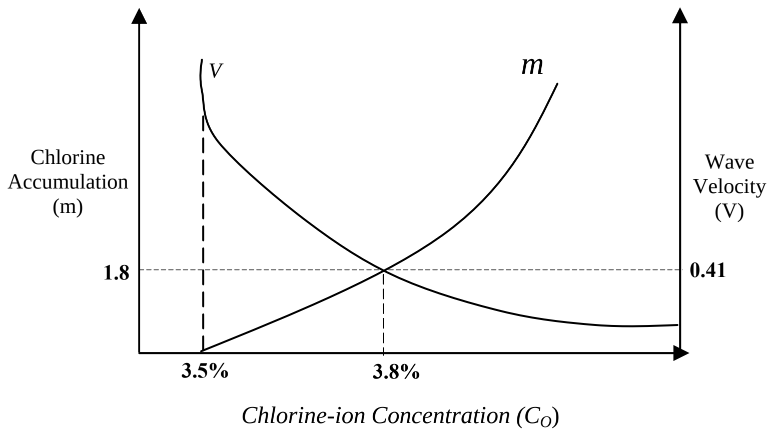


Figure 4.9 Indicate Seawater Velocity, Seawater Chlorine Accumulation and Seawater Chlorine- ion Concentration

The rate of marine steel structure corrosion damage is directly proportional to the amount of chlorine-ion concentration present on the component surfaces. This description is applicable for the coated and uncoated steel structures. However, time for the corrosion damage of a coated steel component is longer than uncoated steel structures by the coating life span (τ) expressed in Equation 3.31. This hypothesis is valid provided the coating material is not allowed chlorine-ion diffusion to the steel component surfaces throughout the life span of the coating material. Sketch

The work also demonstrates that the amount of chlorine ions on the steel surface can be used to quantify the vulnerability of marine structure to corrosion damage. Whenever considerable chlorine ions are present on marine steel structure surfaces, corrosion damage begins. Therefore, adequate cathodic protection device is recommended for the protection of marine steel structures against corrosion

damage as it is applicable to jacket structures. However, if the chlorine-ion concentration distribution on the steel surface is not significant as it is applied to a newly built jacket structure, corrosion process is expected to be lower. In this case, less expensive corrosion control device is recommended. The accomplishment in this study is found to be a very useful data for the operators of jacket platform in the Niger Delta to determine the appropriate time for jacket structure surveying and subsequent required repair works on the structure.

4.4 Jacket Structure Reliability Assessment

The jacket structure reliability assessment method developed in this study is based on parallel and series reliability theories. The parallel system signifies when a failed member sheds load for others as applicable to corroded and failed jacket bracing members. The series system requires only a component to fail, for the system to be unsuccessful. The failure of a jacket leg is a classical example of this phenomenon. Based on the above declarations, the failure modes of a jacket structure are both series and parallel system modes depending on the correlation between the members that is under consideration. The bracing members of a jacket structure belong to the parallel failure mode and most of the bracing needs to yield for failure before the jacket structure collapse mode is wholly developed. The failure modes of a jacket leg are related to series system. The failure of a leg may result in the failure of the whole jacket structures.

A particular jacket platform structure in the Niger Delta is used as a case study and the reliability estimation value of the jacket bracings is presented in Table 4.6 -4.8.

The jacket legs reliability and jacket structure system reliability with reliability factor are documented in Table 4.9 - 4.10 respectively. The reliability technique specified that the reliability and the reliability factor of a newly built jacket structure is 1.0, provided the steel members are free from corrosion dents. The assessment method also reveals that the rate of jacket structure reliability reduces as member corrosion wastages progresses as shown in Figure 4.10. A ratio between reliability of an intact jacket structure (corrosion free) and a corroded jacket structure is referred to in this study as a Reliability Factor (RF). The parameter increases as jacket member corrosion loss increase as demonstrated in Figure 4.11.

Table 4.6 Jacket Bracing Member Group Reliability (Parallel)

Group	ID	Corrosion Loss = tp (%)	Failure Probability (P = tp/100)	Reliability (1 - P)
A	1DA, (Pa)	0.262	0.00262	0.99738
	1D1, (Pb)	1.312	0.01312	0.98688
	1D2, (Pc)	4.462	0.04462	0.95538
	1DB, (Pd)	0.000	0.000	1.000
	Reliability (R_A)	1- [(Pa + Pb + Pc + Pd) – Pa.Pb.Pc.Pd]		**0.9396**
B	2MB, (Pa)	3.412	0.03412	0.96588
	2M2, (Pb)	2.362	0.02362	0.97638
	2ME, (Pc)	3.412	0.03412	0.96588
	2MA, (Pd)	3.412	0.03412	0.96588
	53B, (Pe)	5.512	0.05512	0.94488
	2MD, (Pf)	2.362	0.02362	0.97638
	2MG, (Pg)	1.844	0.01844	0.98156
	2M1, (Ph)	2.362	0.02362	0.97638
	2MH, (Pi)	2.362	0.02362	0.97638
	Reliability (R_B)	1 - [(Pa + Pb + Pc + Pd + Pe + Pf + Pg + Ph + Pi) - Pa.Pb.Pc.Pd.Pe.Pf.Pg.Ph.Pi)]		**0.7717**
C	3DA, (Pa)	0.787	0.00787	0.99213
	3D1, (Pb)	4.462	0.04462	0.95538
	3D2, (Pc)	6.562	0.06562	0.93438
	3DB, (Pd)	None		
	3MB, (Pe)	None		
	Reliability (R_C)	1 – [(Pa + Pb + Pc + Pd + Pe) – Pa.Pb.Pc.PD.Pe]		**0.9475**
D	4ME, (Pa)	5.512	0.05512	0.94488
	4M2, (Pb)	4.462	0.04462	0.95538
	4MA, (Pc)	5.512	0.05512	0.94488
	4M1, (Pd)	9.711	0.09711	0.90289
	4MB, (Pe)	4.462	0.04462	0.95538
	4MG, (Pf)	9.711	0.09711	0.90289
	4MF, (Pg)	1.844	0.01844	0.98156
	Reliability (R_D)	1 - [(Pa + Pb + Pc + Pd + Pe + Pf + Pg) - Pa.Pb.Pc.Pd.Pe.Pd.Pf.Pg]		**0.5879**
E	5BA, (Pa)	17.323	0.17323	0.82677
	5AA, (Pb)	2.362	0.02362	0.97638
	5CA, (Pc)	6.229	0.06229	0.93771
	5DA, (Pd)	14.961	0.14961	0.85039
	52B, (Pe)	6.299	0.06299	0.93701
	51B, (Pf)	1.575	0.01575	0.98425
	53B, (Pg)	8.661	0.08661	0.91339
	5B2, (Ph)	1.575	0.01575	0.98425
	Reliability(R_E)	1 - [(Pa + Pb + Pc + Pd + Pe + Pf + Pg +Ph) - Pa.Pb.Pc.Pd.Pe.Pf.Pg.Ph)]		**0.4102**
F	6M2, (Pa)	11.811	0.11811	0.88189
	6MA, (Pb)	3.150	0.0315	0.9685
	4MD, (Pc)	6.562	0.06562	0.93438
	6MC, (Pd)	4.462	0.04462	0.95538
	6ME, (Pe)	5.512	0.05512	0.94488
	6M1, (Pf)	1.312	0.01312	0.98688
	6MB, (Pg)	1.150	0.0115	0.9885
	4MC, (Ph)	4.462	0.04462	0.95538
	Reliability(R_F)	1 - [(Pa + Pb + Pc + Pd + Pe + Pf + Pg +Ph) - Pa.Pb.Pc.Pd.Pe.Pf.Pg.Ph)]		**0.6158**

Table 4.7 Complete Jacket Bracing Group Reliability (Parallel)

Group	ID	Reliability (R)	Failure Probability P = (1 - R)
A	R_A	0.9396	0.06036
B	R_B	0.7717	0.22834
C	R_C	0.9475	0.05249
D	R_D	0.5879	0.41214
E	R_E	0.4102	0.58985
F	R_F	0.6158	0.38421
Reliability = R_{SG}	$1 - P_A.P_B.P_C.P_D\ P_E.P_F$		**0.999932430**

Table 4.8 Jacket Legs Reliability (Series)

Group	ID	Corrosion Loss = tp (%)	Failure Probability (P = tp/100)	Reliability (1 - P)
Support Legs	L01, (P_{L1})	5.183	0.05183	0.94817
	L02, (P_{L2})	4.450	0.0445	0.9555
	L03, (P_{L3})	3.037	0.03037	0.96963
	L04, (P_{L4})	2.356	0.02356	0.97644
	Reliability (R_{SJ})	$P_{L1}.P_{L2}.\ P_{L3}.P_{L4}$		**0.8578**

Table 4.9 Jacket Structural System Reliability (Series)

Group	ID	Reliability (R)	Failure Probability P = (1 - R)
Support Legs	(R_{SL})	0.8578	0.1215
Jacket Bracings	(R_{SG})	0.999932430	0.0001
Reliability (R_{SJ})	$R_{SL}.R_{SG}$		**0.8577**

Table 4.10 System Reliability and Reliability Factor

S/N	Period	1985	2008
1	**Duration**	**0 yrs**	**23 yrs**
2	Support Legs (R_{SL})	1.0	0.9995
3	Jacket Bracing (R_{SG})	1.0	0.8578
4	Reliability (R_{SJ})	(1.0 x 1.0) = 1.0	(0.9995 x 0.8578) = 0.858
5	Reliability Factor (*RF*)	(1.0/1.0) =1.0	1.0/0.8577) = 1.166

The study also revealed that jacket structure system reliability (R_{sj}) and reliability factor (R_F) of an intact (newly built) jacket structure is 100% and 1.0 respectively. Also, the (R_{sj}) and (R_F) for a corroded jacket structure that is reported in the study are estimated to be 85.8% and 1.166 respectively. These values indicate that the jacket structure reliability factor is inversely proportional to the same jacket structure system reliability value as revealed in Figure 4.12. As the jacket structure system reliability decreases, the reliability factor of the same jacket structure increases proportionally.

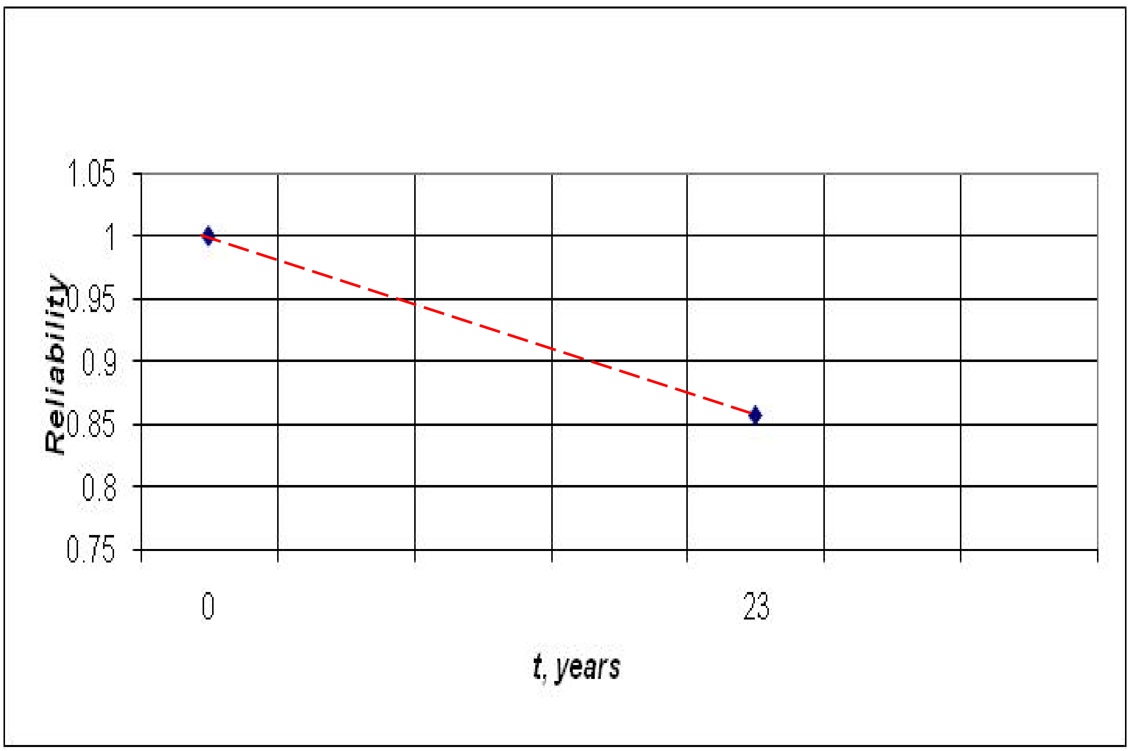


Figure 4.10 Jacket Structures Reliability versus Age

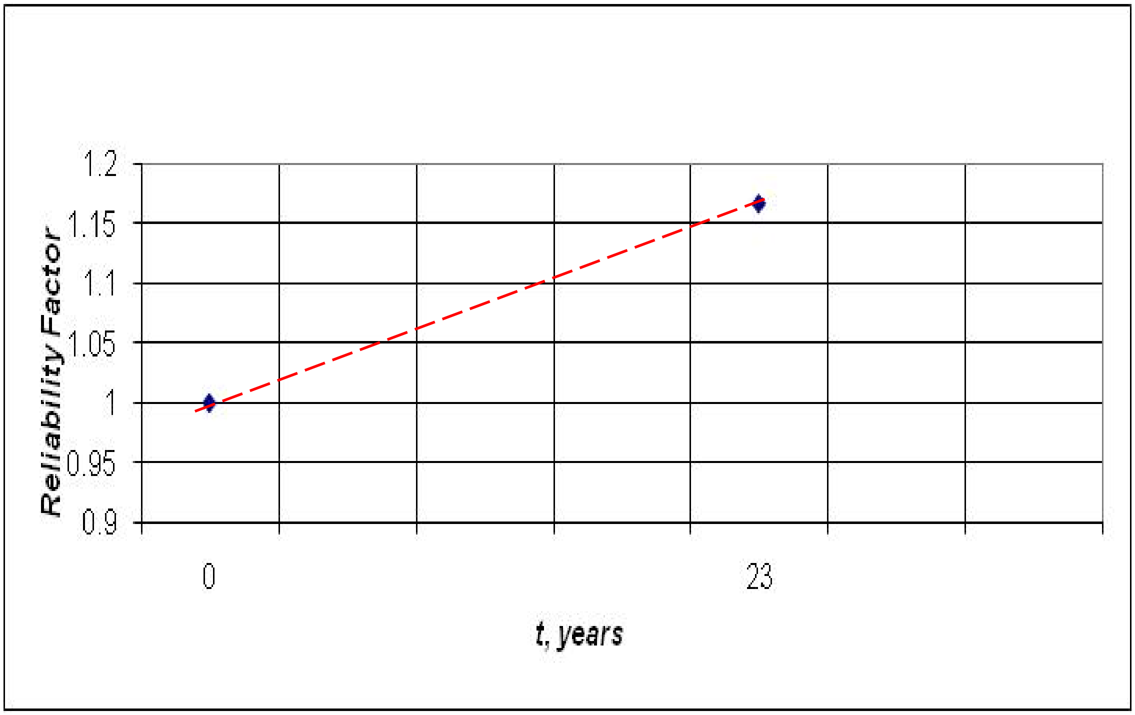


Figure-4.11 Jacket Structure Reliability Factor versus Age

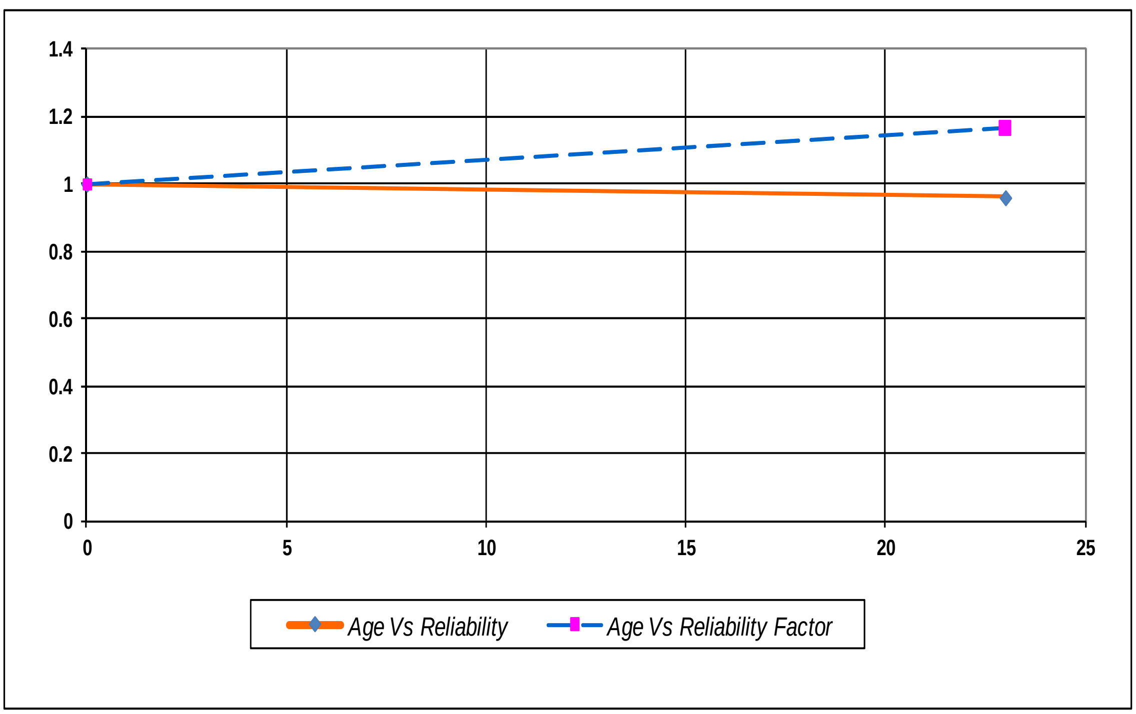


Figure 4.12 Jacket Structure Reliability and Reliability Factor versus Age

The reliability factor provided in this study is an essential parameter to determine existing jacket structure safety and the maximum value recommended for a corroded jacket structure that is in active operation is 1.25. However, individual operator may fix reliability factor value for their jacket structure based on the company best engineering practice.

The study revealed that more jacket bracing members are better. However, the correlation between these members reduces the system benefit. The series system exhibits that more members are worse, but higher reliability of individual members reduces the penalty. However, higher likely failure mode of a structural system does not necessarily indicate significantly lower reliability. The highly indeterminate structures may not necessarily be more reliable than a determinant structure. Whether a system is parallel or in series, the increase in individual component reliability dictates the system reliability. This technique is recommended as the most effective in engineering practice to prevent structure failures.

4.4.1 Benefits of Reliability Assessment Method

The jacket reliability assessment method developed in this study is the appropriate technique and the method eliminates the rigorous exercises associated with SACS and manual calculations. However, manual and SACS method is the proper method for the design of new jacket structures, where reliability assessment method is not appropriate.

The proposed assessment method is a handy tool to monitor jacket structure safety for the member corrosion wastages. The technique can be accomplished with pocket

calculator or Microsoft excel. The benefit of the method includes provision of structural reliability value for the members and the jacket structure system. This accomplishment is significant for the straightforward assessment of a jacket structures particularly when the structure life extension is anticipated. The study outcome shows that the cost of using either manual or SACS method is costly compared with the reliability assessment method proposed in this study.

The detailed multi attribute analysis for three different jacket structure assessment methods and comparative advantages are presented in the Table 4.11.

Table 4.11 Multi Attribute Analysis

S/N	DESCRIPTIONS	CONVENTIONAL METHOD	AUTOMATED MATHOD	RELIABILITY ASSESSMENT
1	Accessibility to calculation tools	Pocket calculator (Best)	SACS software (Poor)	Excel software (Good)
2	The requirement for the calculation review in another location.	Pocket calculator (Best)	SACS software (Poor)	Excel software (Good)
3	Transmission of the finished work to the Client	Hard copy (Average)	Email (Best)	Email (Best)
4	Duration of execution (4-legged jacket platform)	1,860man-hr	1,280 man-hour	985 man-hour
5	Duration of personnel training	160 hours	80 hours	40 hours
6	Output/Accuracy	Average	Good	V.Good
7	Design of new Jacket Structures	Average	V.Good	Worst

Best-100%, Good-75%, Average- 50%, Poor- 25%, Worst -0%

The execution costs for each of the three assessment methods presented in the study are revealed in Table 4.12. The choice of any of the assessment techniques is recommended to depend on the unit check (UC) and the opportunity cost (OC) for economic reasons. (OC) and (UC) are the ratio between the total cost of each method. The lower the unit check (UC) the more cost effective the method. The higher the OC the more beneficial the method compared with the other in Table 4.12.

Table 4.12 Cost Benefit Analysis

S/N	DESCRIPTIONS	CONVENTIONAL METHOD	AUTOMATED MATHOD	RELIABILITY ASSESSMENT
1	Cost of computer hardware (1No)	N20,000	N75,500	N75,500
2	Cost of software (1 user)	N5,000	N2,750,000	N30,000
3	Cost of Execution (N3,000/hr)	N7,680,000	N3,840,000	N2,955,000
4	Cost of Transmission	N15,500	N500	N500
5	Cost of personnel Training (N3,500/hr)	N560,000	N280,000	N140,000
	Total	N8,380,500	N6,946,000	N3,201,000
	Unit Check (UC)	1.0	0.84	0.39
	Opportunity Cost (OC)	1.0	1.19	2.58

4.5 Corrosion and Fatigue Hazard Risk Analysis

Risk-based assessment of a corroded and fatigued jacket component is carried out in the study with special consideration to the established 9 scenarios in Table 3.2.4. The analysis is completed based on the following tools: event tree, scenario outcome, scenarios consequences, qualitative probability and quantitative probability.

The event tree for the scenarios were illustrated in Figure 4.13 and the scenario probability and consequence are presented Figures 4.14 and 4.17 respectively. The quantitative probabilities were shown in Figures 4.13 and 4.14 that provided quantitative values for each of the scenario in the risk assessment matrix. Their values were also presented in Table 4.16. Each of the scenarios is simulated by specifying "Yes" or "No". The probability factors of 90 or 70% also applied to highly likely scenarios and 10% or 30% for low likely scenarios. The assumption considered in the hazard analysis process is based on the probability factor provided in Table 3.6. The summary of the analysis was finally presented in Tables 4.13 and 4.14.respectively.

The risk analysis process commenced with establishment of event tree in Figure 4.13 based on identifying 9 scenarios provided in the Table 3.5. The analysis of the conditions consequence gives associated risk levels for every scenario in the consequence hierarch (I, II, III, and IV) as revealed in Table 4.16. Qualitative probability shows the level of probability of the event occurrences (high –A & B, medium- C & D, low-E).

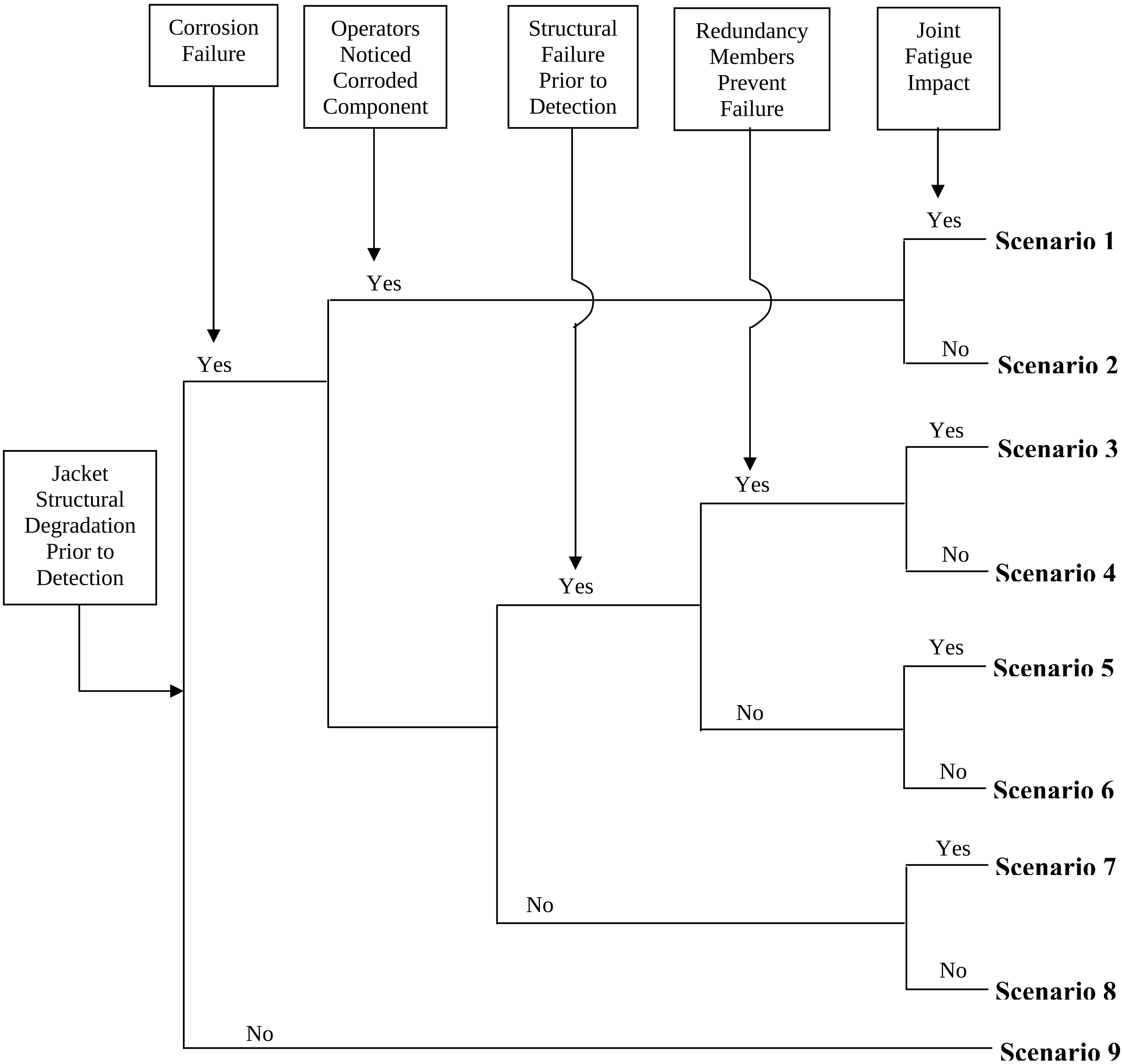
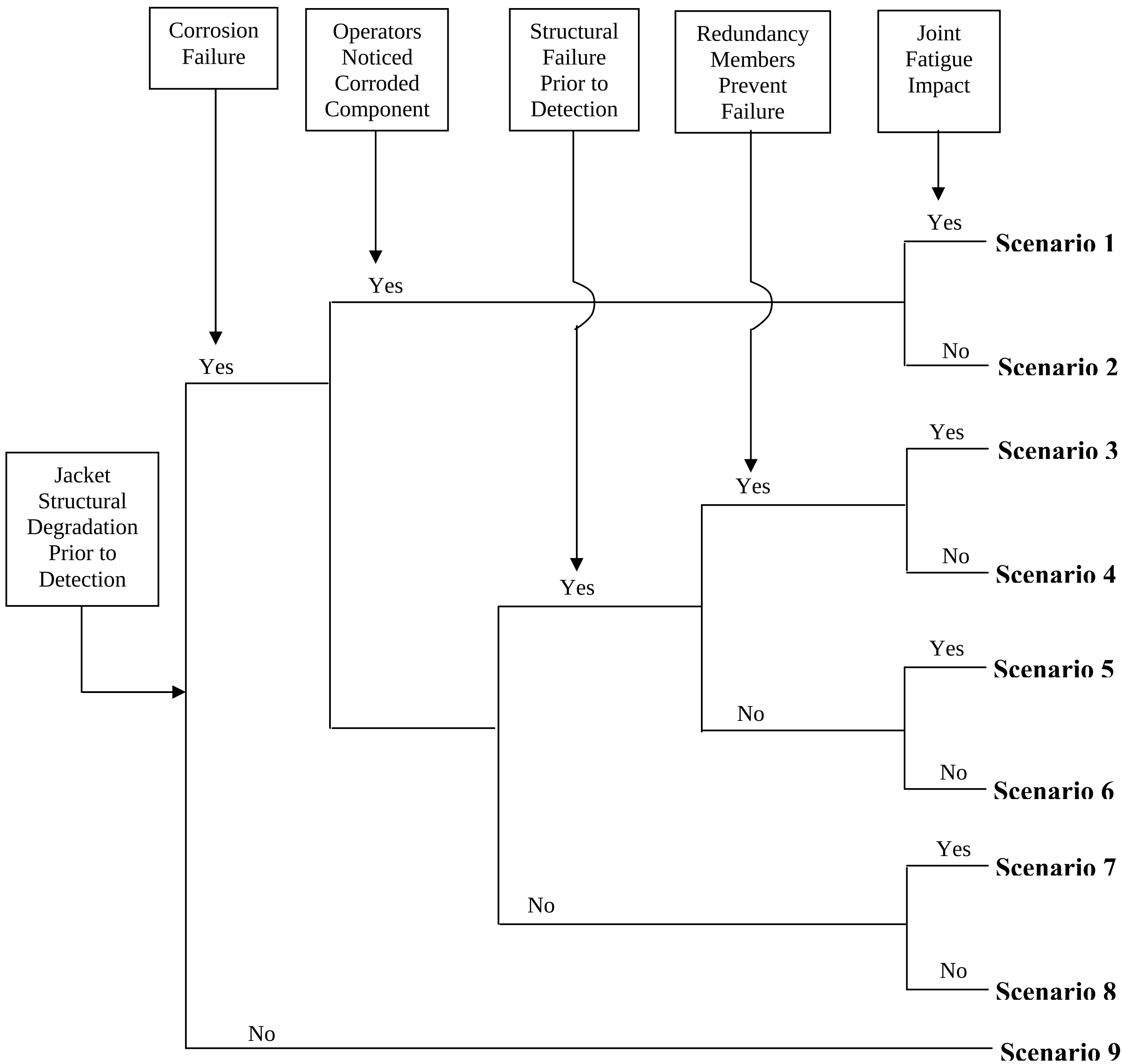


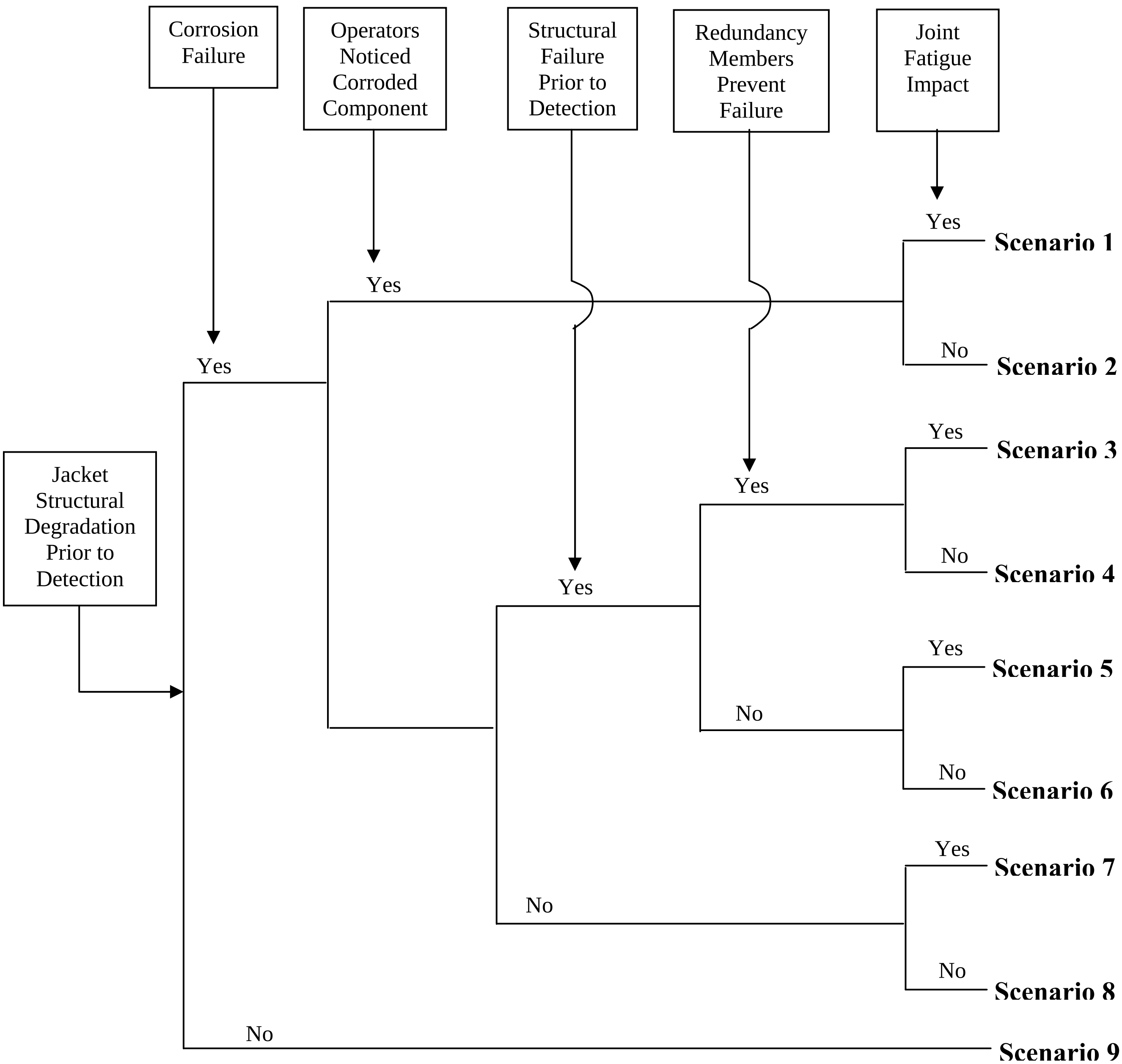
Figure 4.13 Event Tree



Consequences (Health, Public, Financial and Environmental)

Scenario–1: Joint and Member Uniform Corrosion + Little Fatigue; **Scenario–2**: Joint and member Uniform Corrosion + No Fatigue; **Scenario–3**: Joint Localised Corrosion + Little Fatigue; **Scenario–4**: Member Localised Corrosion + Little Fatigue; **Scenario-5**: Member Localised Corrosion + Medium Fatigue; **Scenario–6**: Member Localised Corrosion + No Fatigue; **Scenario–7**: Joint Localised Corrosion + Medium Fatigue; **Scenario–8**: Joint Localised Corrosion + No Fatigue; **Scenario-9**: No Impact

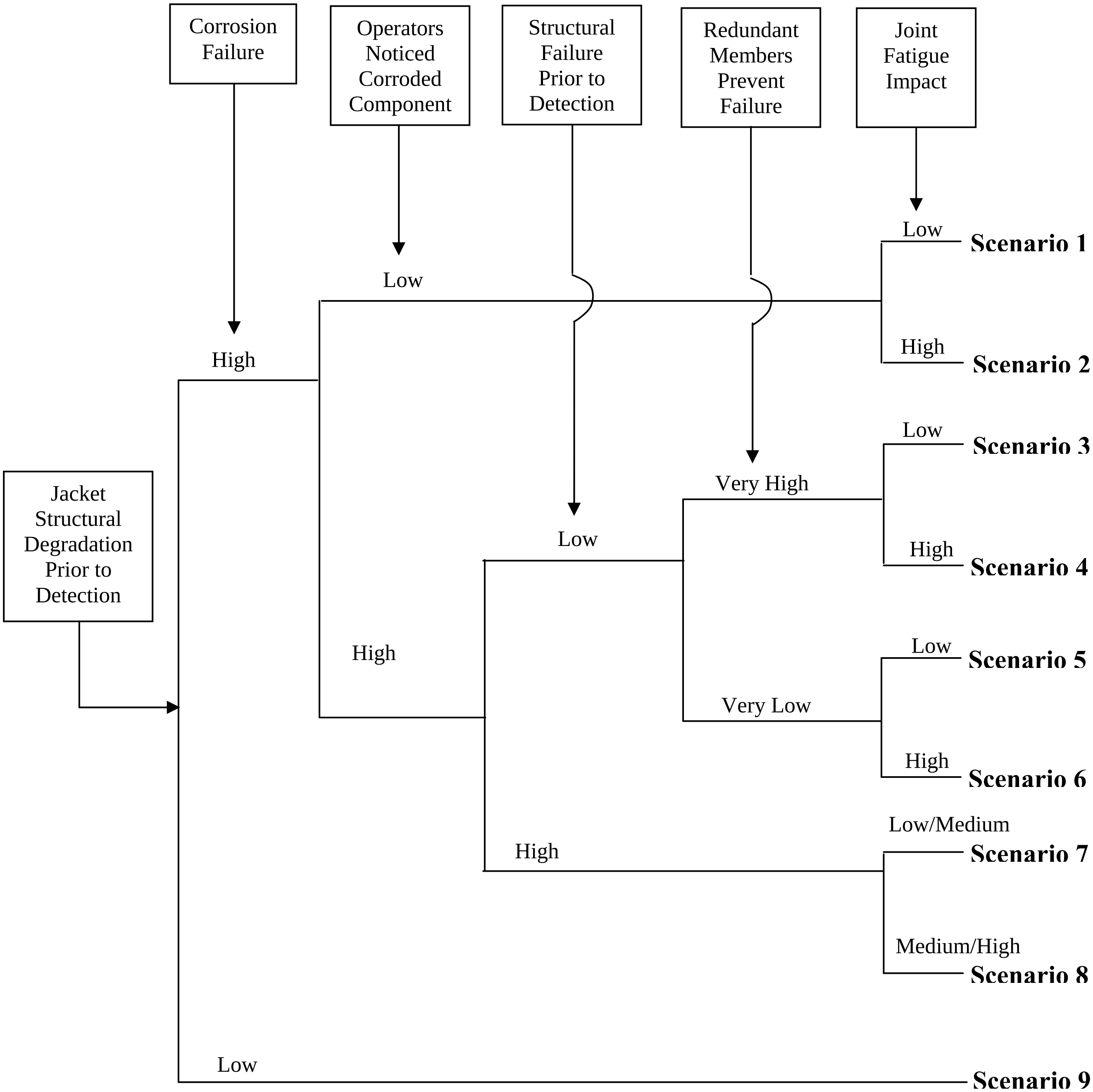
Figure 4.14 Scenarios Outcome



<u>Consequences (Health, Public, Financial and Environmental)</u>

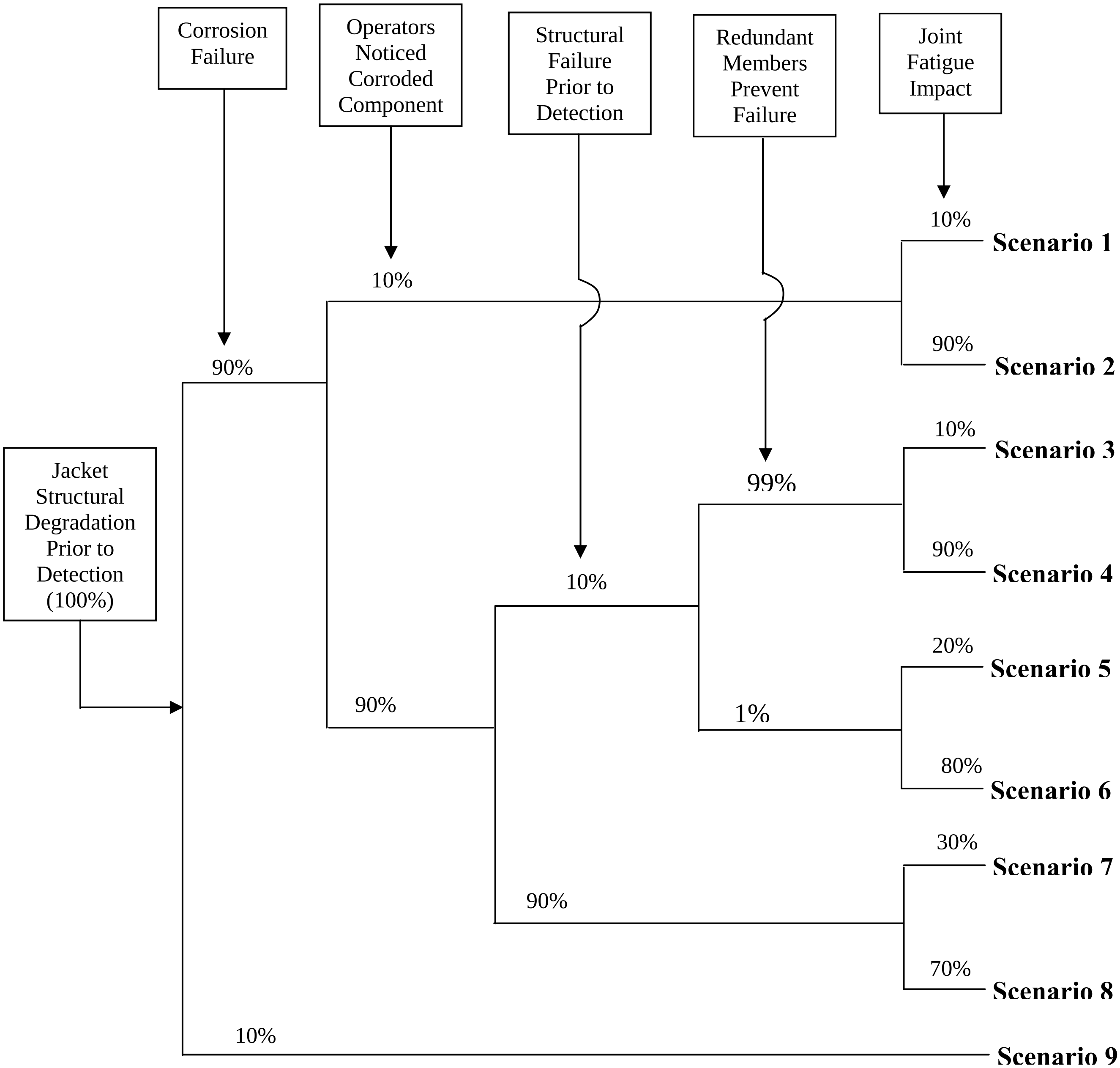
Scenario–1: Joint and member Uniform Corrosion + Little Fatigue **(III)**; **Scenario–2**: Joint and Member Uniform Corrosion + No Fatigue **(IV)**; **Scenario–3**: Joint Localized Corrosion + Little Fatigue **(II)**; **Scenario–4**: Member Localized Corrosion + Little Fatigue **(III)**; **Scenario-5**: Member Localized Corrosion + Medium Fatigue **(II)**; **Scenario–6**: Member Localized Corrosion + No Fatigue **(III); Scenario–7**: Joint Localized Corrosion + Medium Fatigue **(II)**; **Scenario–8**: Joint Localized Corrosion + No Fatigue **(III)**; **Scenario-9**: No Impact **(Not Applicable)**

Figure 4.15, Scenarios Consequences



Scenario 1: **Low**	Scenario 2: **Medium**	Scenario 3: **Low**
Scenario 4: **Medium**	Scenario 5: **Very Low**	Scenario 6: **Low /Very Low**
Scenario 7: **High**	Scenario 8: **High**	Scenario 9: **Medium**

Figure 4.16 Qualitative Probability



Scenario 1: **0.009**	Scenario 2: **0.081**	Scenario 3: **0.008**
Scenario 4: **0.072**	Scenario 5: **0.00016**	Scenario 6: **0.00064**
Scenario 7: **0.219**	Scenario 8: **0.51**	Scenario 9: **0.1**

Figure 4.17 Quantitative Probability

Table 4.13 Event Tree Scenarios

Probability Factors	**Scenarios**								
	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***
Corrosion Failure	***Yes***	***Yes***	***Yes***	***Yes***	***Yes***	***Yes***	***Yes***	***Yes***	***No***
Operators Noticed Corroded Members	***Yes***	***Yes***	***No***	***No***	***No***	***No***	***No***	***No***	***N/A***
Structural Failure Prior to Detect	***N/A***	***N/A***	***Yes***	***Yes***	***Yes***	***Yes***	***No***	***No***	***N/A***
Redundant Members Prevent Failure	***N/A***	***N/A***	***Yes***	***Yes***	***No***	***No***	***N/A***	***N/A***	***N/A***
Joint Fatigue Impact	***No***	***Yes***	***No***	***Yes***	***No***	***Yes***	***No***	***Yes***	***N/A***

Table 4.14 Quantitative Probability Results

Probability Factors	**Scenarios**								
	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***
Corrosion Failure	***90%***	***90%***	***90%***	***90%***	***90%***	***90%***	***90%***	***90%***	***10%***
Operators Noticed Corroded Members	***10%***	***10%***	***90%***	***90%***	***90%***	***90%***	***90%***	***90%***	***N/A***
Structural Failure Prior to Detect	***N/A***	***N/A***	***10%***	***10%***	***90%***	***90%***	***90%***	***90%***	***N/A***
Redundant Members Prevent Failure	***N/A***	***N/A***	***99%***	***99%***	***1%***	***1%***	***N/A***	***N/A***	***N/A***
Joint Fatigue Cracks Impact	***10%***	***90%***	***10%***	***90%***	***20%***	***80%***	***30%***	***70%***	***N/A***
Scenarios Product	***0.009***	***0.081***	***0.008***	***0.072***	***0.0002***	***0.0006***	***0.219***	***0.51***	***0.10***

Table 4.15 **Risks Scenario Analysis Summary**

Probability Factors	***Scenarios***								
	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***
Scenarios Consequences	***III***	***IV***	***II***	***III***	***II***	***III***	***II***	***III***	***N/A***
Qualitative Probability	***Low***	***Med.***	***Low***	***Med***	***Very Low***	***Low/ Very Low***	***High***	***High***	***Med***
Quantitative Probability	***0.009***	***0.081***	***0.008***	***0.072***	***0.0002***	***0.0006***	***0.219***	***0.51***	***0.10***

Table 4.16 Plotting Risk Scenarios on Assessment Matrix

CONSEQUENCE	PROBABILITY →	A	B	C	D	E
	I					
	II		7		3	5
	III		8	4	1	6
	IV			2		

4.5.1 Risk Reduction Technique

The risk levels for the specified 9 scenarios are revealed in the Risk Assessment Matrix (RAM) in Table 4.16. Scenario-7 falls within the highest risk zone on RAM table and consequently required further analysis to reduce the risk level. As scenario-7 risk level is reduced after the application of appropriate hazard mitigation measures, other scenarios with lower risk levels will also reduce further.

The jacket structure in the Niger Delta has two major safety mitigation measures against corrosion in place as listed below in section A.

(A) <u>Preventive Safeguards (in Place)</u>

- **Cathodic protection system (sacrificial or impressed current)**
- **Inspection program**

(B) <u>Mitigation Measures</u>

The following mitigation measures are recommended for further corrosion and fatigue hazard reduction for the jacket structures in the Niger Delta.

- **Introduction of improved structural joint (joint- can)**
- **Corrosion protection devices renewal.**
- **Provision of corrosion allowance.**
- **Good quality welds.**
- **Adherence to platform design life.**

4.5.2 Post Hazard Mitigation Analysis

Subsequent to the above recommended mitigation measures section A and followed by the implementation, corrosion and fatigue hazard are significantly reduced on jacket structure as demonstrated by risk racking for scenario – 7 presented in Table-4.17 and also summarized in section C and D.

Table 4.17 **Scenario -7 Risks Ranking**

R I S K R A N K I N G							
BEFORE RECOMMENDATIONS				AFTER RECOMMENDATIONS			
S_b	P_b	E_b	F_b	S_a	P_a	E_a	F_a
B-II		D-II	C-II	E-II		E-III	E-III

S – Safety, P – Public Disruption, E – Environmental, F – Financial
$_b$ = before recommendations, $_a$ = after recommendations

(C) <u>Before Implementation of Mitigation Measures</u>

- **Safety before mitigation - Risk in Zone 1 - Higher risk (BII)**
- **Safety after mitigation - Risk in Zone 2 - Medium risk (EII)**
- **Environmental before mitigation - Risk in Zone 2 - Medium risk (DII)**

(D) <u>After Implementation of Mitigation Measures</u>

- **Environmental after mitigation - Risk in Zone 3 - Lower risk (EIII)**
- **Financial before mitigation - Risk in Zone 2 - Medium risk (CII)**
- **Financial after mitigation -Risk in Zone 3 - Lower risk (EIII)**

The risk-based assessment performed in this study with special consideration to corrosion and fatigue hazard established jacket structure operation safety in an offshore environment. An understanding of mechanisms that leads to components damage has been provided for the appropriate inspection technique and failure preventive measures. The inspection exercise carried out in the study revealed that jacket components may corrode at the same time subjected to fatigue damage. The study determines risk levels associated with corrosion and fatigue hazard based on the various stages of component damages.

The risk-based assessment carried out in this work includes group discussion and communication with other colleagues in the industry as regards to categorization of corrosion and fatigue hazard. Different damage scenarios are considered with several mitigation measures. The risk analysis is performed based on scenarios consequences and failure probabilities. The consequence hierarchies versus probability of damage occurrence revealed individual scenarios risk levels in the RAM table. Scenario-7 (localised corrosion and medium fatigue) falls within the highest risk zone on RAM table and therefore recommended for mitigation measures.

Material selection is very important activities during engineering design and construction phases and this is done based on several consideration and agreements. The final material selection should be an accord between technical competence and economic factors of the substance. In recommending material for offshore construction, there is a need to list the structure requirements to evaluate the

candidate materials before choosing the most effective. Selection of material is process influence by what it be used for, either for new construction or repairs. In case of a new construction the selection process should start early before the design is finalized by considering the following factors.

- **Mechanical properties of material (material composition, strength etc)**
- **Corrosion resistance bearing of material, mostly in aggressive environment**
- **Service temperature and chemical resistance**
- **Fabricability and welding property of material**
- **Material thermal conductivity**
- **Material availability**

All the above factors are well represented and guided with Industrial Standards in oil and gas industry, such as NACE, API, ASME, ASTM, NORSOK, and DIN. For a repair purpose, there may be less opportunity for a new material selection and the major factors will be centered on simplicity of fabrication on the site and the remaining life span of the facilities to avoid over-designing when considering corrosion allowance.

The inspection outcome of jacket structures in the Niger Delta confirmed that the structures are only protected against corrosion with the application of sacrificial and impressed current cathodic protection systems. Also, inspection is not conducted by the operators on the structure unless new facilities are about to be added. The total prevention of corrosion and fatigue risk are not possible for now as regards to jacket structures. However, the listed measures and guidelines proposed

in the section B above are recommended to mitigate corrosion and fatigue damage on jacket structure.

The risk-based analysis conducted in this study revealed that the combination of corrosion and fatigue hazard exhibit unacceptable risk level threatening the integrity of the jacket structure, in the Niger Delta. The study concludes that after implementation of the above mentioned mitigation measures, corrosion and fatigue risk level is notably reduced as demonstrated in the risk analysis carried out for scenario – 7 summarized in Table-4.18.

Table 4.18 **Scenario -7 Risks Ranking Summary**

SCENARIO -7, RISK STATUS			
S/N	**DESCRIPTIONS**	**BEFORE RECOMMENDATIONS**	**AFTER RECOMMENDATIONS**
1	Structural Safety	B-II (Higher Risk) Risk Zone - 1	E-II (Medium Risk) Risk Zone - 2
2	Public Disruption	Not Applicable	Not Applicable
3	Environmental	D-II (Medium Risk) Risk Zone - 2	E-III (Low Risk) Risk Zone - 3
4	Financial	C-II (Medium Risk) Risk Zone - 2	E-III (Low Risk) Risk Zone - 3

The result of the risk-based assessment demonstrates that jacket structures required survey rules in order to control corrosion and fatigue damages in support of API RP 2A, 2000 recommendation, which stated that marine structures required frequent inspection. Jacket compositions with limited access for inspection has been noted for corrosion and fatigue damage and this area are recommended for high fatigue safety factors during the design stage and effective corrosion mitigation. Emphasis is laid in this study on cathodic protection system revalidation been currently the

most cost effective solutions for the protection of the jacket structure against corrosion in the Niger Delta. The study also recognized the high cost, logistics and environmental concerns involved in replacing depleted anodes. Therefore, recommend non-weld retrofit options that cut down on cost and reduce installation time.

The widespread failure of jacket platforms has been frequently due to the progressive damage to the structure as a result of corrosion and fatigue hazard. Failure will either start with corroded member or a tiny crack in a weld that develops into a through-thickness crack after which the structure begins to lose some resistance against collapse. When a jacket platform in a condition exposed to large wave loads, the structure strength will further reduce as may happen during hurricane and strong rain storm. Hurricane Ivan is one of the several hurricane reported that have damaged offshore jacket platforms in the Gulf of Mexico in recent years. The inspection of the damaged platform showed that the majority of the structures damaged is confined to older jacket platforms attacked by corrosion and fatigue hazard.

Investigation into the failed platform shows that associated jacket structure components were previously damaged by corrosion and fatigue prior to the occurrence of hurricane Lilli. The EI-322 ‘A’ complex platforms in Plate 4.1 found to be seriously suffered from jacket legs, braces and joints damages after the hurricane incident. This kind of damage was found to be peculiar to the platform designed in the late 1970’s, due to deficiency in jacket structure joint formulations.

The large number of jacket platform in the Niger Delta belongs to this category as shown in Plate 4.2.

Plate 4.1 EI-322 'A' complex after Hurricane Lilli (DeFranco et al 2004)

Plate 4.2 Typical Production Jacket Platform in the Niger Delta

Improvement in the jacket structure joint design formulations using joint-can (thicker walled section of the through member) proposed in the study to replace the usual simple joint and prevent joint and member failures. Simple joint may be defined as those, which are without overlapping braces, internal or external stiffening. The outcome of this research work has given practical application to jacket structure assessment against failures, knowing very well that the reliability of the existing jacket structure is imperative for the continuous oil and gas production in the Niger Delta. Since more than half of Nigerian daily crude oil production is via jacket platform with associated pipeline and subsea manifold.

4.6 Summary of Findings

The general conclusions of this research work on offshore structure corrosion damage evaluation, structural reliability assessment of existing jacket platform and risk-based assessment of corrosion and fatigue hazard are summarized in Table 4.19.

Table 4.19 Summary of Findings

S/N	OBJECTIVES	FINDINGS
1	To investigate chlorine accumulation and diffusion process around offshore jacket platform structures.	(a) Fick's law of diffusion was established to account for chlorine-ion accumulation around offshore jacket structures. (b) The Law of diffusion was also acoupled with advection term as a result of seawater continuous movement.

2	**To analyse jacket platform structure corrosion losses in an offshore environment.**	**(a) Jacket structure corrosion losses and fatigued joints were revealed to be higher in the splash zone than any other tide zones.** **(b) The period required for marine steel structures to expriense corrosion damage is longer for coated structure than uncoated structure.**
3	**To develop reliability assessment method of offshore jacket structures.**	**(a) An innovative model for jacket structure reliability method was developed using series and parallel reliability theories.** **(c) Reliability Factor (R_F) was established to indicate the appropriate time for the abandonment of the corroded jacket platform.**
4	**To perform a risk-based assessment with regards to corrosion and fatigue hazard**	**(a) The risk-based assessment method was capable of analyzing several damage scenarios, which make it superior to deterministic approach.** **(b) The study revealed that steel component acting upon by localised corrosion and fatigue hazard concurrently exhibit failure probability and consequence of failure of B and II respectively.** **(c) The reduction in the risk level of damage scenarios in Risk Matrix Table by application of mitigation measures, increases the safety, environmental and financial benefit of the system.**

CHAPTER FIVE

5.0 CONCLUSION

From the research work it can be concluded that:

1. **The seawater within an offshore jacket structure in the Niger Delta, Nigeria was characterized by high chlorine-ion concentration of 3.8%, a chloride accumulation rate of (1.8 mol/m^3/yr) for average ocean wave velocity of 0.47m/s.**

2. **The structural reliability assessment for the corroded jacket structures was established, and the value was 0.858.**

3. **The Reliability Factor (RF) of a corroded jacket structure was estimated to be 1.17, which is less than 1.25 recommended for the corroded jacket platform abandonment.**

4. **Scenario-7 (localised corrosion and medium fatigue) with consequence class II and occurrence probability of group B, falls within the highest risk zone on the Risk Assessment Matrix table.**

5.1 Recommendations of the Study

In order to ensure the establishment of an effective prevetion of offshore jacket structures against unexpected failure, the following recommendadtions are strongly proposed as deduced from the study.

1. **The relationship between chlorine-ion accumulation and diffusion established within the offshore jacket structure characterized by accidental ion release be appropriately applied for monitoring jacket structure corrosion damage.**

2. **A parameter, known as a Reliability Factor (RF) derived in the study to indicate the appropriate time for the corroded jacket platform abandonment.**

3. **A low cost and appropriate jacket structure reliability assessment technique was developed to evaluate offshore jacket platform structural safety.**

4. **The established risk-based assessment technique provides appropriate analysis procedure for hazard and risk management for offshore jacket platform.**

5. **Improved jacket structural joint construction known as joint-can must be estabilished to replace the existing simple joint with less resistance to fatigue and corrosion damages.**

6.0 REFERENCES

Aghakouchak A. and Stiemer. S.F. (2001). "Fatigue Reliability Assessment of Tubular Joints of existing offshore structures". Canadian Journal of Civil Engineering, Vol. 28, pp.691-698.

Andrade, C., and Gonzalez, J. A, "Effect of Carbonation, Chloride and Relative Ambient Humidity on the Corrosion of Galvanized Rebars Embedded in Concrete," British Corrosion Journal. 1982,Vol.17pp.

API RP-2A WSD (2000). Recommended Practice for Planning, design and constructing fixed offshore platforms – Working Stress Design. API Recommended practice 2A-WSD Twenty-first edition, December 2000.

Atul Kumar, Dilip Kumar Jaiswal and Naveen Kumar (2009), Analytical solutions of one-dimensional advection-diffusion equation with variable coefficients in a finite domain, J. Earth System Science, 118, No. 5, pp. 539-549.

Au S.K. and Beck J. L., (1999), "A new adaptive importance sampling scheme for reliability calculation", Structural Safety, Vol. 21, pp. 135-158.

Aven T. and Rettedal W.K. (1998). Bayesian frameworks for integrating QRA and SRA methods. Journal of Structural Safety, Elsevier, Oxford, Vol. 20, pp 155-165.

Beden S. M, Abdullah and Ariffin A. K. (2009), Review of Fatigue Crack Propagation Model for Metallic Components. European Journal of Scientific Research Vol. 28 N0. 3 pp. 364 – 397.

Bedford T.J. and Cooke R.M. (2001). "Probability density decomposition for conditionally dependent random variables modeled by vines". *Annals of* Mathematics and Artificial Intelligence, 32:245–268.

Bokalrud T. and Karlsen A., (1982), "Control of Fatigue Failure in Ship Hulls by Ultrasonic Inspection", Norwegian Maritime Research, Vol. 10, No. 1, pp. 9-15.

Bucher C.G. and Bourgund U., (1990), " A Fast and Efficient Response Surface Approach for Structural Reliability Problems", Structural Safety, Vol. 7, pp. 57-66.

Ciampoli Marcello (1999) A probabilistic methodology to assess the reliability of deteriorating structural elements, Computer Methods in Applied Mechanics and Engineering, Volume 168, Issues 1-4, 6 January 1999, pp 207-220.

Collins J.A. (1993), Failure of Materials in Mechanical Design Analysis, Prediction, Prevention. John Wiley & Son, New York pp. 16-78.

Corrosion Basis Course, LaQue F.I. Chapter 2, Introduction to Corrosion NACE, HoustonTEXAS1970http//:www.Corrosion-Dorctors.org/Corrosion-History/Course.ht#Corrosion Assessed on Friday October 5, 2012.

Dagmar Schmidi Etkin. 1998. Financial Cost of Oil Spills in the United States. Ph.D Thesis. Cuttar Information Corporation, Arlington M.A, United States of America.

Damir Semenski, Hinko Wolf, (2005), "Risk Assessment of Structural Elements of the Offshore Gas and Oil Platforms", University of Zagreb, Department of Mechanical Engineering pp. 516-528

Daniel Straub (2004) Generic Approaches to Risk-based Inspection for Steel Structures. PhD Thesis, Swiss Federal Institute of Technology, Department of Civil Engineering, Zurich.

DeFranco S.J., Fitzhugh J.T., Locke H.A., O'Connor P.E., Straub T.J. and Morahan D.J. (2004). Eugene Island 322 'A' Drilling Platform Decommissioning After Hurricane Lilli. Offshore Technology Conference Proceedings 2004, Houston, Texas, USA, May 3rd - 6th .

Dillion C.P., Forms of Corrosion Recognation and Prevention (2006). An official NACE International Publication Vol. 1 pp45

Emi H, Yuasa M, Kumano A, Arima T, Yamamoto N, Umino M. (1993) study on life assessment of ships and offshore structures (3rd report: corrosion control and condition evaluation for a long life service of ship). Journal of Society of Naval Architect Japan 1993, Vol. 174, pp. 735–44.

Ersdal, G. (2002). On safety of fixed offshore structures, failure paths and barriers, Proceedings of OMAE 2002, the 21st International Conference on Offshore Mechanics andArtic Engineering, Oslo Norway.

Ersdal, G. and Friis-Hansen, A. (2004). "Safety barriers in offshore drill rigs derived from accident investigation, Proceedings of OMAE 2004, the 23rd International Conference on Offshore, Stavanger Norway

Etube, L.S. (2001). Fatigue and Fracture Mechanics of Offshore Structures. Professional Engineering Publishing Limited, London, UK.1st Edition.

Faber M.H., Sorensen J.D. (1999). Aspects of Inspection Planning – Quality and Quantity. Proceeding. Sydney ICASP8 pp. 739 – 746.

Faber M.H., Sorensen J.D., Rackwitz R., Thoft-christensen P., Bryla P. (1992B). Reliability Analysis of an Offshore Structures, 11th Offshore Mechanics and Arctic Engineering Conference, Calgary, Vol II, pp. 449-455.

Freeze R. A. and J.A. Cherry (1979), Ground water Englewood Cliffs, New Jerse, Prenticent Hall.

Gerhard Ersdal (2005). Assessment of Existing Offshore Structures for Life Extension. PhD study University of Stavanger Norway, ISBN 82-7644-273-0, ISSN 0809-6775.

Gonzalez, J. A; Rodriguez, P and Feliu, S; Steel corrosion rates, which start to introduce problems in reinforced concrete structures', 1st Mexican Symposium and 2nd International Workshop Metallic Corrosion , Merida, Yucatan (Mexico) March 1994.

Guedes Soares and Garbatov: (1998), "Reliability Assessment of Maintained Ship Hulls with Correlated Corroded Elements, Unit for Marine Technology and

Engineering, Instituto Superior Tecnico, Universidade Tecnica de Lisboa Paris 1096, Portugal, Marine Structures pp.629-653.

Guedes Soares. C and Garbatov. Y, (1999), Reliability of maintained, corrosion protected plates subjected to non-linear corrosion and compressive loads, Unit of Marine Technology and Engineering, Technical University of Lisbon, Instituto Superior Técnico, Av. Rovisco Pais, 1096 Lisboa, Portugal

Haagensen, P.J. and Skallerud, B. (2004). Fatigue assessment and testing of a repaired tubular T-joint. Proceedings of OMAE 2004, the 23rd Offshore Mechanics and Arctic Engineering, Vancouver, Canada.

Haver, S., Eik, K.J. and Nygaard, E. (2002). Reliability assessment of a generic jacket –effects of airgap choices and current modelling. Proceedings of OMAE 2002, the 21st International Conference on Offshore Mechanics and Artic Engineering. June 23-28, 2002, Oslo, Norway.

ISO (2002) ISO 19900 Petroleum and natural gas industries – Offshore structures – Part 1: General requirements. International Standardization Organization.

ISO (2004). ISO/DIS 19902 Design of fixed steel jackets. DIS Draft. International Standardization Organization.

Kallaby, J. and O'Connor P.E. (1994). "An integrated approach for underwater survey and damage assessment of offshore Platforms", OTC 7487, Offshore Technology Conference Proceedings, Houston, May 1994

Kvitrud, A., Ersdal, G. and Leonardsen, R.L. (2001). On the Risk of Structural failure on Norwegian Offshore Installations, Procedings of ISOPE 2001, 11th

International Offshore and Polar Engineering Conference, Stavanger, Norway.

Marcello Ciampoli (1999) A probabilistic methodology to assess the reliability of deteriorating structural elements, Computer Methods in Applied Mechanics and Engineering, Vol. 168, Issues 1-4, 6 January 1999, pp. 207-220

Martin Smith & Colin Bowley and Lucian Williams, (2002) "In Situ Protection of Splash Zones" Winn & Coales Ltd Paper 02214.

Meijers S. J. H. (2003) Computational Modeling of Chloride Ingress in Concrete. 2003, PhD study Delft University Nertheland , ISBN 90-407-2386-9.

Melchers RE. Corrosion uncertainty modelling of steel structures. Journal Constructional Steel Research 1999, Vol. 52: pp. 3–19.

Melchers, R.E (2003). Assessment of existing structures – approaches and research needs, Journal of structural engineering, April 2001,Vol 27, pp. 406-411.

Moan, T. (1997). Target levels for structural reliability and risk analysis of offshore structures. in Risk and Reliability in Marine Technology. Edited by C. Guedes Soares. A.A. Balkema, Rotterdam.

Moan, T. (2005). Reliability-based Management of Inspection, Maintenance and Repair of Offshore Structures. Journal of Structures and Infrastructure Engineering, Taylor & Francis Publication, Vol. 1, No 1, pp. 33 – 62.

Moan T.. Vardal O.T. (2001). Probabilistic assessment of fatigue reliability of existing offshore platforms. Proc. ICOSSAR 2001. Newport Beach, California.

Nicholas Summerville, (2004) Basic Reliability, An introduction to Reliability Engineering, AuthorHouse, Bloomington, Indiana USA, ISBN 1-4184-2417-X(e).

Pereira, M. (2004). Growth of through-wall fatigue cracks in brace members. Research report 224. Health & Safety Executive, HSE Books.

Pierre. R. Roberge (1999), Handbook of Corrosion Engineering McGraw-Hill, New York USA, ISBN 07-076516-2.

Postlethwaite. J, Neesic. S and Adamopoulos (1992), Modelling Local Mass-Transfer Controlled Corrosion at Geometrical Irregularities.Vasenals Science Forum Vol. 111-112 pp. 53-62.

Rodriguez. J; Ortega, L. M; Casal, J; 1997. Load carrying capacity of concrete structures with corroded reinforcement, Construction and Building Materials, 11(4) pp. 239-248.

Santala M. J. (2002). Eastern Nigeria Shallow Water Metocean Criteria: Version 1.2, Engineering Research Application Report Offshore Division, Houston USA, URC.2002PS.022.

Sharp J.V., (1992)," Ageing offshore structures: a review of recent UK research", Offshore Mechanics and Arctic Engineering, OMAE 1992, V. III-B, Material Engineering, pp. 391-398.

Sobezyk .K, Spencer B.F. Jr. (1992), Randon Fatigue from Data to Theory, Academc Press, Boston pp. 1 – 266.

Sorensen, J.D and Faber, M.H. (2002). Codified Risk-based Inspection Planning. Journal of Structural Engineering International, Vol. 12, No. 3, 2002, pp. 195-199.

Sprouge John. (1999). A Guide to Quantitative Risk Assessment for Offshore Installations. DNV Technica Publication, Hovik Oslo, Norway. 1st Edition. ISBN: 1-870553-365.

Stacey A., Birkinshaw M. and Sharp J.V. (2002). Reassessment issues in life cycle structural integrity management of fixed steel installations. Proceedings of OMAE 2002, the 21st.

Vinnem J.E., Aven, T., Sorum, M and Oien K. (2003). Structured approach to risk indicators for major hazard. In Proceedings of ESREL 2003. Maastricht, The Netherlands, June 15- 18, 2003.

Yong Bai, (2003) Marine structural Design, Elsevier Amsterdam. 1st Edition. ISBN: 0-08-043921-7.

Youping Liu (1998), Modeling the Time-to-Corrosion Cracking of the Cover Concrete in Chloride Contaminated Reinforced Concrete Structures, PhD dissertation submitted to Virginia State University, Department of Civil Engineering, Blacksburg Virgina.