Corrosion Effects on Structural Reliability of an Aging Jacket Platform in Malaysian Waters

by

Low Zhen Teng

14966

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Civil)

JANUARY 2015

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

ABSTRACT

There are much more concerns nowadays on the reliability and integrity asset management of oil and gas sector since that this industry is always being viewed as an ever-changing large scale development under complex environment. In facts, two problems have been identified in this project. Firstly, In Malaysian water where jacket structure is highly adopted as the offshore platforms, 65% these structures are found to be operating exceed its original design life. In addition to the extra loading and fatigue imposed on the jacket members, one of the biggest obstacles being faced by offshore operator is corrosion; which addresses the second problem. In facts, corrosion is a detrimental process which causes material loss and member strength degradation. Putting together these issues, this project aims to analyze corrosion effects on structural reliability of an aging jacket platform in Malaysian water.

From the scope, this project will first review and select an adequate offshore jacket platform as the main source of study. In this case, platform F9, an asset from PETRONAS Carigali Sendirian Berhad located at Sarawak water is chosen. In this project, the structure is assumed to be subjected to general corrosion which is the uniformly distributed material loss with length and width more than three times of the un-corroded wall thickness. Apart from that, the corrosion will be simulated on splash zone of the jacket because this location consists of most critical members in the structure with substantive exposure to corrosion. In particular, the splash zone will be further divided into three groups and applied with different percentages of material loss in order to obtain a comprehensive comparison between members.

In order to address the project objective, the model for F9 will first be simulated in Structural In-place Analysis and Computer Modeling Software (SACS). Each of the member segments area in the predefined group will then be reduced to account for corrosion. Next, non-linear pushover analysis will be done on each set of model to compute the ultimate strength and derive Reserve Strength Ratio upon first member failure and platform collapsing. With the input from SACS analysis, reliability analysis will be conducted in MATLAB. In this stage, series of algorithm will be utilized to derive reliability index of the particular jacket platform. Ultimately, the final result will be expressed in term of probability of failure and to be compared with previous researches as well as industrial benchmark.

ACKNOWLEDGEMENT

First and foremost, I would like express my appreciation to my Final Year Project Supervisor, Professor Dr. Kurian Velluruzhathil John for providing substantive support to my project. His guidance has made this course an enjoyable yet valuable journey.

Meanwhiles, I would like to express my sincere gratitude to Ir. Mohamed Mubarak bin Abdul Wahab for setting aside quality time to guide me in my project. His initiative and support is a catalyst for me to advance further. In addition, the appreciation is addressed to Dr Muhammad Raza Ul Mustafa, coordinator of Final Year Project II for his assistance in arranging seminars and organinzing the course structure throughout the program.

Apart from that, I also whole heartedly thanks to Dr Ng Cheng Yee as my internal examiner for her advices and generosity in evaluating my project. In addition, I would also like to extend my deep appreciation to my external examiner, Mr. Nigel Wayne Nichols for his willingfullness to share his knowledge and provide constructive comment to my project.

Not to forget, special thanks to my dear parents who have been the source of my willpower and motivation throughout my life. Especially during my final year of study, they have been fully supportive and caring.

Thank you.

TABLE OF CONTENTS

LIST OF FIGURE

LIST OF TABLE

CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

1.1 Background

Over the past decades, exploration and production technologies in Malaysia upstream industry had been improving by leaps and bounds, particularly in deep water areas to enhance field productivity. With regard to enhanced oil recovery, demand for effective asset management had been escalating. While the resource optimization is being prioritized, integrity and reliability of the offshore structures should not be compromised. In specific, 65% of offshore platforms in Malaysian Water were found to be exceeding the original design life which range from 20-30 years (Wong, Ayob, Kajuputra & Mukherjee, 2014). With respect to these predicaments, there are much more concerns nowadays on the ability of structure to withstand loadings in which it may not have been originally designed for.

In addition to these loadings, offshore platforms were substantively subjected to environmental loading such as wave, wind and tidal as well as varies uncertainties throughout its service life. For instances, jacket legs platform which utilizes steel structure to provide a firm support at water depth less than 200 meters are prone to corrosion due to significant exposure in seawater immersion. For a corrosion to take place, corroded metal will lost its electron to water and oxygen, forming hydroxyl ion. These ions will then react with ferrous ions and further oxidized to produce hydrated ferric oxide, brownish rust that are commonly observed. Further deterioration will not only damage the structure but also substantively degrade platform's capacity to perform its designated functions.

Meanwhile, reliability is the probability that a system will deliver its function over a specific period of time. In particular, structural reliability governs the process to calculate and predict the chance of limit state violations at any stage during structure's life. Within this reliability framework, there are two major concerns governing the outcome, namely load on system and structural capacity. System load is a random variable with stochastic process within a given time horizon (Melchers, 2005). On the other hand, structural capacity is a function of strength which is subjected to uncertainties in terms of fatigue and corrosion. In the worst case scenario, upcrossing of system load beyond its capacity results in structural failure. From both elements, uncertainty is a crucial to express the relative frequency of certain realizations for random variables.

Relationship between corrosion as the uncertainty and the structural system resistance can thereby be scrutinized through several means, one of it involve static pushover analysis. As a non-linear method, characteristics of jacket steel members in plastic stage are fully utilized in order to predict deformation imposed on structures. In this case, similar theory is adopted to determine the ultimate capacity with responses to environmental loading. In particular, this analysis simulates possible variation of components and applies factored extreme design events to the extent that first member failure or structural collpase had taken place. While the iterative analysis is running, potential failure of various structural components can be observed and monitored from every single load step. The program will be terminated given that prescribed criteria are satisfied.

Based on the output from pushover analysis, Reserve Strength Ratio (RSR), as the ratio of failure strength with design strength can then be formulated as an approach to examine the structural reliability. Eventually, final results will be expressed in terms of probability of failure for different corrosion cases occurred on critical zones in jacket members. From civil engineering perspectives, the use of relevant corrosion data and existing Malaysian Water jacket platform model in conducting this study is vital to adequately reflect the actual condition.

1.2 Problem Statement

In Malaysian water where jacket platform design is highly adopted, it was found out that many of these offshore structures are currently operating beyond the design life. With on-going corrosion being taken place on aging upstream facilities, structure reliability and operation will be affected. The implication of corrosion is an imperative factor to review the reliability while justifying the adequacy of these structures. This paper relates corrosion impact on structural reliability through determination of Reserve Strength Ratio which will be further derived into the probability of platform failure.

1.3 Objective And Scope Of Study

This project aims to analyze corrosion effects on structural reliability of an aging jacket platform in Malaysian water. With respect to the objective, the implication of material loss and deterioration will be related to the structure ultimate capacity degradation. Information on corrosion are gathered and simulated on jacket platforms of Malaysian water which scatters across Peninsular Malaysia, Sabah and Sarawak. To date, there are approximately 300 fixed offshore structures that are mostly located at shallow water and operating exceed its design life, thereby being termed as "aging platform" (Zawawi, Liew & Na, 2012). In this project, platform F9, a four-legged jacket platform from PETRONAS Carigali Sendirian Berhad (PCSB) located at Sarawak water will be used as the main source of study. Based on the corrosion data, the structural reliability will be scrutinized by looking into the Reserve Strength Ratio (RSR) of F9 platform which is determined from non-linear pushover analysis. After that, from a probabilistic approach, RSR will be used as an input together with specific algorithm to compute final result in terms of probability of platform failure.

At the same time, the scope of the study clearly defines corrosion based on characteristics, principle and model used for the analysis. In specific, being located at the middle of the sea which possesses significant electrolytes that escalate corrosion, jacket structures are highly prone to corrosion despite that cathodic protection and surface coating had been applied. Thus, distinctive differences were observed between corrosion behavior of onshore, coastal and offshore facilities. In this project, two main references will be used throughout the project, namely PETRONAS Technical Standard: Design of Fixed Offshore Structures (Working Stress Design) as well as American Petroleum Institute Recommended Practice 2A-WSD.

In specific, the structure is assumed to be subjected to general corrosion which is the uniformly distributed material loss with length and width more than three times of the un-corroded wall thickness. This paper will mainly focus on aerobic corrosion of offshore jacket structures which occurs under the presence of oxygen throughout the jacket members, to be simulated based on industrial practice, inspection and maintenance guideline adopted from PCSB. Twelve cases of corrosion implication will be generated to provide a useful insight on the results for further comparison and interpretation in later stage.

By that, existing jacket structural model will be simulated in Structural In-place Analysis and Computer Modeling Software (SACS) with the corrosion input. The scope involves modification of steel structural member in static in-place analysis to account for material loss due to deterioration. In facts, the simulation will be conducted on splash zone area of the jacket structure due to its standing as the critical structural region which is subjected to significant corrosion. The splash zone will be further divided into three groups and applied with different percentages of material loss. Since that most of the jacket member is made of tubular section to resist environmental load from all direction in similar behaviors, the material loss will be done through reduction of tubular members' diameter and thickness. Next, from metocean data, incremental load effects will be generated in non-linear pushover analysis on the entire jacket structure that had been subjected to different extents of corrosion. When the structure had yielded and lost its stiffness, its ultimate strength capacity in terms of base shear upon first member failure and collapsing can be determined to compute Reserve Strength Ratio.

Besides, the scope of study will also include the reliability analysis done in MATLAB with principles based on Response Surface Method, a collection of mathematical and statistical techniques for empirical modeling. Meanwhile, probabilistic values of waves, wind and current at Malaysian water will be created to define an algorithm with alterable variables to accommodate different situations. In this case, First Order Reliability Method (FORM) which characterizes these random variables by their first order function expansion will be used. Ultimately, reliability index, β will be computed to represent the probability of failure for particular platform. In overall, this projects aims to address the objectives based on two stages which involved static non-linear analysis and reliability assessment. Both phases are interelated in order to provide a feasible prediction for F9 platform reliability which approaches can be utilized on other platforms in Malaysian water too. It was believed that the determination of β value is imperative in a way that returns period of extreme condition which will cause structure failure can be obtained and disseminated to the platform operators in order to safeguard life, asset and environment.

CHAPTER 2

LITERATURE REVIEW

2.0 LITERATURE REVIEW

While there is much more concerns nowadays on the state-of-the-art technologies in petroleum exploration and production, the structural reliability of offshore platforms should not be looked from a narrow and shallow context. In particular, South China Sea which accommodates most of the Malaysia jacket platforms was described by Qi, Zhang and Shi (2010) as a dynamic, complex sea facing with extreme wind, wave and current stretching all the way along its area from North to South. In line with intense environment across the South China Sea, Wong, Ayob, Kajuputra and Mukherjee (2014) quoted that the ageing offshore structures in Malaysia on South China Sea had been escalating with 65% of it exceeding its design life upon 2014. Under these predicaments, Stacey and Sharp (2007) added that besides than extreme environment loading, offshore installation also cooped up with several failure mechanisms such as fatigue and corrosion.

Generally, jacket legs platforms serve the purpose to support topside at water depths up to 200 meters as well as to withstand environmental and accidental load during oil extraction operation (Honarvar, Bahaari, Asgarian & Alanjari, 2007). Dong, Moan and Gao (2011) too, expressed that besides than oil and gas sector, jacket had been adopted as substructure for wind turbine to withstand cumulative fatigue damage generated by wind loads. Despite these advantages, Rodrigues and Jacob (2005) used the words “redundant” to describe ageing jacket legs structures which are subjected to progressive collapse under failure mode triggered by corrosion and damage. According to the authors, there is a tremendous need to perform global non-linear analysis which identifies the strength reserve between the first member failure and the global failure of the structure. Bao, Wang and Li (2009) had conducted similar pushover analysis for a jacket platform in Bohai, China by modeling the members with large displacement and modifying non-linear beam-column elements as linear elements. From their study on corrosion and damaged members, Residual Strength Factor (RSF) was derived from ratio of ultimate lateral capacity of the degraded platform to original platform, and the lowest RSF was observed along with lowest Reserved Strength Ratio, indicating that particular direction was dangerous case for the platform.

At the same time, Asgarian and Lesani (2009) shared the same perception that similar approach can be used through finite elements model of jacket to observe the structural behavior. In terms of support type, Zhang and Jin (2010) highlighted that bearing capacity with fixed support is larger than that of nonlinear spring support, indicating pile-soil interaction should be simulated from the latter mode for more critical results. In addition, Wong et al. declared that most of the offshore platforms are designed to be fit-for-purpose. However, with plenty of structural degradation mechanisms, reliability and safety of an offshore structure can be exposed to several types of failure and threats. To name a few, they criticized that many of the ageing platforms in Malaysia are experiencing serious corrosion.

From their study on corrosion rate with respect to time, Melchers and Jeffrey (2005) quoted that the relationships between both parameters tend to become non-linear as time goes by. Zhang, Beer, Quek and Choo (2010) elaborated the scenario by dividing corrosion into several phases, namely kinetic, oxygen diffusion and anaerobic stages. From the research done by Zhang et.al, they used a simple plate model to relate the corrosion impact to ultimate resistances which were later subtracted by environmental loads to compute reliability. In the attempt to look after and analyze ageing jacket structures, attention had been given to the prediction of corrosion losses and maximum pit depth (Melchers & Jeffrey). Salau, Esezobor and Omotoso (2011) shared the similar insight that as corrosion areas are spreading, stress concentration developed at the tip of the defect increases. They compared three jacket models with series of data and concluded that structure subjected to corrosion and fatigue was categorized in high risk zone and extremely vulnerable to failure. Momber, Plagemann and Stenzel (2014) termed this phenomenon as “corrosive stress” which plays a significant role together with fatigue stress in jacket degradation. To explain the relationship between mechanical and corrosive stress, a corroded component with fatigue crack is more vulnerable to failure mechanism than uncorroded member with fatigue crack. However, Melchers and Jeffrey expressed that the types of alloy will not significantly govern the corrosion process until bacterial invaded the system. Regardless of the type of steel being used, Wheat and Liu (2005) highlighted that corrosion protection is essential for marine structures while latest technology enables corrosion inhibitor, electrical and chemical sensor to be applied throughout the substructure and topside coating system.

Parameters such as fatigue, corrosion and environmental loads are viewed as uncertainties which help to derive reliable predictions regarding the safety of the engineering structures (Zhang et al.). To scrutinize into this issue, Melchers and Jeffrey used a model within a probabilistic framework to predict the future behavior and performance under these uncertainties. From the results, they expressed that laboratory corrosion model possesses limitation to replicate the actual process taken place during field exposure. To relate it with structure, Zhang et al. added that this probabilistic model express material loss due to corrosion as a function of time. With respect to that, a bias function was introduced to account for difference between predicted loss and actual loss derived from data. Melchers (2005) cited that asset management utilizes reliability analysis to estimate the probability of structure safety within the life cycle. To study on structural reliability, he suggested that First Order Reliability Method (FORM) can be used to approximate the actual probability function with iteration process. By that, effect of corrosion can be interpreted in software based on time-invariant theory. With respect to that, similar reliability assessment using FORM had been done by Silva, Garbatov and Soares (2014) too, to derive at a reliability index which showed that localized corrosion is more likely to cause structural failure comparing to distributed corrosion. However, they pointed out that random corrosion is more likely to be triggered by bacterial corrosion or in the case of liquid accumulation. In randomly distributed corrosion wastage, they reported that the structure responded to corrosion degradation with sharp decrement in reliability index few years after coating failure.

Platform life extension, in another word, delay in decommissioning is crucial for offshore structure to be used beyond its design life without compromising the structural integrity (Solland, Sigurdsson & Ghosal, 2011). Galbraith, Sharp and Terry (2015) addressed the concern that besides than changing loads, fatigue and corrosion, accumulation of changes made for operational effects over the years can also depreciate an offshore structure. Copello and Castelli (2013) claimed that reassessment can be done through the update of model with sufficient data from inspection and monitoring. This statement is agreed by Haagensen, Larsen and Vardal (2014) who pointed out that traditional approach which do not consider the actual site data during design tend to produce conservative estimation of structure life. Wright (2011) in his researched indicated that the key to life extension is to prolong the mature stage of life cycle where the production is steady. With respect to that, Hudson (2009) highlighted that identifying key asset reliability through risk management was crucial to assess the status of structure. Alternatively, from a technical perspective, similar outcome can also be achieved through the comparison of Reserve Strength Ratio (RSR) with standard to measure the ratio between the design loads and the collapse capacity of the structure (Ersdal, 2005). Apart than corrosion and fatigue addressed by Momber et. al, the author also included a wider scope of failure modes in structure which also addressed loss of stability, dropped object and progressive damage. In facts, in order to justify that an ageing offshore platform is fit for purpose, demonstration of adequate performance through structural assessment is a necessary requirement (Galbraith, Sharp & Terry).

There are many different approaches being used to simulate corrosion and reliability. To start with corrosion modeling, Paik and Kim (2012) used actual corrosion data to derive a time-dependent empirical corrosion model for marine structure. From the results, probability density distribution patterns for corrosion were varied and irregular as the ages of structures increased. However, Bekker et. al (2011) criticized that simple probabilistic corrosion model tend to have lesser self-descriptiveness and reliability. Thus, they proposed three types of advanced models, namely regression, deductive and inductive method in simulating corrosion. In facts, the authors showed preference on inductive model due to its accuracy in corrosion damage distribution and stable result throughout the study life. On the other hand, instead of empirical model, Mejri, Cazuguel and Cognard (2010) proposed a similar time-variant simulation but with two dimensional mechanical model to study structure corrosion. Under the complex stochastic loads application and non-linear degradation, the authors highlighted that robust simplified numerical strategies should be utilized to balance between local or global scale modeling. With regard to that, Chaves and Melchers (2014) added that the biggest challenge in this case was the inconsistency of maximum corrosion depths with its ever-changing characteristic from a long-term perspective because it was always being poorly and wrongly estimated or modeled.

Apart from that, Mohd and Paik (2014) used Multifinger Imaging Tools (MIT) to detect the corrosion of well tube which results can be statistically analyzed into probability function for prediction of time-dependent corrosion behavior. The following figure demonstrated the sample of results obtained from the MIT measurement expressed in material loss proposed by Mohd and Paik.

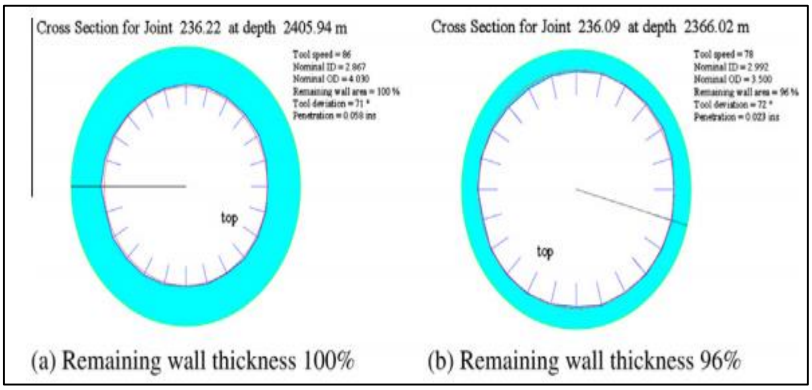


Figure 2.1: Typical Cross Sectional View of a Corroded Tube (Mohd & Paik, 2014)

Sharing the similar view with Mohd and Paik, Wang, Wharton and Shenoi (2014) stressed the importance on material thickness with respect to corrosion by using three types of plates in their study, namely perfect thick, perfect thin and imperfect plates to examine the implication. They believed that various thickness changes due to corrosion imply a necessity to determine the ultimate strength as to rationalize structural behavior with respect to the degradation. Despite the usefulness of corrosion data to be considered into structural members, the implication of corrosion should not be overlooked. Solland, Sigurdsson and Ghosal in one of their case study expressed the concern that when a member degraded, it can possibly increase the failure probability of nearby members. It is due to the reasons that moments and stresses for the degraded members had been redistributed to the surrounding members resulting from large robustness and redundancy of jacket members. Under multiple failure mechanisms and complex predicaments, Wong, Ayob, Mukherjee, Kajuputra and Salleh (2014) used the term of “requalification” to relate the ultimate strength analysis to the reliability of the platform. Thus, similar models being adapted with link to reliability shall be scrutinized next.

Based on Zhang et.al study on uncertainty, a probabilistic corrosion model was implied to measure the impact on ultimate resistance which explicitly affects the overall reliability. Asgarin and Lesani, on the other hand mentioned that pushover analysis as part of reliability test is widely adopted to assess ultimate limit state of jacket structure by applying load and displacement to the extend where the structure collapses. In their research, a non-linear fiber element named as “Fiber Beam-Column Post Buckling Element” is used for the modeling of jacket member behavior within the non-linear deformation and load-displacement range. Similar approach had been used by Wong et al. in determining the ultimate strength of jacket structures in Malaysia water. Based on their case study of an eight-legged jacket leg platform which had been subjected to substantive scouring across the the 15 years’ service life, Wong et.al compared the implication of structure failure and component failure, and reported that vertical bracing of the jacket members are highly subjected to failure upon analysis even though it allows the structure to deflect without collapse. With similar approaches to find the critical location, Kovalenko and Kim (2009) who did durability evaluation of offshore structures concluded that corrosion occurrences were dominated at splash zone and underwater zone rather than above water. In addition, from the limit state equation of global failure mode, Bao, Wang and Li (2009) were able to determine the reliability of the platform with Monte Carlo simulation method. They first computed Reserves Strength Ratio (RSR) by dividing the ultimate lateral capacity in terms of the ultimate base shear to the base shear produced by 100-year return period, and then used the lowest RSR among the load direction for the analysis. There were two important findings from Bao et al. Firstly, the corrosion had greatly impacted the reliability compared to damaged member. Secondly, it was found out that diagonal bracing significantly influent residual strength and system reliability, which agreed upon results obtained by Wong et al. mention earlier.

Critically, most of the previously done researches prioritize on derivation of system reliability based on overall system strength, which are rather straightforward and may have overlooked the importance of structural component roles in strength degradation. Thus, this project aims to fill in the observed gap by providing a more explicit modeling of jacket platform with respect to the corrosion, which will be simulated in reliability analysis eventually. It was believed that the focus on member strength degradation due to material loss utilizes a more direct approach in scrutinizing relationship between corrosion and reliability.

CHAPTER 3

METHODOLOGY

3.0 METHODOLOGY

3.1 Research Methodology

Corresponding to the corrosion which takes place on offshore jacket platforms, the theory adopted will be based on model developed by Melchers. Assumptions are made that corrosion at ageing fixed offshore structure is caused by aerobic corrosion activity in phase one and two as proposed in Melchers's model. In particular, the corrosion is governed by concentration of oxygen and diffusion of oxygen through the rusted area to deteriorate the member. During both phases, corrosion occurs under simultaneous presence of water and oxygen which is highly relevant to the offshore steel structures which have significant exposure to the sea water. Anaerobic corrosion, in this case, is omitted due to information on presence of bacteria is limited.

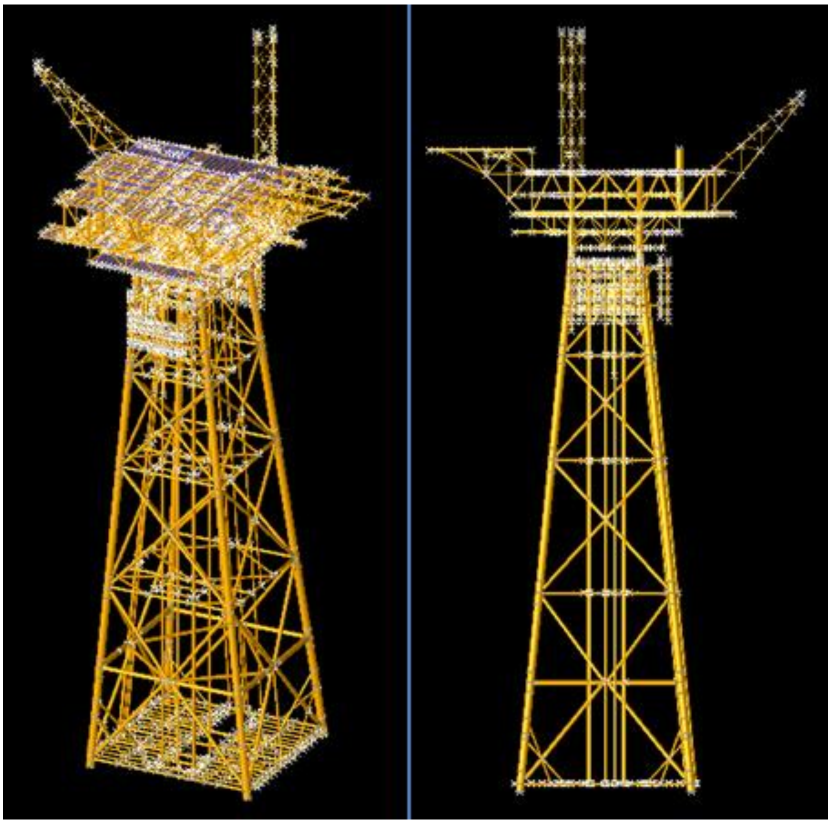


Figure 3.1 An Overview and Perspective of the Studied Platform

In this project, platform F9, an existing four-legged jacket model located at Kumang Cluster, Sarawak water selected from PETRONAS Carigali Sdn. Bhd. assets will be viewed in SACS and modified with respect to the corrosion.

First and foremost, the splash zone area of the jacket platform is identified from the SACS model. From the technical standard provided by PETRONAS, splash zone is defined as that region below +5.0m MSL and above -3.0m MSL for Malaysian waters with seabed subsidence calibration. As explained earlier, splash zone is chosen as the main focus due to its location which is extensively exposed to corrosion effects. Once that all the members located within the splash zone had been selected, the corrosion will be applied on three groups of members:

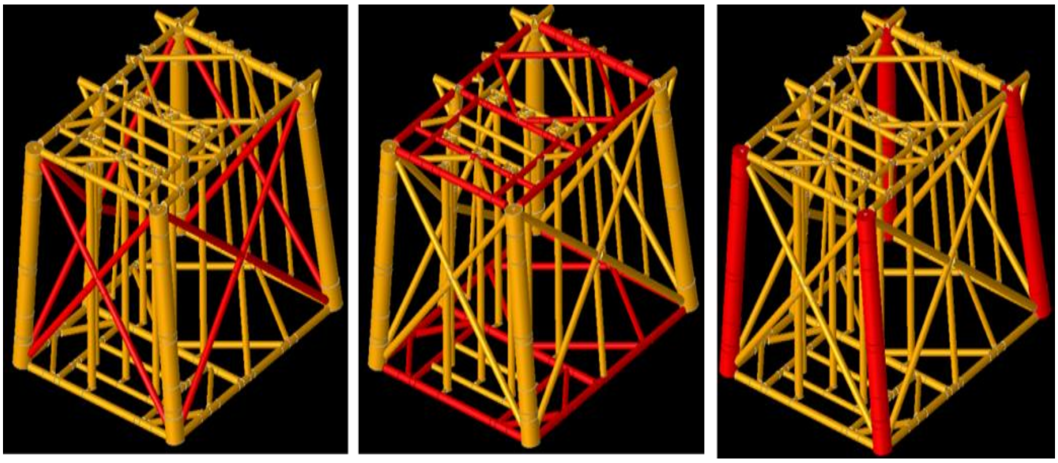


Figure 3.2 Members of Group 1, 2 and 3 (from left) are Highlighted

Table 3.1 Splash Zone Member Classification

Group	Members With Corrosion
1	All the diagonal bracings
2	All the horizontal and vertical bracing
3	All the jacket leg

In each group, the material loss due to corrosion will be expressed in terms of reduction of total volume based on percentages. For example, given that corrosion occurred on particular circular hollow section member. Based on the member dimension, the total volume of steel is computed. Next, the reduction in volume will be applied to calculate remaining volume of steel after corrosion. By that, backward calculation will be used to determine equivalent member diameter assumed than the thickness remained constant. The newly defined equivalent diameter with respect to the corrosion loss will be used to replace the existing member. As the result, smaller diameter is expected to yield more critical result than the original member without corrosion. Nevertheless, similar approach will be repeated by setting the outer diameter as constant in order to calculate equivalent thickness.

As mentioned above, the rate of corrosion will be expressed in terms of reduction in member volume. In this paper, 10% and 25% reduction will be applied respectively. The reason is because based on PCSB topside inspection guideline, material loss more than 25% is considered as advanced deterioration (P1), which will undergo maintenance immediately. Therefore, possibility of splash zone member with deterioration more than 25% is less likely to be existed without replacement for a long period of time. Mean whiles, material loss from 10% - 25% is termed as significant deterioration. By that, four different scenarios will be implemented as summarized in the following table.

Table 3.2 Simulation Cases for Each Group of Member

Simulation	**Material Loss**	**Constant**	**Variable**
Case 1	10.00%	Thickness	Equivalent Diameter
Case 2	10.00%	Diameter	Equivalent Thickness
Case 3	25.00%	Thickness	Equivalent Diameter
Case 4	25.00%	Diameter	Equivalent Thickness

Apart from that, the load case applied on the structures will be combination of dead load and live load. Extra attention should be paid to environmental data which includes wave, wind, current, tidal and even seismic load if applicable. Additional loads due to changes across the years will be added to the original load cases to achieve more accurate outcomes. Once that all the loads had been simulated, the system will determine the critical load combinations and applied to the platform for largest impact during static analysis.

Upon completion of member replacement, push-over analysis will be conducted. The platform model will then be subjected to incremental load until the structure collapse in order to study the consequence of strength deterioration. This type of non-linear approach aims to predict force and deformation demands imposed on the structure. In particular, the storm load and live load will be applied from all eight different directions to determine the most critical direction. However, for platform F9, the total number of analysis for each case will be nine instead of eight due to load combination 07 and 08 are both accounted for load from direction 270° as created by the model file developer. In SACS, collapse files will be inserted alongside with the platform model to iterate the increasing environmental load. The following example had highlighted some of the important aspects within each collapse file:

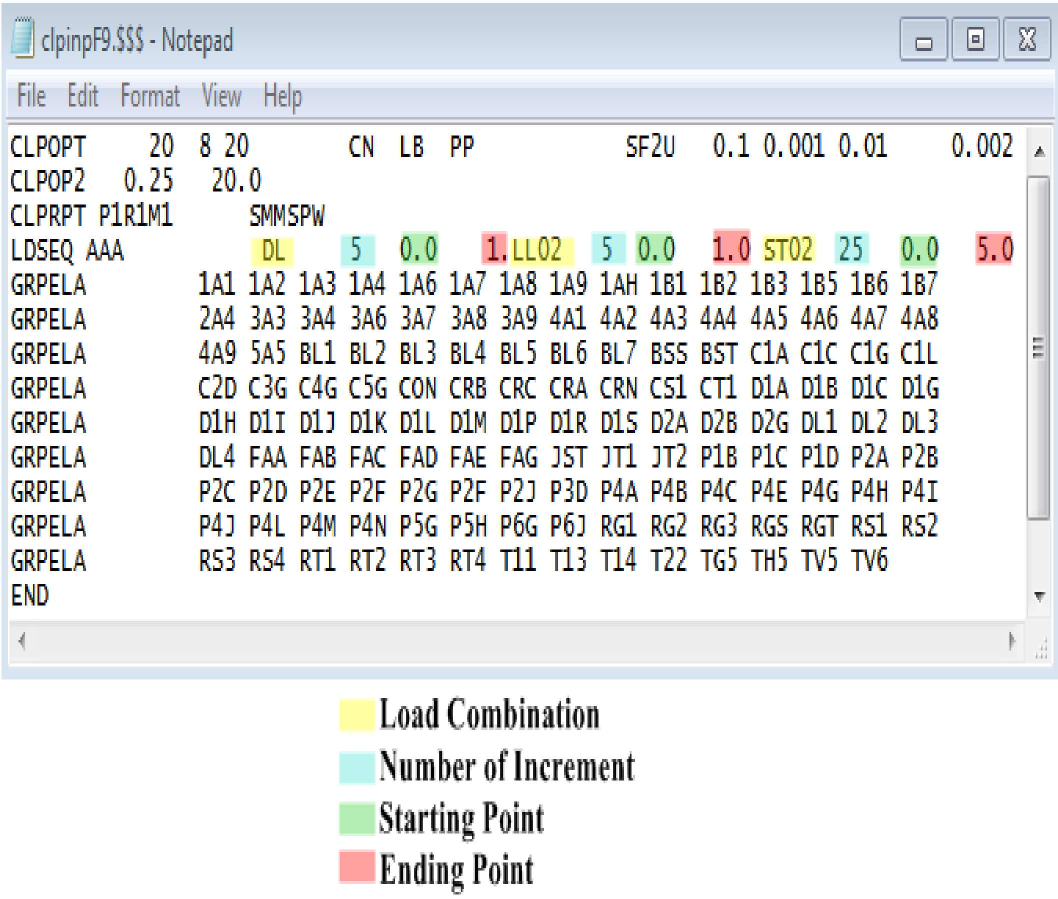


Figure 3.3 Example of Collapse File with respect to Direction 45°

It should be noted that the direction for live load combination and storm load combination with respect to 100 years return period should always be in the same direction. Similar concept is applied to the selected load, load factor modification and load combination implemented in the modified SACS model file.

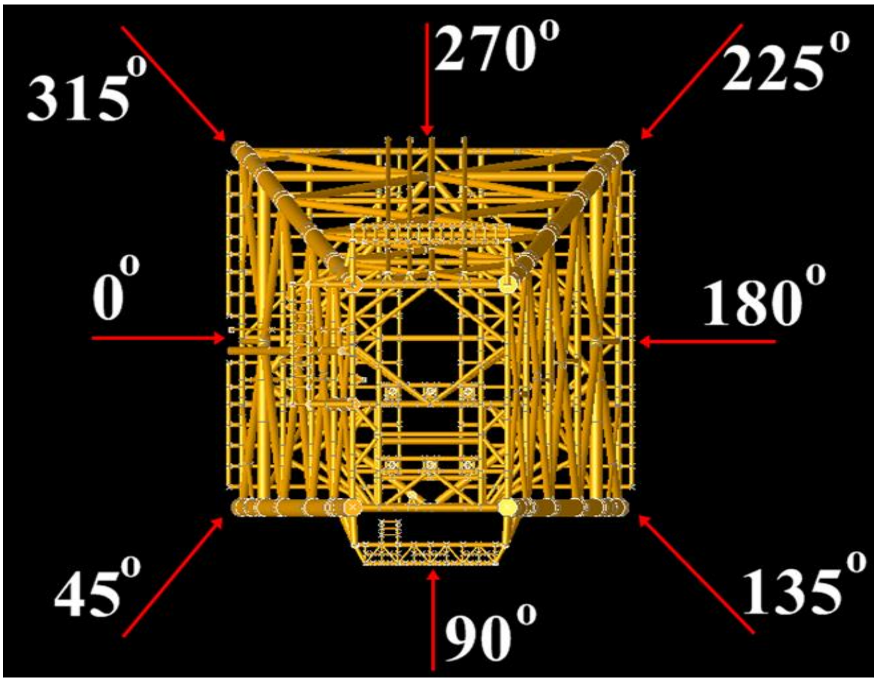


Figure 3.4 Loading Directions in Pushover Analyses

Based on the collapse results, the ultimate strength for first member failure will be divided by design allowable strength respectively in order to calculate the Reserve Strength Ratio (RSR) for each corrosion case:

$$Reserve\ Strength\ Ratio = \frac{Ultimate\ Strength}{Design\ Strength}$$

In particular, the strengths will be obtained from the base shear which is derived at load step with first member failure during pushover analysis. From the outcome, the results will be compared to analysis that was done during the past and the value of RSR will be interpreted according to the industrial benchmark.

With the input from pushover analysis, the reliability of the respective jacket platform will be scrutinized. This can be achieved through the principles of First Order Reliability Method (FORM) in MATLAB software. As the name suggested, FORM refers to the first order expansion of the function which utilizes mean and standard deviation as the main input and output. The variable X is statistically independent while the limit state function involved can be linear or non-linear.

The value of RSR will be incorporated into series of algorithm provided by research team in the MATLAB in order to compute reliability index, β. The code was developed with reference to Finite Element Reliability Using MATLAB

(FERUM) project initiated in University Of California, Berkeley during 1999. Over the years, FERUM provided step-by-step tutorial in accessing structural reliability and had become an effective tools since then. To be specific, an interface function, “shell” is vital to utilize the data created by the user. In addition, an input file is required to contain and syntax the data field while g-function file will prompt for appropriate code to compute the probability of failure. Putting these functional packages together for platform F9, the respective MATLAB code developed by the research team was put into usage. Particularly, the limit state function in this case is calculated by deducing the system load from system resistance. While the load parameter is constant in this case, the resistance can be computed from the following formula:

$$Resistance = \beta * RSR * \big((c1 * (Hd * 2)\big) + (c2 * Hd) + \big(c3 * (Ub * 2)\big) + (c4 * Ub) + \big(c5 * (Wb * 2)\big) + (c6 * Wb) + c7)$$

```
function g = gfun_pilesoil(Bi,Hs,Ai)
%% This function defines the Limit State Function
% Resistance Model defined by RSR value.
% Load model defined by Metocean Loading.
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%DATA FIELDS IN 'Resistance Model'                          %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%This functions is intented to generate resistance
% No factor is included.
RSR = 3.321;
Hd = 11.7;
c1 = 0.04232;
c2 = 0.09672;
c3 = 2.298;
c4 = 0.9034;
c5 = -0.04453;
c6 = 0.9760;
c7 = 0.2843;
Ub = 1.20;
Wb = 24.00;
Resistance = Bi.*RSR.*((c1.*(Hd.^2))+(c2.*Hd)+(c3.*(Ub.^2))+(c4.*Ub)+(c5.*(Wb.^2))+(c6.*Wb)+c7);
%%
```

Figure 3.5 G-Function for MATLAB Coding and Alteration of RSR Value

Where c1, c2, c3, c4, c5 and c6 is the parameter for wave loading curve, beta is the random number generated in response to RSR coefficient, Hd is the maximum wave height, Ub is the current velocity, Wb is the wind speed, which was all adopted from previous literature by Ersdal (2005). In this case, the coding fixed the response surface coefficient, response surface model and uncertainty model. The only outstanding parameter in this function is RSR, which should be obtained from pushover analysis for each simulation case. Once that all the parameter had been input into the coding, the g-function was run.

```
disp('    ____________________________________________________________________ ');
disp('  | Welcome to FERUM Version 4.0 (Finite Element Reliability Using Matlab) |');
disp('  | For more information, visit: http://www.ifma.fr/FERUM/                 |');
disp('  | Note: All the analysis options below assumes that necessary data       |');
disp('  |       are available in the current Matlab workspace.                   |');
disp('    ____________________________________________________________________ ');
disp(' ');
disp('   0: Exit');
disp('   1: Help');
disp('  10: FORM Analysis');
disp('  11: FORM Analysis - Multiple design point');
disp('  12: SORM Analysis - Curvature Fitting method with computation of the Hessian');
disp('  13: SORM Analysis - Point Fitting method');
disp('  20: Distribution analysis');
disp('  21: Importance Sampling / Monte Carlo Simulation Analysis');
disp('  22: Directional Simulation Analysis');
disp('  23: Subset Simulation Analysis');
disp('  33: 2SMART Analysis');
disp('  40: RBDO - Smooth Nested Bi-Level Approach (using the gradient of Pf w.r.t. thetag)');
disp('  50: Sobol'' Global Sensitivity Analysis');
disp(' ');
analysistype = input('  CHOOSE OPTION FROM THE LIST ABOVE: ');
analysisopt.analysistype = analysistype;
```

Figure 3.6 List of Reliability Analysis available in FERUM

Next, in the input function, First Order Reliability Method was prompted to complete the analysis, which will provide a systematic overview of the reliability parameters. The determination of reliability index is crucial in order to calculate probability of platform failure, Pf as the final results. The data will be available to be retrieved from the workspace in the 'gformresults' folder together with other function such as analysis operation, analysis type, finite element model g-function data and probability data. In facts, this statistical value is useful to be used as practical results so that reminder can be provided to the regional operator in the potential of devastating environmental loading predicaments.

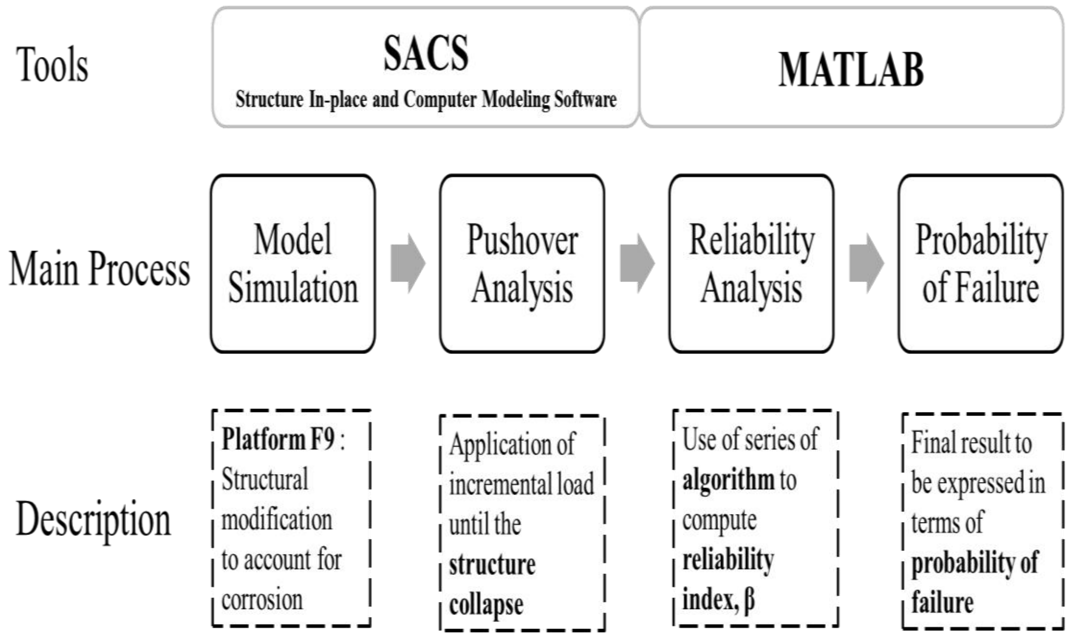


Figure 3.7 Process Flow of the Overall Project

3.2 Project Activities

- Planning and Research

  - During the beginning stage, the formulation of problem statement will be conducted based on internship observation, discussion and consultation with Supervisor.

  - Once that the topic had been identified, extensive study into previous paper on corrosion, reliability and life extension will be done, followed by comparison between papers and critical literature review.

- Sampling and Data Collection

  - Data sources required for the analysis will be identified. Information of corrosion will be gathered through large sampling from various sources through empirical, actual or experimental model.

  - The data will be validated and compared in order to improve the accuracy and determine the best approach to be implemented for further analysis.

- Model Simulation

  - A model for existing jacket platform at Malaysian water will be selected and run in Structural In-place Analysis And Computer Modeling Software (SACS).

  - Modification will be done with respect to the corrosion according to the predefined member groups and simulation cases. There are total of 12 cases of corrosion simulated by inducing member section diameter or thickness reduction.

- Pushover Analysis

  - Factored environmental loads will be applied on the jacket structure until the pre-established criteria. From the base shear of first member failure, Reserve Strength Ration will be computed.

- Results Interpretation and Reliability Analysis

  - Results will be validated with respect to previous similar works done by other authors. The trend of the results will be interpreted and compared between different cases of corrosion.

  - Reliability analysis will be conducted in MATLAB with series of algorithm in order to determine the reliability index and probability of platform failure.

- Final Report and Presentation

  - All the findings will be compiled and critical analysis will be done to conclude the project. Technical paper of final year project will be completed, following by final presentation to the judge panel for wrapping up of project.

  - The value of the project will be utilized to provide valuable information for the offshore operators in enhancing the structure integrity and reliability.

3.3 Key Project Milestones

1) Completion Of Extensive Planning And Research

   - With respect to the problem statement, extensive study had been done to determine the best approach to address the problem. Based from the comparisons between previously done researches, it was realized that most of the structural reliability had been derived from a mathematical approach. From the discussion with supervisor, modeling approach will be utilized to examine the corrosion impact.

2) Completion Of Modeling And Pushover Analysis

   - Model simulation was conducted based on corrosion input for all 12 cases followed by static analysis to perform Unity Check for the modified members. Next, series of pushover analyses from eight directions for each case was completed. Reserve Strength Ratio (RSR) values were obtained to address the first objectives on studying corrosion effects.

3) Completion Of Reliability Analysis

   - From the input of RSR, the platform reliability index was derived with series of algorithm in MATLAB. The final results were expressed in terms of probability of platform F9 failure for each of the corrosion cases. The results will be validated based on previously done researches and industrial benchmark while addressing second objective to relate corrosion with reliability.

4) Completion Of Final Year Project

   - Submission of final dissertation as well as technical paper to supervisor, internal examiner and external judge panel. Completion of viva presentation in order to deliver the value of project. The significance of findings in terms of potential return period for extreme environmental loading will be optimized toward the industry and society to safeguard life and assets.

3.4 Gantt Chart

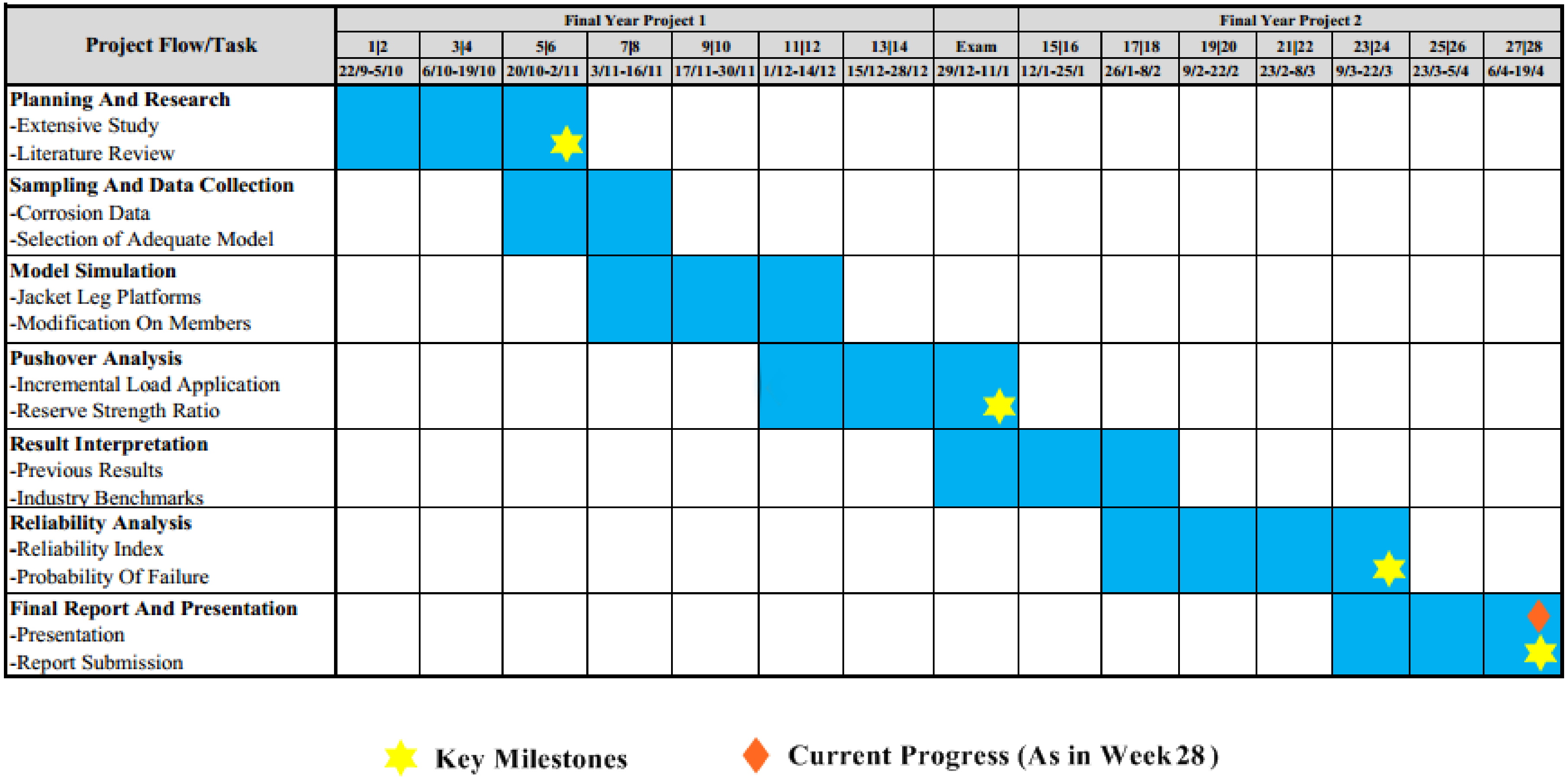


Figure 3.8 Project Gantt Chart

CHAPTER 4

RESULTS AND DISCUSSION

4.0 RESULTS AND DISCUSSION

4.1 Unity Check For Modified Member Segments

From the three defined group of members within splash zone area of F9 Jacket Platform, member modifications was simulated in SACS. In total, there are 16 Circular Hollow Section (CHS) bracing member segments, 110 CHS horizontal member segments and 14 Concentric Tubular member segments for the jacket leg. These members were modified based on 10% and 25% material loss respectively with diameter and thickness as the variables to account for the corrosion effects. Once that the members dimension had been updated, the static in-place analysis was run to study the impacts. From the “postvue” data generated, the preliminary result will be reported in terms of member maximum Unity Check (UC) value.

Table 4.1 Member Properties for the Modified Sections

Member Properties	Magnitude
E	200000000 kN/m^2
G	80000000 kN/m^2
F_y	345000 kN/m^2
Density	7.849 tonne/m^3

Theoretically, each members will develop stresses in responds to the load combinations being applied on the system. In this case, there are three types of stresses being prioritized, which is axial stress, bending stresses in major and minor axis. By dividing each of these stress with the allowable stress, the individual UC can be calculated. Eventually, the summation of these individual UC is the member maximum UC value. Since that UC measure the ratio of member stresses to its allowable limit, it is essential to have UC smaller than 1 to prevent member being overstressed than its capacity. From all the 12 different cases of members modification based on material loss, the members maximum UC had been reported and compared with the original member without corrosion.

The following figures summarized the dimension modification and resulting UC for one of the members, bracing 601-501X:

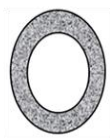
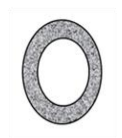
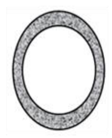
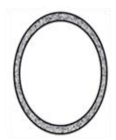
	Original (Without Corrosion)	Case 1 10% Material Loss (Decrease in D)	Case 2 25% Material Loss (Decrease in D)	Case 3 10% Material Loss (Decrease in t)	Case 4 25% Material Loss (Decrease in t)
Modeling					
Member Section Properties	D = 58.6 cm t = 1.34 cm	D = 52.9 cm t = 1.34 cm	D = 44.3 cm t = 1.34 cm	D = 58.6 cm t = 1.20 cm	D = 58.6 cm t = 0.99 cm
					
Unity Check	0.36	0.70	1.74	0.58	0.69

Figure 4.1 Modification of Member 601-501X with Respect to Corrosion

Similar procedure was repeated for another 139 member segments, and the maximum UC ratio for each of the four cases was recorded. The results had been tabulated in the spreadsheet attached in Appendix.

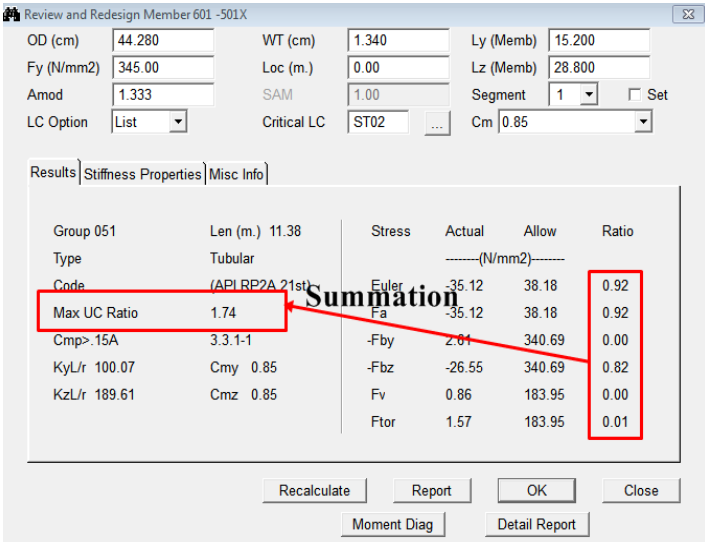


Figure 4.2 Maximum UC Computation

Based on the UC ratio, several distinctive trends of results had been observed. Firstly, most of the members in all four cases reported an UC increment with respect to the reduction in member dimension. Fundamentally, this can be explained by the principles of member stress which is derived from applied force divided by the member cross-sectional area. Provided that the constant forces had been applied on the member with decreased in cross-sectional area with respect to the corrosion, the stress is expected to be escalated. From the result, it was observed that in most of the member segments, axial and bending stresses were increased with respect to the section modification.

However, this explanation may not be fully consistent in every scenario since that the members segment in jacket structure are in space truss arrangement with various connections to other member which are subjected to several load combinations. This provided an insight on the reason why certain members undergone slight decrement in UC in Case 3 despite the reduction in area. For example, during design, the cross-sectional area across a member can be different in order to account for different stresses being developed. Change in size between segments of a particular member may have affected the load transfer mechanism. During the modification, some segments were reduced and unintentionally match other segment well, thereby implicitly contributed to lesser stresses being developed on the respective member segment. However, the decrement in the member segments' UC is minimal and only occurred at several segment in Case 3 which still reported an increment at the rest of the cases.

In order to provide a better understanding on the trend of preliminary results for the studied member segments, the UC values for each group had been plotted in two graphs with respect to reduction in diameter and thickness respectively. The x-axis of the graph recorded the UC value while the y-axis represented the percentage of material losses. It should be noted that 0% section decrement indicated the original member without corrosion. The UC value for original member was essential to be included in both graphs to act as the baseline value for the future assessment. Each of the line in the graph represented the member segment. In the case of Group 2-horizontal members, only 15 member segment with highest UC ratio had been selected for analysis. In addition, the gradient for each of the line will be calculated to measure the stiffness and study the relationship between each member segments. The following shows the plotted graphs from preliminary results:

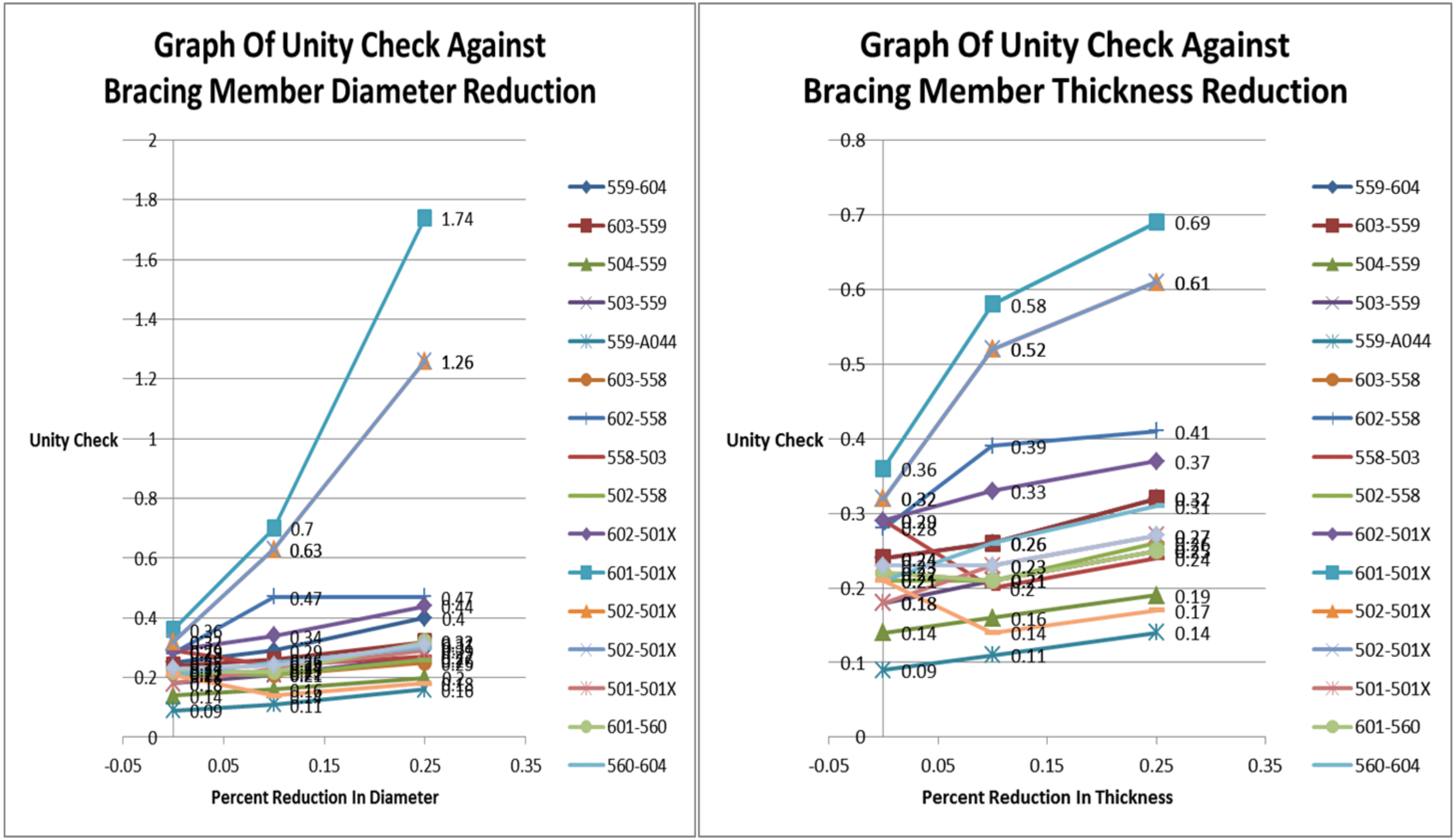


Figure 4.3 Graph of UC Against Bracing Member (Group 1) Reduction

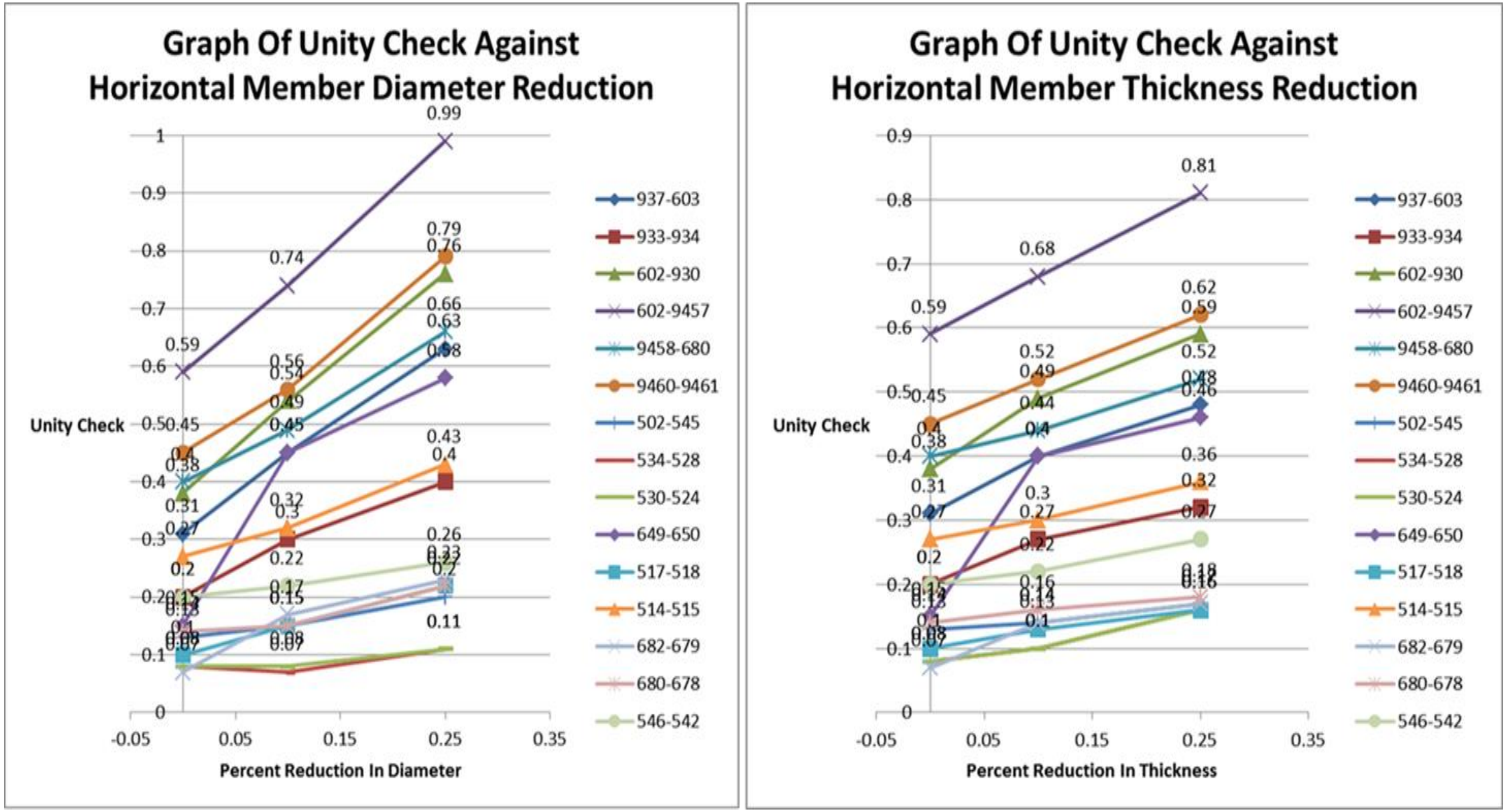


Figure 4.4 Graph of UC Against Horizontal Member (Group 2) Reduction

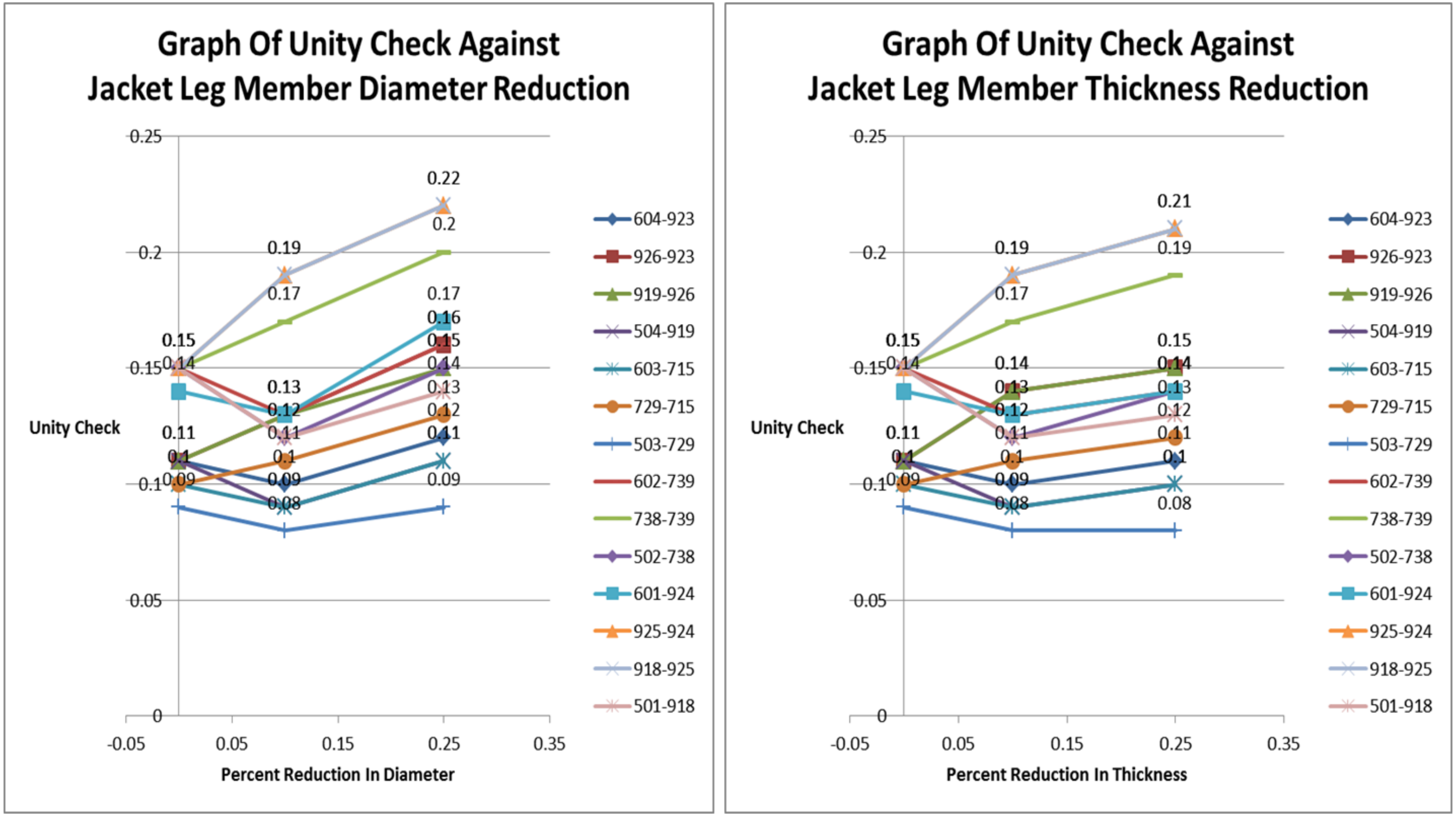


Figure 4.5 Graph of UC Against Jacket Leg (Group 3) Reduction

From all six graphs, a trend had been observed that if the initial UC value was small, the gradient of the graph will be small too, which indicate an almost linear increment in UC. This can be observed particularly from graph for bracing members which members with small initial UC has the gradient between 0.28 to 0.42. However, if the UC value is high, the gradient will be stiffer with respect to material losses. As for member segment 559-604 in the first graph, the gradient is 5.63 which are much steeper than other members with small initial UC.

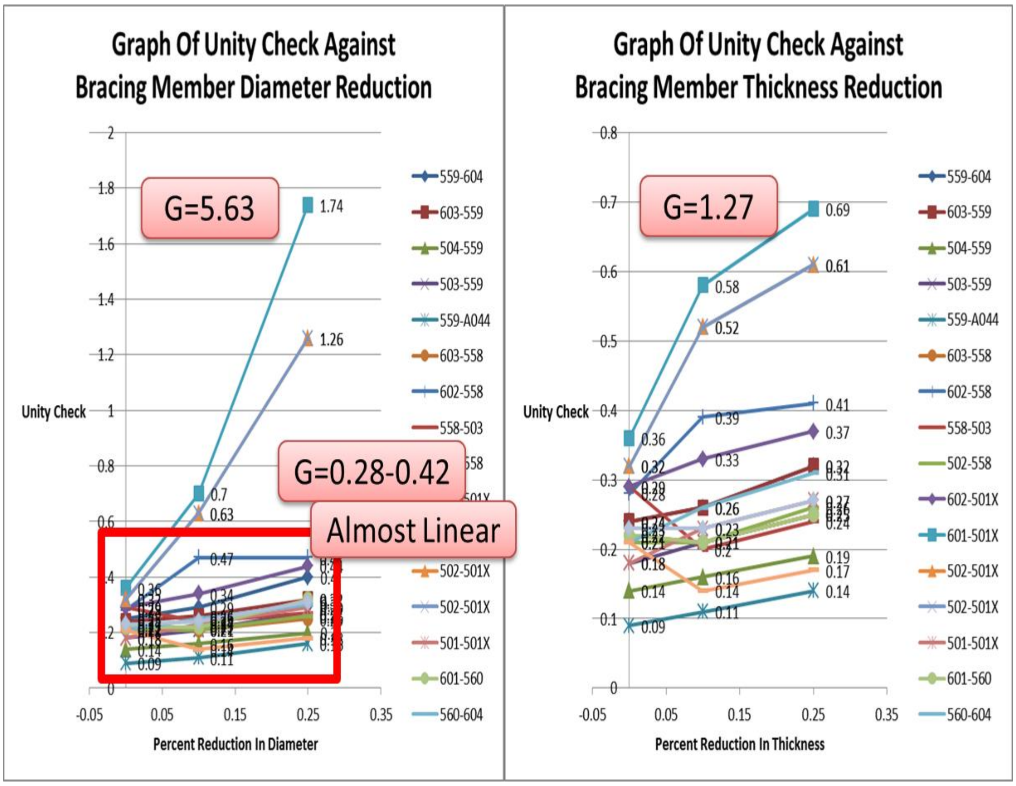


Figure 4.6 Interpretations of Trends and Gradient of Bracing Members

Similar trend had been observed in both diameter and thickness reduction, with exception that the thickness reduction has smaller change in UC compared to that of diameter reduction. For the same member of 559-604, the gradient with respect to thickness reduction is only 1.27 compared to that of diameter reduction which was 5.63 as discussed earlier.

Comparing all three groups of members, bracing members had the most critical increment in UC, followed by horizontal members (G = 0.12-1.67) and lastly jacket leg (G = 0.15 to 0.27). In facts, jacket legs was least affected by material loss. It can be due to larger member incorporated with pile are being used in Concentric Tubular member for jacket leg, thus the reduction in material only account for minimal area loss in each segment.

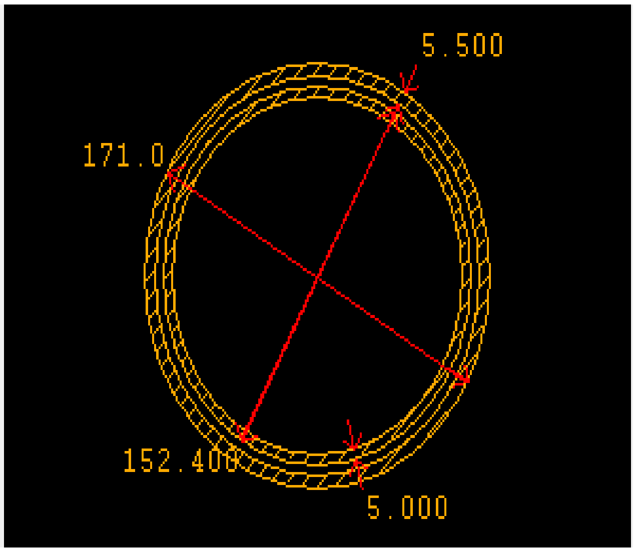


Figure 4.7 Typical Cross Section of Concentric Tubular Member

In overall, reduction in D and t caused increase in UC because member stress is inversely proportional to the section area of the member.

$$\uparrow \sigma = \frac{Axial\ Force}{Area} \downarrow$$

However, all of the reported findings are only preliminary results for this project; the actual corrosion effects should be scrutinized later when the input from this stage was being put forward for further analyses.

4.2 Reserve Strength Ratio

During the pushover analysis, all the modified models for F9 platform were subjected to incremental load in its respective 100 year storm case load combination 'ST' to the multiplier of five. The member responses in sequence were observed and any convergence or member failure was taken note. Since that the load was applied to manifest member's plasticity and ultimate strength, the corrosion effects toward the entire jacket structure is the highlight of this section. Meanwhile, the change in deflection as load factors increasing governed the process of incremental stresses for the modified member segments. From the analysis, the Reserve Strength Ratio (RSR) was calculated based on first member failure and all the results are concluded as the following:

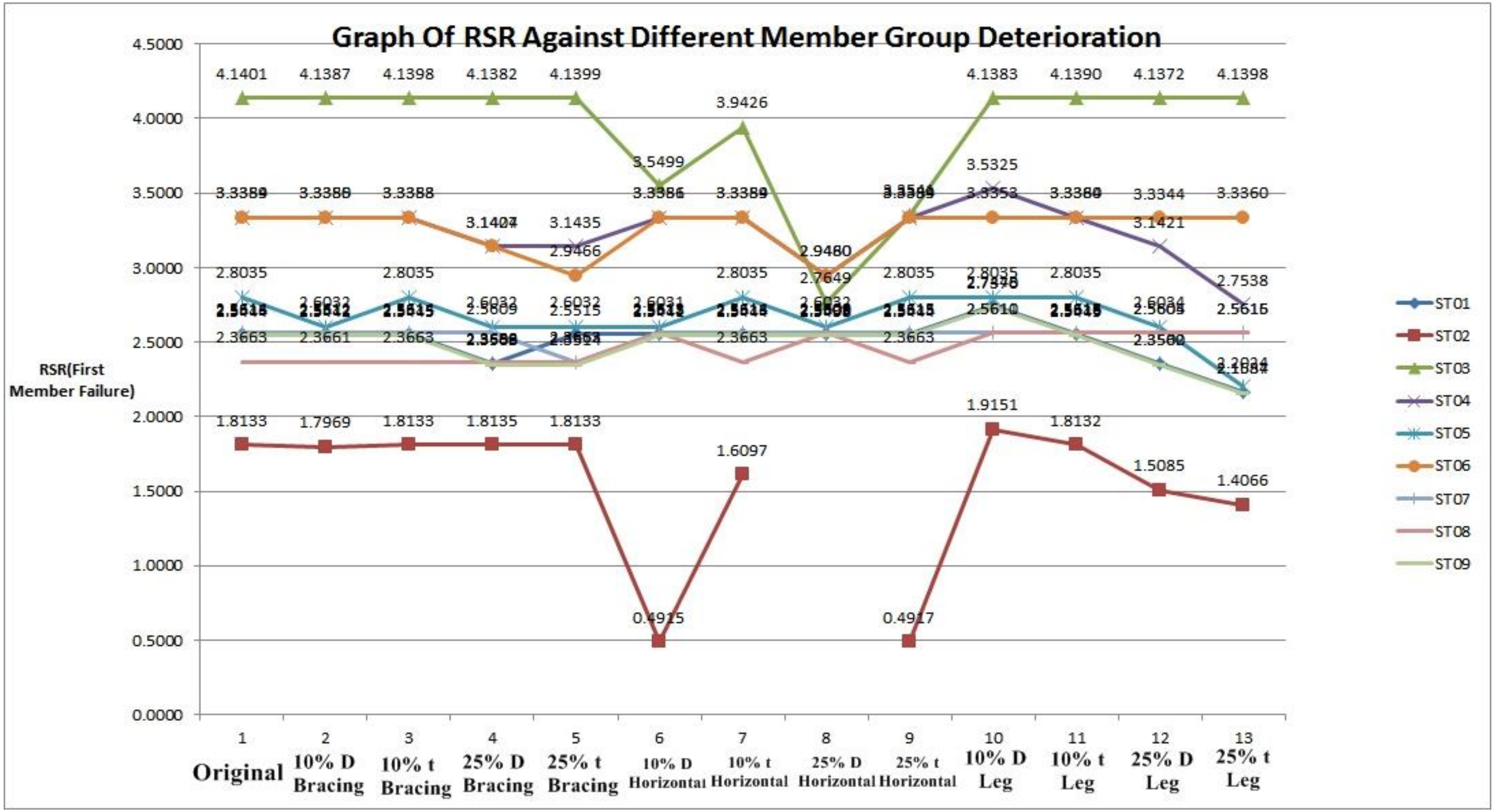


Figure 4.8 RSR Value for All Corrosion Cases in All Storm Directions

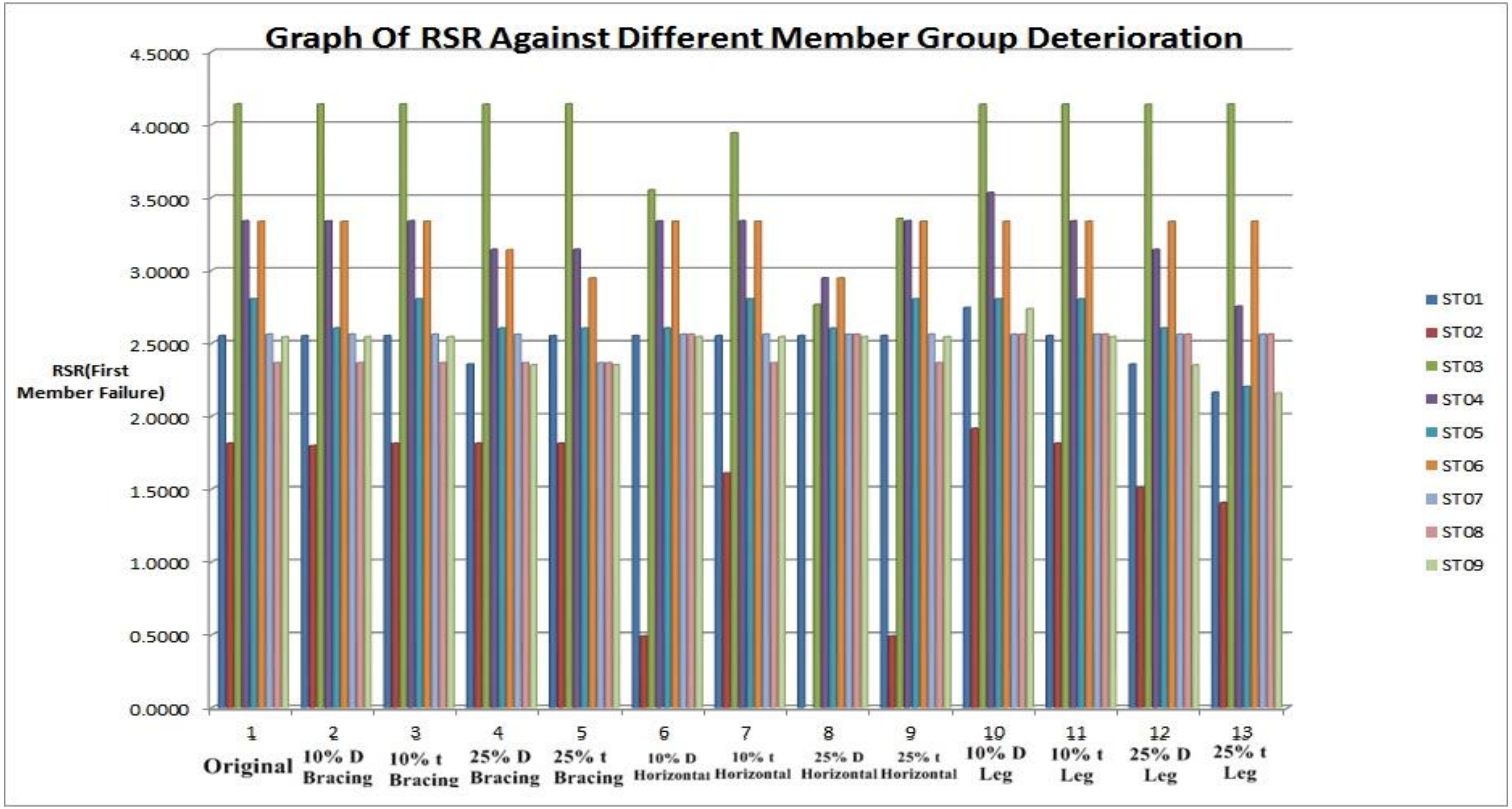


Figure 4.9 Compiled RSR Value for All Corrosion Cases in All Storm Directions

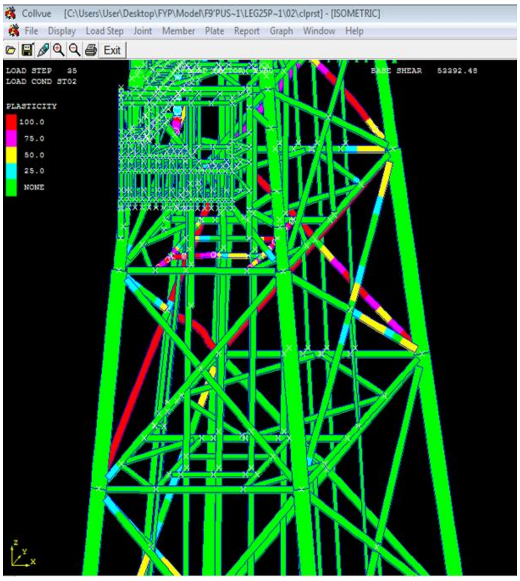


Figure 4.10 Pushover Analysis Results Showed Large Deflection within Jacket

The base shear was obtained from the collapse view at load step which indicated the first member failure had occurred. By dividing this value with the design base shear at load multiplier of one for extreme storm condition, Reserve Strength Ratio was computed. In order to validate the magnitude of RSR, API RP 2A-WSD was referred. Based on the code, the assessment criteria for platform outside of United States should have at least 0.8 RSR for low failure consequence, unmanned platform. At the same time, PETRONAS Technical Standard set the minimum requirement of 1.32 RSR for the platform with similar characteristic as outlined in API. Both of this value acts as the bottom line for the RSR obtained through pushover analysis. From the results, most of the RSR value is higher than the acceptable value except certain outliers with respect to ST02.

In comparison with the original model without corrosion implication, all the modified cases overlooked a slightly drop in RSR value. This can be explained by implementation of thinner member sections which had reduced the strength of the members within the splash zone to withstand the incremental loads during extreme storm condition. However, in overall the decrement in RSR was ranged from 0% to 0.33%, which indicated not significant changes across the modification. Nevertheless, some trends observed from the result in pushover analysis were able to provide insights on critical storm direction as well as the influence of material loss from different angles.

In particular, the horizontal members RSR show the highest drop in RSR compared to bracing or jacket leg members. By static, the tubular member for horizontal members had its strength greatly reduced in the case of material loss. From a dynamic perspective, the observed trend can be explained by its location which accounts for larger equivalent added masses on horizontal bracing compared to diagonal bracing of equal length when the storm direction is perpendicular to the member, thus increasing the mass and decreasing the natural frequency of the jacket structure. However, besides than merely accusing that the corrosion impact had taken a toll in this group, another potential explanation for this predicament can be due to horizontal members contribute to largest portion of members, thus more section had been reduced relatively.

Nevertheless, all the first member failure had taken place in same member segment, which is Member A045-501X as illustrated below:

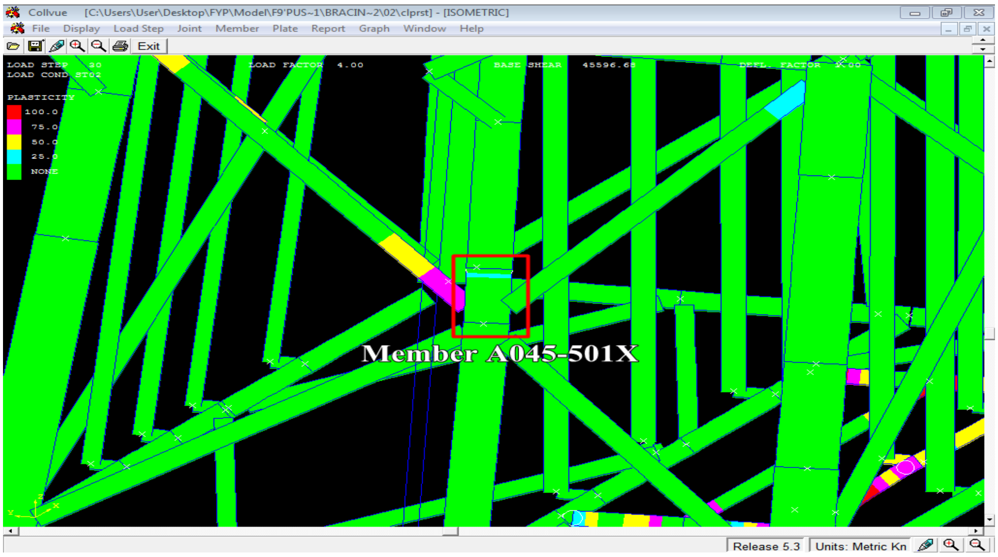


Figure 4.11 First Member Failure and Level of Plasticity Developed

As shown in the collapse view, member A045-501X located at a critical direction in connection with four diagonal bracings. The application of load under extreme weather condition had developed on excessive amount of stresses between these members before it behaved plastic. This member failed at storm load with 2.6 multiplier. Its strategic location progressively led to other members' failure as the analysis proceeded. In figure above, another notable observation showed the sign of horizontal member failure at the bottom parts of splash zone, which is in line with discussion above that this group was more prone to the corrosion impacts.

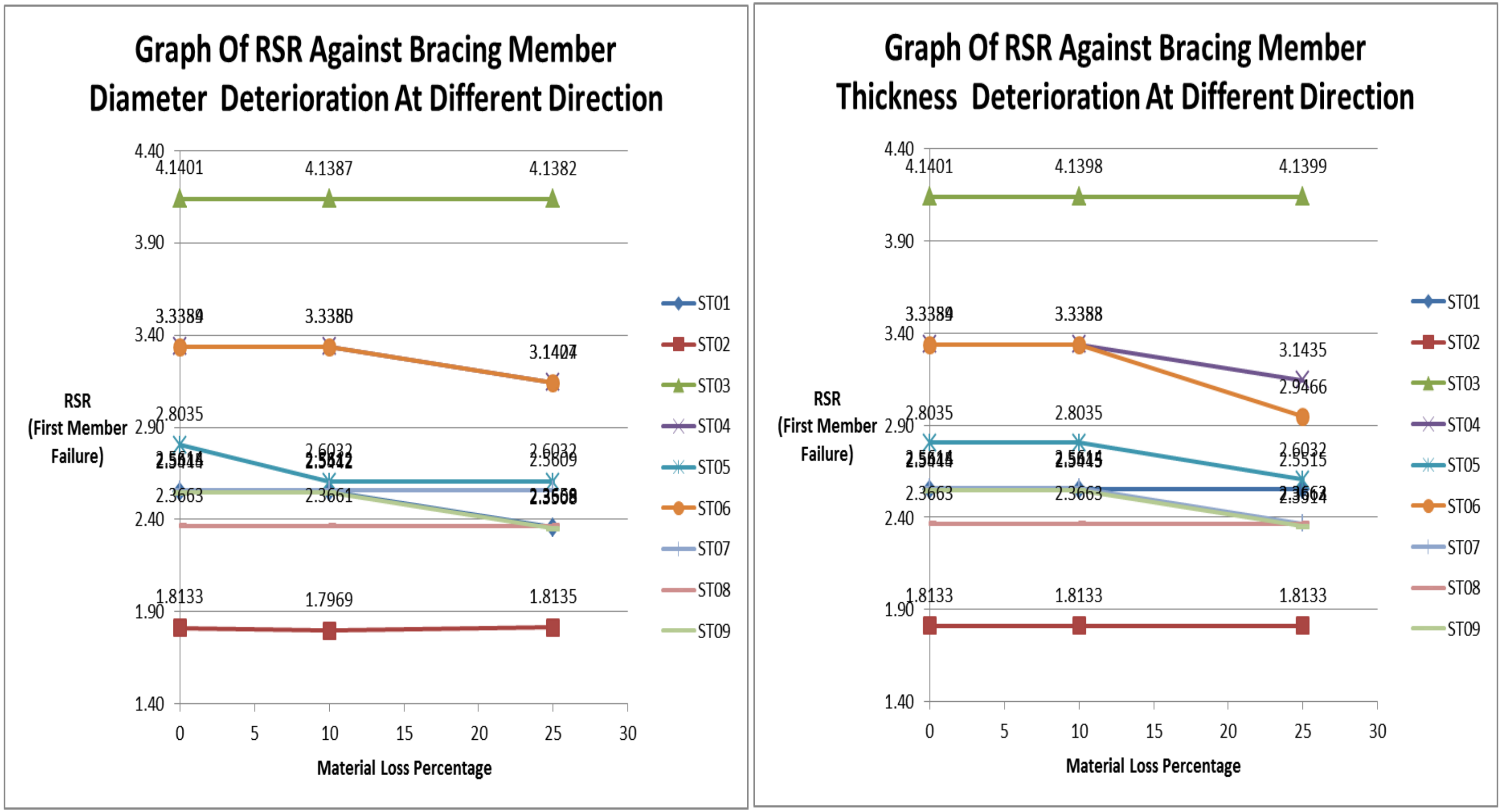


Figure 4.12 Graph of RSR Against Bracing Member Reduction

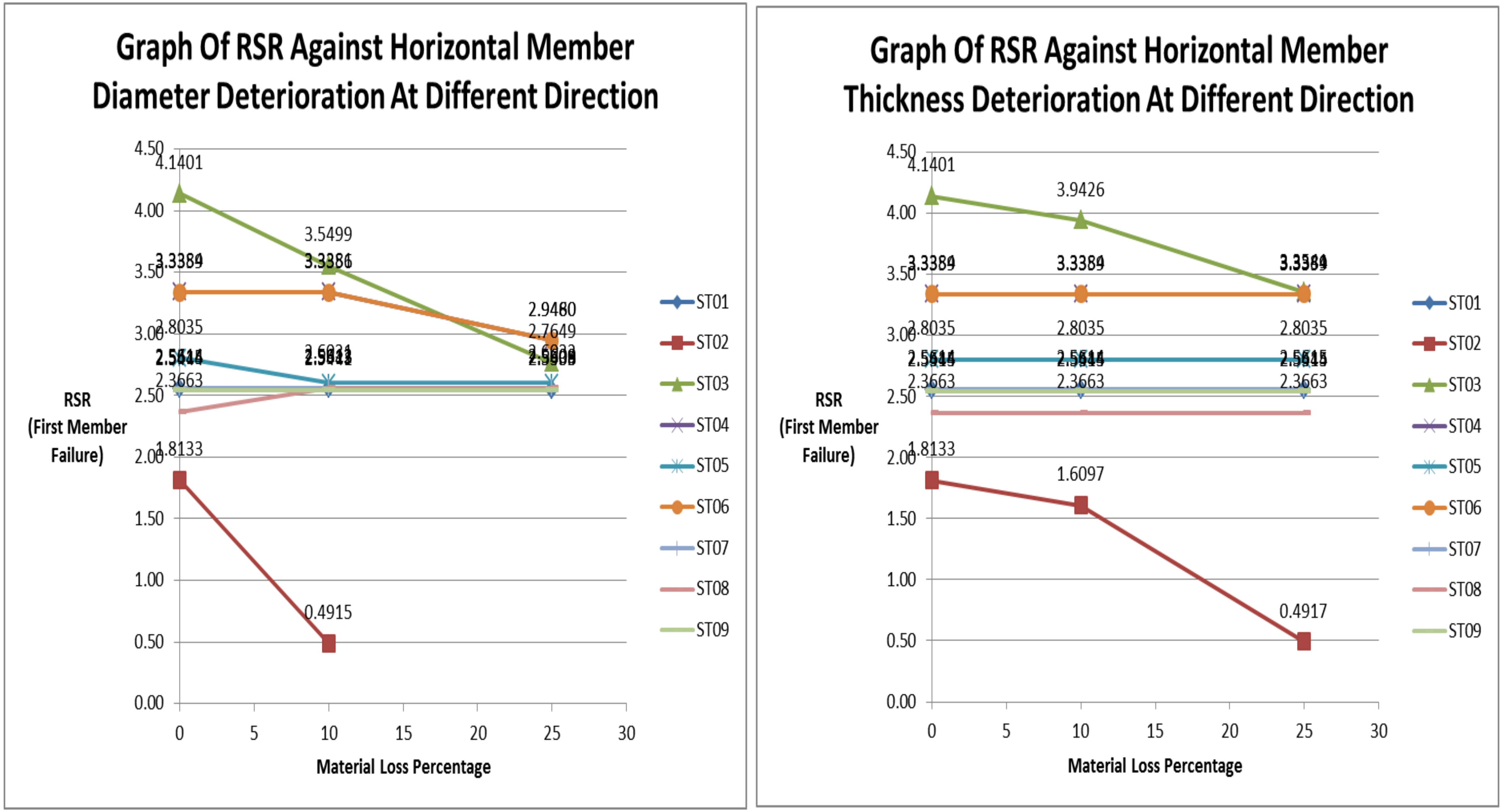
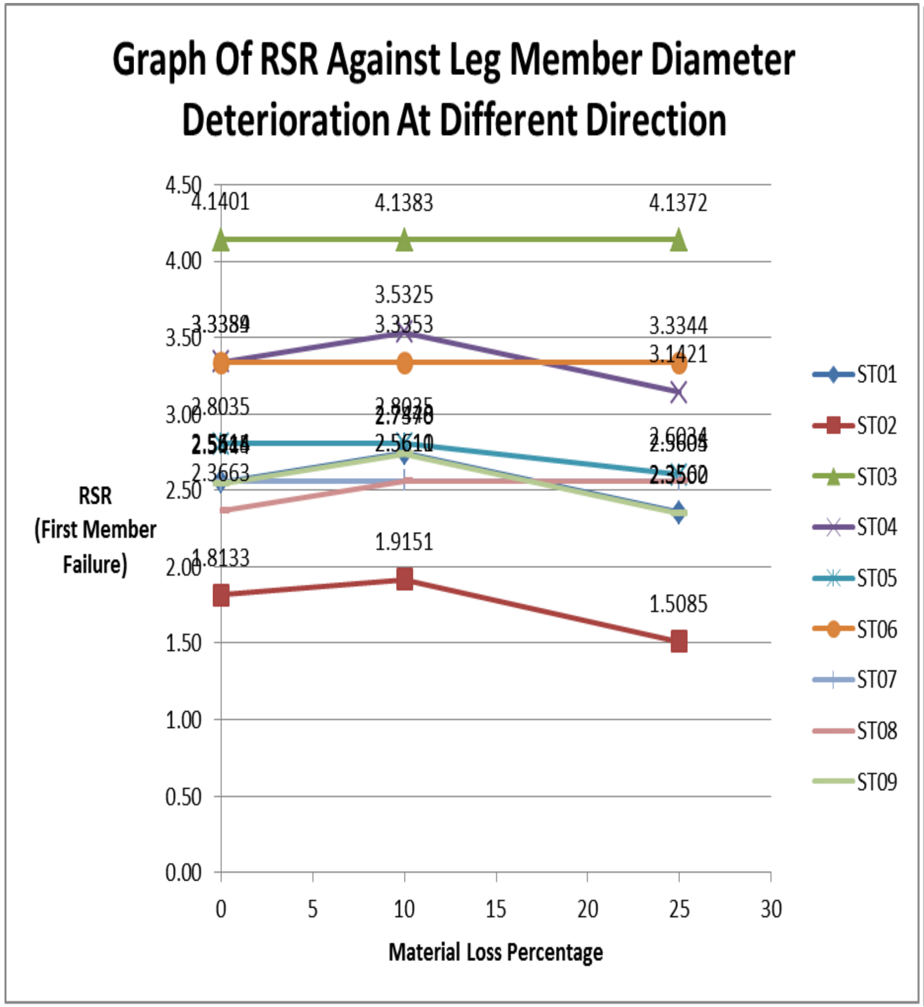


Figure 4.13 Graph of RSR Against Horizontal Member Reduction



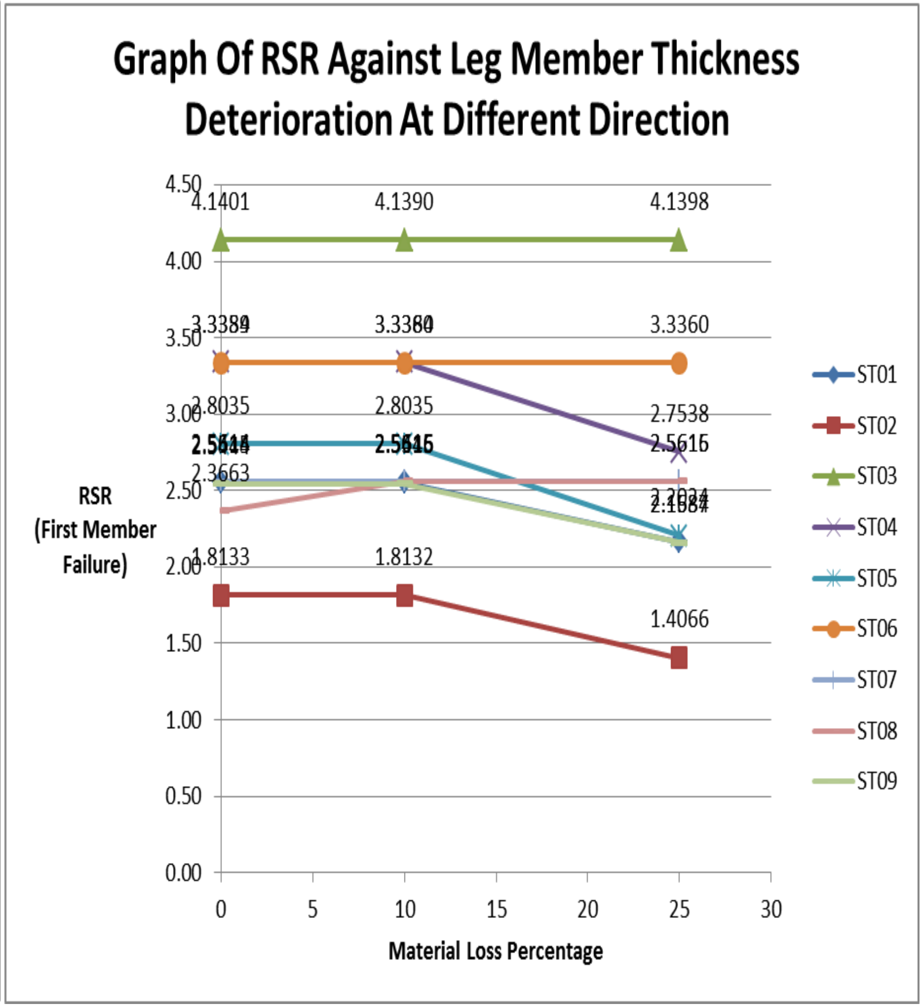


Figure 4.14 Graph of RSR Against Leg Member Reduction

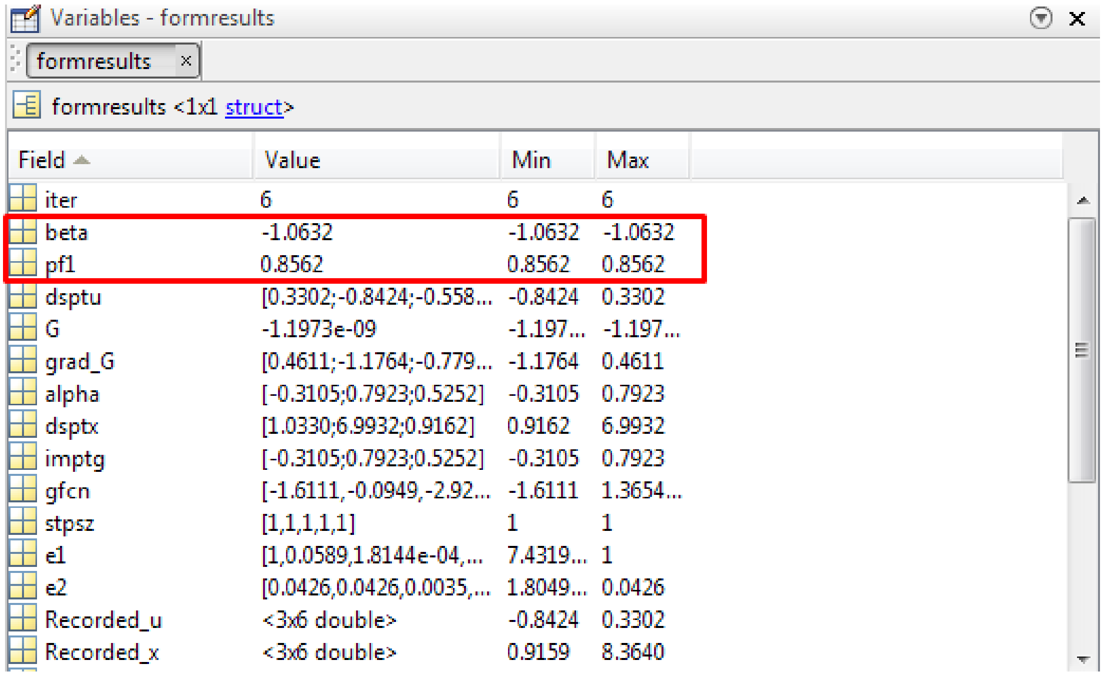
To scrutinize this finding, Figure 4.8 showed the graphs of Horizontal RSR value against percentage of diameter and thickness reduction respectively. Based on the results, ST03 which indicates storm combination from 135° direction had highest RSR value, while ST02 that shows storm combination from 45° direction were in critical condition due to extraordinary low RSR upon section reduction. For instances, ST02 with 10% depletion in horizontal members' diameter has RSR at 0.4915, which is 3.68 time lower than the original RSR. The extent of impact can be due to the facts that larger amount of load case was considered in that particular direction to reflect the actual environmental loading on platform orientation. At 25% diameter reduction, the entire platform collapsed even before the load multiplier reached one. This finding highlighted that combination of corrosion impact with extreme wave at 45° direction is extremely detrimental and stern actions is prompted to prevent the occurrence for this predicaments.

On the other hand, both of the graphs in Figure 4.8 pointed out the difference between diameter and thickness reduction in affecting the RSR. To be specific, decrease in member's diameter was found to have more chronic impact than thickness reduction in the change in RSR. For instances, at ST03, the gradient for diameter impacted RSR was -0.0548, which is much steeper than thickness impacted RSR with gradient of -0.0321. This finding is in conjunction with the Unity Check results in previous context, where the change in diameter had made the cross-sectional area become smaller and implicitly affect the path for load transfer as well as stress distribution.

Comparing the results in terms of variation of UC and RSR, the preliminary results focused more on the implication of corrosion toward the individual member segments. From the context, some of the members had developed critical UC by having its dimension reduced. The first part of static assessment brought a transition into pushover analysis, in which RSR for storm from all directions were accounted for. In facts, the results from both assessments are interrelated. For example, one of the horizontal member 602-9457 had shown dramatic change over the UC from 0.59 to 0.99 when 25% diameter was loss. In addition, this member was found to be the first member that had failed in pushover analysis. The combination of results findings was able to provide a guideline for monitoring of critical member groups. In facts, the final stage on reliability analysis in the following context will include the probability of failure for each case in providing a comprehensive understanding on the reliability of F9 platform.

4.3 Probability Of Failure

With respect to the previous results, RSR value from pushover analyses was input into reliability analysis. Next, the subsequent analysis was run with the assistance of FERUM coding in MATLAB. Two important parameters can be obtained from each simulation cases, namely reliability index and probability of failure.



Variables - formresults

formresults

formresults <1x1 struct>

Field	Value	Min	Max
iter	6	6	6
beta	-1.0632	-1.0632	-1.0632
pf1	0.8562	0.8562	0.8562
dsptu	[0.3302;-0.8424;-0.558...	-0.8424	0.3302
G	-1.1973e-09	-1.197...	-1.197...
grad_G	[0.4611;-1.1764;-0.779...	-1.1764	0.4611
alpha	[-0.3105;0.7923;0.5252]	-0.3105	0.7923
dsptx	[1.0330;6.9932;0.9162]	0.9162	6.9932
imptg	[-0.3105;0.7923;0.5252]	-0.3105	0.7923
gfcn	[-1.6111,-0.0949,-2.92...	-1.6111	1.3654...
stpsz	[1,1,1,1,1]	1	1
e1	[1,0.0589,1.8144e-04,...	7.4319...	1
e2	[0.0426,0.0426,0.0035,...	1.8049...	0.0426
Recorded_u	<3x6 double>	-0.8424	0.3302
Recorded_x	<3x6 double>	0.9159	8.3640

Figure 4.15 Results from First Order Reliability Method (FORM)

Based on the findings, reliability index ranged from 7.4815 to -1.0645 which resulted in probability of failure platform falling in between 3.67 x 10^{-14} to 0.8564. Due to plenty of simulation cases and direction-dependent implications, extensive tabulated results had been summarized in Appendix section. Since that the overall comparison between the studied members had been discussed in the previous sections, the following discussion will scrutinize into the impact of corrosion by focusing on most critical member groups in response to thickness and diameter depletion. From the results, the reliability of horizontal members was greatly affected by the material loss especially in the case of diameter decrement. To be specific, the following table indicated Probability Of Failure for horizontal members from 45° storm load at ST02.

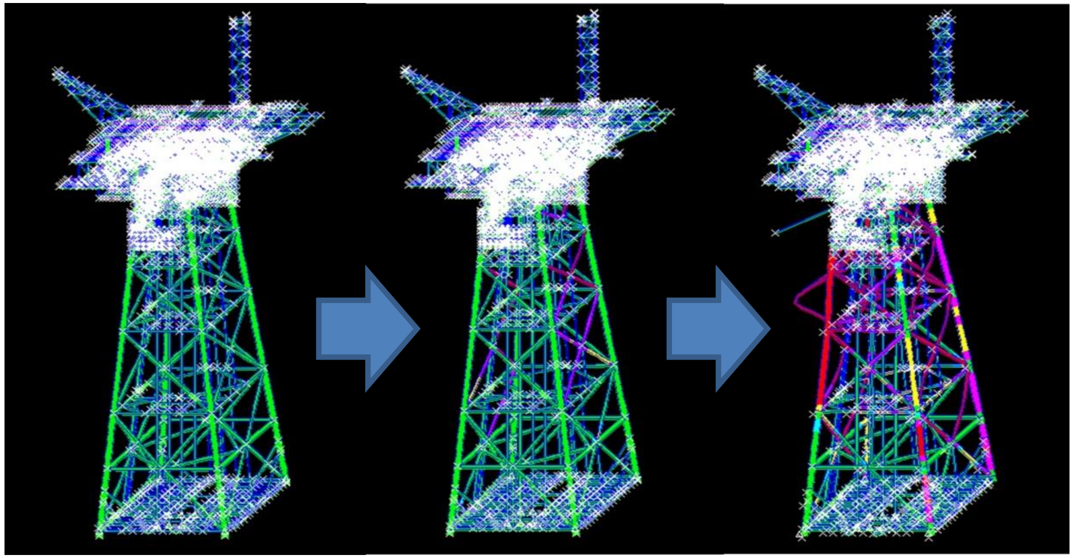


Figure 4.16 Sequence of Progressive Collapse during Extreme Incremental Load

Table 4.2 Most Critical Findings from Reliability Analysis

Case	Load	Base Shear	1st Member Failure	RSR	β	Pf	Remarks
Horizontal 10% D	ST02	18016.04	8854.26	0.4915	-1.0645	0.85644672	*1st member failure before ST01 reaching 1.0 multiplier.
Horizontal 25% D	ST02	-	3523.67	-	-	-	*Structure **collapse** before ST01 reaching 1.0 multiplier.
Horizontal 10% t	ST02	18077.95	29100.88	1.6097	3.6162	1.49E-04	-
Horizontal 25% t	ST02	18074.77	8886.89	0.4917	-1.0632	8.56E-01	*1st member failure before ST01 reaching 1.0 multiplier.

Based on the results, it can be observed that the trend for the pushover analysis and reliability analysis was in a positive consistent correlation. To be specific, in this case, the RSR value was directly proportional to the reliability index, β and inversely proportional to the probability of failure:

$$RSR \propto \beta \propto \frac{1}{Pf}$$

This trend can be explained from the coding of MATLAB which even though include multiple system and environmental parameters, but the only variable was the RSR value. However, this approach was believed to be adequate in this project since that the true intention is to examine the corrosion implication on critical members. This is in line with literature by Dong, Moan and Gao (2012) who stated that corrosion effects and material degradation would reduce the reliability index. With reference to the API standard, the Pf for unmanned platform with 1000 years of return period should be smaller than 1 x 10^{-4}. From the data, all the corrosion simulation yield acceptable Pf ultimately in exception of few cases in ST02 direction, which involved large live load combinations. The results showed that the decrement in Platform F9 splash zone member sections do not actually possessed threats to the structural integrity except several scenarios in horizontal member groups. In facts, the Pf for horizontal members was found to be biggest among the three studied groups and stern attentions should be given.

In addition to the discussion epitomized earlier, the critical Pf on horizontal member can be explained by the members' role when corrosion invaded. As a fact, reduction in member capacity did not imply that system strength will be compromised; it depends on whether the member was participating in failure mechanism. As demonstrated from the collapse of sequence and reliability analysis, the load path of horizontal member was completely disrupted when corrosion took place. During corrosion, a new loading distribution will be developed based on the altered forms, dimension of yielding and the connection to the intact members. The additional load imposed on the uncorroded members reduced the margin of safety and implicitly decreased the ultimate capacity of the jacket structure. Unlike other redundant member groups which were able to redistribute the member stresses upon component failure, the horizontal member in splash zone was subjected to excessive stresses and deflections in the case of extreme loads, which made this group of members rather critical. This finding was in line with Bao, Wang and Li (2009)'s research which quoted that due to high degree of redundancy of the platform, most of the members meet the API code requirement despite the ultimate strength had been degraded.

Furthermore, comparing the effects of diameter and thickness reduction, the former was found to be significantly decreasing the member capacity. For instances, the 10% material loss in terms of diameter resulted in probability of failure at 0.85645 while 10% thickness depletion at the same direction gave much smaller Pf at 0.000149. Coincidence, 25% thickness depletion yield equivalent results of Pf to that of 10% diameter loss. In conjunction with the discussion above, the results indicated that change in diameter has significant effect in the weakening the system strength. Thus, it is recommended that in the design of the jacket structure, thicker steel member should be used instead of larger member to counter for the impact of corrosion. From another perspective, member's diameter should also be kept within smaller range since that it also contribute to the wave parameter in the Morrison's Equation. Putting together these findings, thicker section should be deployed on horizontal member in addition to comprehensive design of load distribution path in order to optimize the steel capacity.

In addition to the type of member groups, this project concluded that direction of the environmental loads also play an imperative role in affecting the structural reliability. In this case, load from 45° led to the largest deviation of Pf from the baseline value. This is in conjunction with Ayob et. al (2014)'s similar study on an eight-legged drilling and production platform, which claimed that the environmental load coming perpendicular to the platform weak axis will cause largest impact. Thus, the ultimate strength of the member was dependent on the wave, wind and current direction too. In conclusion, with respect to the corrosion, most simulation cases of platform F9 were able to meet the acceptable annual probability of extreme load cases with the probability of failure ranging from 3.67 x 10^{-14} to 0.8564. In facts, horizontal member was critically affected by the material loss especially in terms of diameter change. The results were essential to be utilized as information to enhance and improve the existing platform reliability.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.0 CONCLUSION AND RECOMMENDATION

While corrosion had been taking a toll on Malaysian water offshore jacket structures which are mostly being operated exceeding its design life, this project aims to address two objectives. Firstly, the effects of corrosion in degrading jacket members' strength within splash zone area was be studied by using pushover analysis. Secondly, the input from first objective was fully utilized to conduct structural reliability assessment in order to derive probability of platform failure with respect to predefined corrosion. In comparison with the previous similar works done by other researchers; this project was dedicated to fill in the gap in offshore corrosion study through a direct modeling and mathematical approach.

During the first stage of the project, 10% and 25% of material loss had been simulated into and SACS model of F9 platform, an asset from PCSB. There are twelve set of preliminary results to account for corrosion taken place in different members within splash zone area. Initially, static analysis was run on the modified platforms to observe the change in member stresses with respect to the members' depletion. Next, pushover analysis was conducted to observe the jacket structure ability to withstand extreme incremental loadings. At this phase, Reserve Strength Ratio (RSR) was derived from the base shear developed by first member failure. Upon completion, reliability analysis was conducted to address second objective through the computation of platform's failure probability with respect to corrosions.

From the results, the Unity Check ratio had been examined and most of the member segments demonstrated increased in axial and bending stresses with respect to decreased cross-sectional area. From the two approaches used in section reduction, the decreased in diameter yielded higher UC compared to decrease in thickness for the same member segment. On the other hand, RSR for the platform in each case had been scrutinized. Based on the findings, the group in which horizontal members were applied with material loss showed greater decrement in RSR compared to another two groups. The results were not in line with the UC findings due to the approach in pushover analysis prioritized on the corrosion impacts on the entire jacket instead of individual members. Nevertheless, in overall the platform is able to yield standard acceptable RSR value in all of the directions except several cases from 45°. It was concluded that due to large amount of load cases had been considered in this directions, the incremental load had developed an excessive amount of stresses to escalate the component and structural failure.

Proceeding to reliability analysis, the outcome from first stage was used to study platform reliability by deriving probability of failure in MATLAB. The study of corrosion impact is vital in order to relate the consequence of member strength deterioration to the entire structures while achieving the second objective. The probability of failure for F9 platform ranged from 3.67×10^{-14} to 0.8564 with critical impacts on horizontal members from 45°. The significant result was caused by uneven stress distribution between the deteriorated members in addition to the facts that most horizontal components in splash zone participated in failure mechanism. As a recommendation, thicker member should be used instead of larger member due to smaller corrosion implication with respect to change in thickness. For further implementation, this project can be improved with actual corrosion data from the industry in order to escalate the accuracy of results. By referencing into inspection reports and data, sampling of information such as pitting corrosion can be simulated within the analysis to provide a wider perspective in this study. In addition, with the presence of industrial data, it will provide an opportunity to open up a new frontier in exploring topics such as anaerobic corrosion impact on offshore structures.

Apart from that, the algorithm used in MATLAB can be enhanced to allocate for more considerations to make the result even comprehensive. For example, other factors such as fatigue, dynamic and accidental loadings can be taken as optional part of the analysis so that the combinations of different scenario can be examined. In addition, pile-soil interaction can be included in the pushover analysis to account for the supports provided by the foundation system. Nevertheless, the corrosion can be applied on less critical member such as member groups that are not belongs to splash zone areas so that the results will not be biased and bounded by conservative limitation. In short, it was believed that these outcomes can be converted into useful information such as reminder for operator, especially on the return period of potential extreme environmental loading so that precautions can be developed in advance.

REFERENCES

Ayob, M. S., et al. Requalification of Offshore Jacket Structures in Malaysian Waters, Offshore Technology Conference.

Asgarian, B., & Lesani, M. (2009). Pile–soil-structure interaction in pushover analysis of jacket offshore platforms using fiber elements. *Journal of Constructional Steel Research, 65*(1), 209-218.

Bekker, A. T., et al. Steel Constructions Corrosion Wear Processes Modeling of Sea Hydraulic Engineering Structures, International Society of Offshore and Polar Engineers.

Bao, Y. X., Wang, J. R., & Li, H. J. *A Safety Assessment Method On Aging Offshore Platforms With Damages*.

Chaves, I. A. and R. E. Melchers (2014). "Extreme value analysis for assessing structural reliability of welded offshore steel structures." Structural Safety 50: 9-15.

Copello, S., & Castelli, P. (2013). *Life Extension of a Fixed Offshore Platform Structure Based on Monitoring Results.* Paper presented at the Offshore Mediterranean Conference and Exhibition.

Dong, W., Moan, T., & Gao, Z. (2011). Long-term fatigue analysis of multi-planar tubular joints for jacket-type offshore wind turbine in time domain. *Engineering Structures, 33*(6), 2002-2014.

Dong, W., Moan, T., & Gao, Z. (2012). Fatigue reliability analysis of the jacket support structure for offshore wind turbine considering the effect of corrosion and inspection. *Reliability Engineering & System Safety, 106*, 11-27.

Ersdal, G. (2005). Assessment of existing offshore structures for life extension. *Department of Mechanical and Structural Engineering and Material Sciences, University of Stavanger, Norway*.

Galbraith, D. N., Sharp, J. V., & Terry, E. *Managing life extension in Ageing offshore Installations*.

Haagensen, P., Larsen, J., & Vårdal, O. (2014). Long Term Effectiveness of Life Extension Methodologies Applied to Offshore Structures. *Procedia Materials Science, 3*, 2187-2194.

Hairil Mohd, M., & Paik, J. K. (2013). Investigation of the corrosion progress characteristics of offshore subsea oil well tubes. *Corrosion Science, 67*(0), 130-141. doi:

Honarvar, M., Bahaari, M., Asgarian, B., & Alanjari, P. (2007). Cyclic inelastic behavior and analytical modelling of pile–leg interaction in jacket type offshore platforms. *Applied Ocean Research, 29*(4), 167-179.

Hudson, B. (2009). Platform Life Extension. *Offshore Europe*.

Kovalenko, R. G. and L. V. Kim Durability Evaluation of Marine And Offshore Structures, International Society of Offshore and Polar Engineers.

Mejri, M., et al. (2011). "A time-variant reliability approach for ageing marine structures with non-linear behaviour." Computers & Structures 89(19–20): 1743-1753.

Melchers, R. E. (2005). The effect of corrosion on the structural reliability of steel offshore structures. *Corrosion Science, 47*(10), 2391-2410.

Melchers, R. E., & Jeffrey, R. (2005). Early corrosion of mild steel in seawater. *Corrosion Science, 47*(7), 1678-1693.

Melchers, R. E., & Jeffrey, R. (2008). Probabilistic models for steel corrosion loss and pitting of marine infrastructure. *Reliability Engineering & System Safety, 93*(3), 423-432.

Momber, A., Plagemann, P., & Stenzel, V. (2015). Performance and integrity of protective coating systems for offshore wind power structures after three years under offshore site conditions. *Renewable Energy, 74*, 606-617.

Paik, J. K. and D. K. Kim (2012). "Advanced method for the development of an empirical model to predict time-dependent corrosion wastage." Corrosion Science 63(0): 51-58.

PETRONAS Carigali Sendirian Berhad. (2013). PCSB Topside Inspection Guideline For

Offshore Structures. Malaysia: Petroliam Nasional Berhad.

PETRONAS Technical Standard. (2012). 34.19.10.30 Design of Fixed Offshore Structures. Malaysia: Petroliam Nasional Berhad.

Qi, Y., Zhang, Z., & Shi, P. (2010). Extreme Wind Wave And Current In Deep Water of South China Sea. *International Journal of Offshore and Polar Engineering, 20*(01).

Rodrigues, P. F. N., & Jacob, B. P. (2005). Collapse analysis of steel jacket structures for offshore oil exploitation. *Journal of Constructional Steel Research, 61*(8), 1147-1171.

Salau, M., Esezobor, D., & Omotoso, M. (2011). Risk based assessment for offshore jacket platform in Niger delta, Nigeria (corrosion and fatigue hazards).

Solland, G., Sigurdsson, G., & Ghosal, A. (2011). *Life Extension and Assessment of Existing Offshore Structures.* Paper presented at the SPE Project and Facilities Challenges Conference at METS.

Stacey, A., & Sharp, J. (2007). Safety factor requirements for the offshore industry. *Engineering Failure Analysis, 14*(3), 442-458.

Wang, Y., et al. (2014). "Ultimate strength analysis of aged steel-plated structures exposed to marine corrosion damage: A review." Corrosion Science 86(0): 42-60.

Wheat, H., & Liu, G. (2005). *Using Smart Coatings in Offshore Structures.* Paper presented at the The Fifteenth International Offshore and Polar Engineering Conference.

Wong, B. S., Ayob, M. S., Kajuputra, A. E., & Mukherjee, K. (2014). *Global Ultimate Strength Assessment of Existing Offshore Jacket Structures.* Paper presented at the Offshore Technology Conference-Asia.

Wright, I. (2011). Ageing and Life Extension of Offshore Oil and Gas Installations. *Offshore Europe*.

Zawawi, N. W. A., Liew, M., & Na, K. (2012). *Decommissioning of offshore platform: A sustainable framework.* Paper presented at the Humanities, Science and Engineering (CHUSER), 2012 IEEE Colloquium on.

Zhang, M., Beer, M., Quek, S., & Choo, Y. (2010). Comparison of uncertainty models in reliability analysis of offshore structures under marine corrosion. *Structural Safety, 32*(6), 425-432.

Zhang, Y., & Jin, W. (2010). *Reliability Evaluating of a Jacket Plat Form Example*. Paper presented at Twentieth International Offshore and Polar Engineering Conference.

APPENDICES

Unity Check (UC) Results

Category	Member	Length	D	t	D1 -10%	D2 - 25%	t1 - 10%	t2 - 25%	UC0	UC1	UC2	UC3	UC4
Group 1-Diagonal Members													
Diagonal	559-604	12.2671	58.6	1.34	52.874	44.285	1.203	0.9991	0.25	0.29	0.4	0.29	0.34
	603-559	11.8549	58.6	1.34	52.874	44.285	1.203	0.9991	0.24	0.26	0.32	0.26	0.32
	504-559	13.0692	61	2	55.1	46.25	1.794	1.4871	0.14	0.16	0.2	0.16	0.19
	503-559	13.4919	61	2	55.1	46.25	1.794	1.4871	0.18	0.21	0.27	0.21	0.25
	559-A044	8.10171	61	2	55.1	46.25	1.794	1.4871	0.09	0.11	0.16	0.11	0.14
	603-558	9.29629	58.6	1.34	52.874	44.285	1.203	0.9991	0.22	0.21	0.25	0.21	0.25
	602-558	8.99015	58.6	1.34	52.874	44.285	1.203	0.9991	0.28	0.47	0.47	0.39	0.41
	558-503	11.2316	61	2.54	55.154	46.385	2.276	1.8839	0.29	0.24	0.27	0.20	0.24
	502-558	11.5377	61	1.27	55.027	46.0675	1.141	0.9474	0.21	0.21	0.26	0.21	0.26
	602-501X	12.7163	58.6	1.34	52.874	44.285	1.203	0.9991	0.29	0.34	0.44	0.33	0.37
	601-501X	11.3763	58.6	1.34	52.874	44.285	1.203	0.9991	0.36	0.7	1.74	0.58	0.69
	502-501X	13.654	61	2	55.1	46.25	1.794	1.4871	0.32	0.63	1.26	0.52	0.61
	501-501X	10.6362	61	2	55.1	46.25	1.794	1.4871	0.18	0.23	0.29	0.23	0.27
	601-560	9.2571	58.6	1.34	52.874	44.285	1.203	0.9991	0.22	0.22	0.32	0.21	0.25
	560-604	8.9511	58.6	1.34	52.874	44.285	1.203	0.9991	0.21	0.25	0.3	0.26	0.31
	560-501	11.1855	61	2.54	55.154	46.385	2.276	1.8839	0.21	0.14	0.18	0.14	0.17
	504-560	11.4914	61	1.27	55.027	46.0675	1.141	0.9474	0.23	0.24	0.31	0.23	0.27
Group 2-Horizontal Members													
Horizontal	604-632	2.568	61	2	55.1	46.25	1.794	1.4871	0.03	0.36	0.47	0.33	0.37

	657-632	6.289	61	3	55.2	46.5	2.685	2.2201	0.01	0.1	0.12	0.09	0.09
	682-657	5.619	61	2.54	55.154	46.385	2.276	1.8839	0.02	0.15	0.2	0.13	0.14
	682-603	4.7694	61	2.54	55.154	46.385	2.276	1.8839	0.08	0.31	0.42	0.27	0.29
	937-603	2.5588	76.2	2.54	68.834	57.785	2.278	1.8883	0.31	0.45	0.63	0.4	0.48
	936-937	1	76.2	2.54	68.834	57.785	2.278	1.8883	0.08	0.13	0.17	0.12	0.14
	935-936	2	76.2	2.54	68.834	57.785	2.278	1.8883	0.17	0.27	0.37	0.25	0.3
	690-935	0.642	76.2	2.54	68.834	57.785	2.278	1.8883	0.18	0.28	0.37	0.26	0.3
	934-690	0.358	76.2	2.54	68.834	57.785	2.278	1.8883	0.2	0.29	0.38	0.27	0.31
	933-934	1	76.2	2.54	68.834	57.785	2.278	1.8883	0.2	0.3	0.4	0.27	0.32
	932-933	1	76.2	2.54	68.834	57.785	2.278	1.8883	0.17	0.25	0.32	0.23	0.27
	931-932	1	76.2	2.54	68.834	57.785	2.278	1.8883	0.14	0.2	0.28	0.18	0.22
	930-931	1	76.2	2.54	68.834	57.785	2.278	1.8883	0.12	0.1	0.12	0.09	0.11
	602-930	1.8428	76.2	2.54	68.834	57.785	2.278	1.8883	0.38	0.54	0.46	0.49	0.59
	602-9457	2.8884	61	2	55.1	46.25	1.794	1.4871	0.59	0.74	0.99	0.68	0.81
	9457-9458	1	61	2	55.1	46.25	1.794	1.4871	0.31	0.44	0.58	0.4	0.47
	9458-680	0.881	61	2.54	55.154	46.385	2.276	1.8839	0.4	0.49	0.66	0.44	0.52
	680-9459	0.119	61	2.54	55.154	46.385	2.276	1.8839	0.34	0.41	0.57	0.39	0.45
	9459-9460	1	61	2.54	55.154	46.385	2.276	1.8839	0.46	0.43	0.55	0.4	0.46
	9460-9461	1.7	61	2	55.1	46.25	1.794	1.4871	0.45	0.56	0.79	0.52	0.62
	9461-9462	1	61	2	55.1	46.25	1.794	1.4871	0.21	0.2	0.31	0.18	0.22
	649-9462	1.1905	61	2	55.1	46.25	1.794	1.4871	0.52	0.71	1.07	0.64	0.78
	649-614	5.6795	61	1.59	55.059	46.1475	1.427	1.1844	0.15	0.17	0.18	0.17	0.19
	601-614	2.568	61	2	55.1	46.25	1.794	1.4871	0.08	0.09	0.1	0.09	0.11
	601-611	1.5508	61	3	55.2	46.5	2.685	2.2201	0.05	0.24	0.33	0.22	0.25

	611-944	2.608	61	3	55.2	46.5	2.685	2.2201	0.06	0.13	0.19	0.11	0.13
	944-945	0.8	61	2	55.1	46.25	1.794	1.4871	0.06	0.17	0.21	0.15	0.18
	613-945	5.892	61	2	55.1	46.25	1.794	1.4871	0.06	0.17	0.21	0.16	0.18
	604-613	1.5508	61	2	55.1	46.25	1.794	1.4871	0.05	0.25	0.32	0.23	0.26
	523-504	4	61	2.54	55.154	46.385	2.276	1.8839	0.06	0.05	0.06	0.05	0.06
	535-523	4.85	61	2.54	55.154	46.385	2.276	1.8839	0.04	0.04	0.04	0.04	0.04
	A044-535	0.934	61	2.54	55.154	46.385	2.276	1.8839	0.06	0.07	0.08	0.07	0.09
	542-A044	5.741	61	2.54	55.154	46.385	2.276	1.8839	0.06	0.07	0.08	0.07	0.08
	503-542	5.8194	61	2	55.1	46.25	1.794	1.4871	0.13	0.16	0.26	0.14	0.16
	548-503	4.7618	61	1.59	55.059	46.1475	1.427	1.1844	0.12	0.14	0.2	0.14	0.16
	547-548	3	61	2	55.1	46.25	1.794	1.4871	0.11	0.11	0.16	0.1	0.12
	546-547	0.142	61	2	55.1	46.25	1.794	1.4871	0.06	0.07	0.12	0.06	0.08
	546-590	1.858	61	2	55.1	46.25	1.794	1.4871	0.05	0.06	0.08	0.06	0.08
	590-545	2	61	1.59	55.059	46.1475	1.427	1.1844	0.09	0.1	0.14	0.1	0.12
	502-545	4.0458	61	1.59	55.059	46.1475	1.427	1.1844	0.13	0.15	0.2	0.14	0.17
	502-543	5.4944	61	2	55.1	46.25	1.794	1.4871	0.08	0.08	0.08	0.09	0.1
	543-541	0.325	61	2.54	55.154	46.385	2.276	1.8839	0.04	0.05	0.06	0.06	0.07
	540-541	1.675	61	2	55.1	46.25	1.794	1.4871	0.1	0.11	0.16	0.11	0.13
	591-540	2.7	61	2	55.1	46.25	1.794	1.4871	0.06	0.08	0.1	0.08	0.09
	529-591	1.6905	61	2	55.1	46.25	1.794	1.4871	0.08	0.08	0.1	0.09	0.11
	529-522	4.2405	61	2	55.1	46.25	1.794	1.4871	0.09	0.1	0.11	0.11	0.12
	522-501	4	61	2.54	55.154	46.385	2.276	1.8839	0.1	0.1	0.11	0.1	0.11
	501-519	3.0208	61	1.59	55.059	46.1475	1.427	1.1844	0.08	0.08	0.1	0.08	0.1
	519-520	3.241	61	2	55.1	46.25	1.794	1.4871	0.12	0.15	0.19	0.14	0.17

	521-520	6.525	61	2	55.1	46.25	1.794	1.4871	0.08	0.08	0.1	0.08	0.09
	521-504	3.0208	61	2	55.1	46.25	1.794	1.4871	0.11	0.1	0.13	0.1	0.12
	613-623	3.106	50.8	2	45.92	38.6	1.792	1.4843	0.02	0.11	0.13	0.1	0.11
	631-623	1.178	50.8	2.54	45.974	38.735	2.273	1.8793	0.02	0.03	0.15	0.03	0.03
	640-631	2.272	50.8	2.54	45.974	38.735	2.273	1.8793	0.03	0.04	0.05	0.04	0.04
	656-640	2.839	50.8	2.54	45.974	38.735	2.273	1.8793	0.02	0.07	0.09	0.06	0.07
	656-676	1.789	45.7	2.54	41.384	34.91	2.272	1.8761	0.01	0.07	0.08	0.07	0.07
	676-679	1.6279	45.7	2.54	41.384	34.91	2.272	1.8761	0.02	0.11	0.16	0.1	0.1
	611-615	3.106	50.8	2	45.92	38.6	1.792	1.4843	0.07	0.08	0.12	0.07	0.09
	624-615	1.178	50.8	2.54	45.974	38.735	2.273	1.8793	0.03	0.04	0.06	0.03	0.04
	633-624	2.272	50.8	2.54	45.974	38.735	2.273	1.8793	0.06	0.07	0.11	0.06	0.07
	650-633	2.839	50.8	2.54	45.974	38.735	2.273	1.8793	0.05	0.11	0.14	0.09	0.11
	650-667	1.789	45.7	2.54	41.384	34.91	2.272	1.8761	0.07	0.13	0.17	0.12	0.13
	667-678	1.6279	45.7	2.54	41.384	34.91	2.272	1.8761	0.06	0.11	0.1	0.08	0.08
	518-521	2.495	50.8	2	45.92	38.6	1.792	1.4843	0.15	0.1	0.13	0.09	0.11
	518-528	3.45	50.8	2	45.92	38.6	1.792	1.4843	0.18	0.12	0.17	0.11	0.13
	534-528	3.145	50.8	0.95	45.815	38.3375	0.853	0.7091	0.08	0.07	0.11	0.1	0.16
	514-519	2.495	50.8	2	45.92	38.6	1.792	1.4843		0.2	0.29	0.18	0.22
	524-514	3.45	50.8	2	45.92	38.6	1.792	1.4843	0.1	0.07	0.08	0.07	0.08
	530-524	3.145	50.8	0.95	45.815	38.3375	0.853	0.7091	0.08	0.08	0.11	0.1	0.16
	623-632	1.839	45.7	2	41.33	34.775	1.792	1.4824	0.02	0.07	0.09	0.05	0.06
	622-623	0.408	45.7	1.59	41.289	34.6725	1.426	1.1816	0.02	0.05	0.07	0.04	0.05
	621-622	1.076	45.7	1.59	41.289	34.6725	1.426	1.1816	0.01	0.06	0.07	0.06	0.06
	620-621	2.374	45.7	1.9	41.32	34.75	1.702	1.4092	0.01	0.07	0.06	0.05	0.06

	620-619	0.538	45.7	1.9	41.32	34.75	1.702	1.4092	0.02	0.04	0.04	0.04	0.04
	619-618	0.538	45.7	1.9	41.32	34.75	1.702	1.4092	0.04	0.09	0.13	0.09	0.1
	618-617	2.374	45.7	1.9	41.32	34.75	1.702	1.4092	0.04	0.07	0.08	0.07	0.07
	616-617	1.076	45.7	1.59	41.289	34.6725	1.426	1.1816	0.03	0.04	0.04	0.04	0.04
	615-616	0.408	45.7	1.59	41.289	34.6725	1.426	1.1816	0.03	0.03	0.04	0.03	0.03
	614-615	1.839	45.7	2	41.33	34.775	1.792	1.4824	0.05	0.08	0.09	0.07	0.07
	633-640	8.792	45.7	2	41.33	34.775	1.792	1.4824	0.02	0.07	0.08	0.06	0.07
	657-656	1.839	50.8	1.27	45.847	38.4175	1.14	0.9463	0.03	0.06	0.07	0.05	0.06
	655-656	0.408	50.8	2.54	45.974	38.735	2.273	1.8793	0.02	0.05	0.06	0.04	0.04
	654-655	1.076	50.8	2	45.92	38.6	1.792	1.4843	0.02	0.06	0.06	0.05	0.06
	654-653	2.912	50.8	2	45.92	38.6	1.792	1.4843	0.02	0.07	0.08	0.06	0.07
	652-653	2.912	50.8	2	45.92	38.6	1.792	1.4843	0.04	0.08	0.1	0.08	0.08
	652-651	1.076	50.8	2	45.92	38.6	1.792	1.4843	0.04	0.04	0.06	0.04	0.05
	650-651	0.408	50.8	2.54	45.974	38.735	2.273	1.8793	0.04	0.04	0.06	0.04	0.04
	649-650	1.5306	50.8	1.27	45.847	38.4175	1.14	0.9463	0.15	0.45	0.58	0.4	0.46
	517-518	1.179	45.7	1.59	41.289	34.6725	1.426	1.1816	0.1	0.15	0.22	0.13	0.16
	516-517	3.45	45.7	1.59	41.289	34.6725	1.426	1.1816	0.1	0.11	0.14	0.1	0.12
	515-516	3.45	45.7	1.59	41.289	34.6725	1.426	1.1816	0.18	0.22	0.3	0.2	0.24
	514-515	1.179	45.7	1.59	41.289	34.6725	1.426	1.1816	0.27	0.32	0.43	0.3	0.36
	524-528	9.258	45.7	1.59	41.289	34.6725	1.426	1.1816	0.03	0.05	0.04	0.05	0.06
	534-535	3.57	61	2	55.1	46.25	1.794	1.4871	0.11	0.08	0.09	0.09	0.1
	534-533	1.433	61	2	55.1	46.25	1.794	1.4871	0.06	0.07	0.08	0.07	0.08
	532-533	3.45	61	2	55.1	46.25	1.794	1.4871	0.12	0.13	0.18	0.13	0.15
	532-531	3.45	61	2	55.1	46.25	1.794	1.4871	0.06	0.06	0.08	0.06	0.07

	530-531	1.433	61	2	55.1	46.25	1.794	1.4871	0.07	0.08	0.11	0.07	0.09
	530-529	3.2618	61	2	55.1	46.25	1.794	1.4871	0.12	0.09	0.11	0.09	0.1
	682-679	2.63409	45.7	1.59	41.289	34.6725	1.426	1.1816	0.07	0.17	0.23	0.14	0.17
	673-679	3.02843	45.7	2.54	41.384	34.91	2.272	1.8761	0.03	0.08	0.11	0.08	0.09
	673-661	2.23215	45.7	2.54	41.384	34.91	2.272	1.8761	0.02	0.07	0.08	0.06	0.07
	660-653	0.6881	45.7	2.54	41.384	34.91	2.272	1.8761	0.03	0.02	0.02	0.02	0.02
	670-660	2.23215	45.7	2.54	41.384	34.91	2.272	1.8761	0.03	0.03	0.05	0.03	0.03
	678-670	3.02843	45.7	2.54	41.384	34.91	2.272	1.8761	0.04	0.09	0.1	0.08	0.08
	680-678	2.63409	45.7	1.59	41.289	34.6725	1.426	1.1816	0.14	0.15	0.22	0.16	0.18
	690-680	7.96109	45.7	1.59	41.289	34.6725	1.426	1.1816	0.07	0.09	0.11	0.08	0.09
	690-682	7.96109	45.7	1.59	41.289	34.6725	1.426	1.1816	0.05	0.07	0.09	0.06	0.07
	542-532	10.0185	50.8	0.95	45.815	38.3375	0.853	0.7091	0.16	0.18	0.22	0.18	0.23
	541-538	9.82471	50.8	0.95	45.815	38.3375	0.853	0.7091	0.1	0.1	0.14	0.13	0.23
	546-541	10.0195	50.8	0.95	45.815	38.3375	0.853	0.7091	0.1	0.11	0.14	0.13	0.23
	546-542	10.0195	50.8	0.95	45.815	38.3375	0.853	0.7091	0.2	0.22	0.26	0.22	0.27
Group 3-Jacket Legs Members													
Jacket Legs	604-923	3.63607	168.6	4.3	152.17001	127.52501	3.86	3.2038	0.11	0.1	0.12	0.1	0.11
	926-923	6.01182	164	2	147.8	123.5	1.798	1.4953	0.11	0.13	0.16	0.14	0.15
	919-926	3.37178	164	2	147.8	123.5	1.798	1.4953	0.11	0.13	0.15	0.14	0.15
	504-919	4.16562	170	5	153.5	128.75	4.486	3.7215	0.11	0.09	0.11	0.09	0.1
	603-715	2.69689	168.6	4.3	152.17001	127.52501	3.86	3.2038	0.1	0.09	0.11	0.09	0.1
	729-715	4.79732	165.2	2.6	148.94	124.55	2.336	1.9423	0.1	0.11	0.13	0.11	0.12
	503-729	9.8205	170	5	153.5	128.75	4.486	3.7215	0.09	0.08	0.09	0.08	0.08
	602-739	2.69689	168.6	4.3	152.17001	127.52501	3.86	3.2038	0.15	0.13	0.16	0.13	0.14

	738-739	4.79732	165.2	2.6	148.94	124.55	2.336	1.9423	0.15	0.17	0.2	0.17	0.19
	502-738	9.8205	170	5	153.5	128.75	4.486	3.7215	0.15	0.12	0.15	0.12	0.14
	649-A043	2.66693	119.5	2.3	107.78	90.2	2.066	1.7167	0.43	0.22	0.21	0.22	0.25
	A043-A045	4.77024	119.5	0.8	107.63	89.825	0.72	0.5965	0.34	0.45	0.51	0.46	0.56
	A045-501X	1.78033	119.5	0.8	107.63	89.825	0.72	0.5965	0.31	0.41	0.46	0.42	0.52
	529-501X	7.97073	121.9	3.5	110.06	92.3	3.141	2.6031	0.1	0.05	0.06	0.05	0.06
	601-924	3.63607	168.6	4.3	152.17001	127.52501	3.86	3.2038	0.14	0.13	0.17	0.13	0.14
	925-924	6.01182	164	2	147.8	123.5	1.798	1.4953	0.15	0.19	0.22	0.19	0.21
	918-925	3.37178	164	2	147.8	123.5	1.798	1.4953	0.15	0.19	0.22	0.19	0.21
	501-918	4.16562	170	5	153.5	128.75	4.486	3.7215	0.15	0.12	0.14	0.12	0.13

<u>Tabulation Of Reserve Strength Ratio, Reliability Index And Probability Of Failure</u>

No	Case	Load	Base Shear	First Member Failure	RSR	Reliability Index	Probability Of Failure
1	**Original**	ST01	8187.85	20891.49	2.5515	5.6854	6.53E-09
		ST02	18075.29	32775.49	1.8133	4.1613	1.58E-05
		ST03	8956.02	37079.17	4.1401	7.4815	3.67E-14
		ST04	9283.86	30992.87	3.3384	6.7573	7.03E-12
		ST05	9344.75	26198.20	2.8035	6.0788	6.05E-10
		ST06	9134.30	30471.01	3.3359	6.7545	7.17E-12
		ST07	9222.15	23621.62	2.5614	5.7018	5.93E-09
		ST08	9221.86	21821.64	2.3663	5.3597	4.17E-08
		ST09	9122.84	23212.12	2.5444	5.6735	7.00E-09
2	**Bracing 10% D**	ST01	8130.01	20741.22	2.5512	5.6849	6.55E-09
		ST02	17954.32	32262.05	1.7969	4.1197	1.90E-05
		ST03	8900.93	36837.88	4.1387	7.4804	3.70E-14
		ST04	9226.67	30798.44	3.3380	6.7568	7.05E-12
		ST05	9279.02	24154.72	2.6032	5.7705	3.95E-09
		ST06	9077.79	30278.85	3.3355	6.7541	7.19E-12
		ST07	9167.80	23480.59	2.5612	5.7015	5.94E-09
		ST08	9167.52	21691.18	2.3661	5.3593	4.18E-08
		ST09	9063.61	23059.57	2.5442	5.6731	7.01E-09
3	**Bracing 10% t**	ST01	8178.72	20867.80	2.5515	5.6854	6.53E-09
		ST02	18058.45	32745.29	1.8133	4.1613	1.58E-05
		ST03	8949.05	37047.20	4.1398	7.4812	3.68E-14
		ST04	9275.65	30965.02	3.3383	6.7572	7.04E-12

		ST05	9334.69	26170.06	2.8035	6.0788	6.05E-10
		ST06	9126.21	30443.50	3.3358	6.7544	7.17E-12
		ST07	9215.16	23603.67	2.5614	5.7018	5.93E-09
		ST08	9214.88	21804.87	2.3663	5.3597	4.17E-08
		ST09	9114.40	23191.68	2.5445	5.6736	6.99E-09
4	**Bracing 25% D**	ST01	8053.59	18981.62	2.3569	5.3422	4.59E-08
		ST02	17791.59	32265.76	1.8135	4.1618	1.58E-05
		ST03	8825.61	36521.70	4.1382	7.4801	3.71E-14
		ST04	9149.01	28752.93	3.1427	6.5309	3.27E-11
		ST05	9190.28	23924.47	2.6032	5.7705	3.95E-09
		ST06	9001.71	28268.54	3.1404	6.5281	3.33E-11
		ST07	9094.55	23290.04	2.5609	5.701	5.95E-09
		ST08	9094.28	21515.29	2.3658	5.3587	4.19E-08
		ST09	8984.49	21120.56	2.3508	5.3309	4.89E-08
5	**Bracing 25% t**	ST01	8179.10	20868.66	2.5515	5.6954	6.53E-09
		ST02	18058.61	32746.13	1.8133	4.1613	1.58E-05
		ST03	8949.04	37047.98	4.1399	7.4813	3.68E-14
		ST04	9275.61	29158.04	3.1435	6.5319	3.25E-11
		ST05	9334.76	24300.10	2.6032	5.7705	3.95E-09
		ST06	9126.28	26891.19	2.9466	6.2795	1.70E-10
		ST07	9215.34	21805.40	2.3662	5.3595	4.17E-08
		ST08	9215.07	21805.35	2.3663	5.3597	4.17E-08
		ST09	9114.72	21432.55	2.3514	5.332	4.86E-08
6	**Horizontal 10% D**	ST01	8144.07	20777.78	2.5513	5.685	6.54E-09
		ST02	18016.04	8854.26	0.4915	-1.0645	0.85644672

		ST03	8899.52	31592.12	3.5499	6.9774	1.50E-12
		ST04	9240.99	30847.09	3.3381	6.7569	7.05E-12
		ST05	9296.64	24200.50	2.6031	5.7704	3.96E-09
		ST06	9091.90	30326.90	3.3356	6.7542	7.18E-12
		ST07	9167.28	23479.27	2.5612	5.7015	5.94E-09
		ST08	9166.98	23479.33	2.5613	5.7017	5.93E-09
		ST09	9077.49	23094.24	2.5441	5.673	7.02E-09
7	**Horizontal 10% t**	ST01	8188.17	20892.40	2.5515	5.6854	6.53E-09
		ST02	18077.95	29100.88	1.6097	3.6162	1.49E-04
		ST03	8960.58	35327.74	3.9426	7.3288	1.16E-13
		ST04	9285.64	30998.90	3.3384	6.7573	7.03E-12
		ST05	9345.06	26198.99	2.8035	6.0788	6.05E-10
		ST06	9136.27	30477.72	3.3359	6.7545	7.17E-12
		ST07	9226.92	23634.10	2.5614	5.7018	5.93E-09
		ST08	9226.62	21833.14	2.3663	5.3597	4.17E-08
		ST09	9124.80	23217.22	2.5444	5.6735	7.00E-09
8	**Horizontal 25% D**	ST01	8080.13	20611.73	2.5509	5.6844	6.57E-09
		ST02	-	3523.67	-	-	-
		ST03	8816.63	24377.50	2.7649	6.022	8.62E-10
		ST04	9177.73	27055.63	2.9480	6.2814	1.68E-10
		ST05	9225.40	24015.33	2.6032	5.7705	3.95E-09
		ST06	9029.19	26599.83	2.9460	6.2787	1.71E-10
		ST07	9086.60	23269.16	2.5608	5.7009	5.96E-09
		ST08	9086.30	23269.21	2.5609	5.701	5.95E-09
		ST09	9011.20	22922.92	2.5438	5.6725	7.04E-09

9	**Horizontal 25% t**	ST01	8188.19	20892.54	2.5515	5.6854	6.53E-09
		ST02	18074.77	8886.89	0.4917	-1.0632	8.56E-01
		ST03	8960.57	30054.24	3.3541	6.7744	6.24E-12
		ST04	9285.62	30998.90	3.3384	6.7573	7.03E-12
		ST05	9345.03	26198.97	2.8035	6.0788	6.05E-10
		ST06	9136.25	30477.66	3.3359	6.7545	7.17E-12
		ST07	9226.92	23634.40	2.5615	5.702	5.92E-09
		ST08	9226.62	21833.17	2.3663	5.3597	4.17E-08
		ST09	9124.81	23217.47	2.5444	5.6735	7.00E-09
10	**Leg 10% D**	ST01	8091.80	22210.32	2.7448	5.9919	1.04E-09
		ST02	17895.69	34271.62	1.9151	4.4108	5.15E-06
		ST03	8867.08	36694.25	4.1383	7.4801	3.71E-14
		ST04	9196.80	32487.71	3.5325	6.9602	1.70E-12
		ST05	9253.77	25943.35	2.8035	6.0788	6.05E-10
		ST06	9042.69	30160.16	3.3353	6.7539	7.20E-12
		ST07	9128.42	23378.15	2.5610	5.7012	5.95E-09
		ST08	9128.13	23378.30	2.5611	5.7013	5.94E-09
		ST09	9028.86	24712.06	2.7370	5.9801	1.11E-09
11	**Leg 10% t**	ST01	8197.20	20915.75	2.5516	5.6855	6.52E-09
		ST02	18097.89	32815.39	1.8132	4.161	1.58E-05
		ST03	8966.72	37113.12	4.1390	7.4807	3.70E-14
		ST04	9294.19	31027.26	3.3384	6.7573	7.03E-12
		ST05	9353.74	26223.22	2.8035	6.0788	6.05E-10
		ST06	9141.79	30496.98	3.3360	6.7546	7.16E-12
		ST07	9229.52	23641.45	2.5615	5.702	5.92E-09

		ST08	9229.23	23641.52	2.5616	5.7022	5.91E-09
		ST09	9130.75	23233.06	2.5445	5.6736	6.99E-09
12	**Leg 25% D**	ST01	7947.34	18725.62	2.3562	5.3409	4.62E-08
		ST02	17598.54	26547.59	1.5085	3.3202	4.50E-04
		ST03	8722.42	36086.48	4.1372	7.4793	3.74E-14
		ST04	9053.70	28447.82	3.1421	6.5302	3.28E-11
		ST05	9064.36	23597.78	2.6034	5.7708	3.94E-09
		ST06	8897.02	29666.61	3.3344	6.7529	7.25E-12
		ST07	8981.49	22996.48	2.5604	5.7002	5.98E-09
		ST08	8981.30	22996.88	2.5605	5.7004	5.98E-09
		ST09	8880.88	20870.42	2.3500	5.3294	4.93E-08
13	**Leg 25% t**	ST01	8197.30	17736.25	2.1637	4.9631	3.47E-07
		ST02	18097.87	25456.67	1.4066	3.0038	0.001333106
		ST03	8966.62	37119.79	4.1398	7.4812	3.68E-14
		ST04	9293.92	25593.66	2.7538	6.0054	9.54E-10
		ST05	9353.46	20599.81	2.2024	5.0423	2.30E-07
		ST06	9141.57	30496.70	3.3360	6.7546	7.16E-12
		ST07	9229.47	23641.38	2.5615	5.702	5.92E-09
		ST08	9229.23	23641.36	2.5616	5.7022	5.91E-09
		ST09	9130.80	19707.54	2.1584	4.9521	3.67E-07