TIME DEPENDENT RELIABILITY ASSESSMENT OF MALAYSIA’S JACKET PLATFORM

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Time Dependent Reliability Assessment of Malaysia's Jacket Platform

by

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Bachelor of Engineering (Hons)

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Universiti Teknologi PETRONAS,

32610, Bandar Seri Iskandar,

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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A project dissertation

submitted to the

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BANDAR SERI ISKANDAR, PERAK

September 2016

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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MOHAMAD HAIQAL BIN AZHAR

ABSTRACT

The offshore jacket platform is certainly facing the harsh environment in the sea. Typically, the resistance of the jacket platform is assumed to be constant throughout its design life. However, the exposure of jacket platform to the sea environment and occurrence of corrosion will definitely reduce the resistance of the platform. The situation could lead to the failure of the jacket platform as the environmental load will be continuously acting on the structure. Hence, the time dependent reliability method is extremely needed to assess the reliability of the jacket platform in different reference time. By performing time dependent reliability method, the probability of failure of the jacket platform in different reference time is expected as the outcome of this study. The time dependent reliability analysis is conducted based on limit state function. In order to satisfy the limit state function, the variables such as resistance and load are scrutinized. In this study, platform A located near shore of Bintulu, Sarawak is selected. The pushover analysis is conducted utilizing SACS software. The analysis is conducted in different nine directions and Reserve Strength Ratio (RSR) in every 10 years until 50 years is recorded. The probability of failure is obtained by analyzing the time dependent probability model using the First Order Reliability Method (FORM). The Finite Element Reliability Using MATLAB (FERUM) is adopted to perform FORM. The result from the pushover analysis showed that the critical RSR is from direction 45˚ which is the lowest compared to other directions. The RSR results showed downward trend which proved the resistance of the structure decrease over time. The result of FORM displayed upward trend and it proved that the probability of failure increased over time. Hence, the relationship between RSR and Probability of failure has been made in which the probability of failure is inversely related to RSR in different reference time.

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CHAPTER 1

INTRODUCTION

1.1 Background

At present, offshore jacket platform is commonly used for production of oil and gas around the world. With regard of downturn trend of crude oil price, the operational cost related to oil and gas industry was optimized. However, this cost optimization should not compromise the safety of the structure and necessary assessment of oil and gas platform should be conducted. Otherwise, it will contribute to the failure of the platform in which will lead to devastated consequences to human. Therefore, a lot of approaches were studied to assess the reliability and integrity of the offshore platform. Most of the reliability assessment method are traditional in which the resistance of the structure was considered constant throughout it design life. Hence, the reliability assessment method that considers the degradation of resistance of structure is more realistic.

By time, the resistance of a jacket platform decreases from its original value due to corrosion, fatigue, fracture and so on. Hence, realistic reliability assessment approach should be developed in order to assess the structure which consider the changing of resistance over time (Bai et al.,2015). Three main elements that play a huge role in the reliability assessment of the structure are the limit state function, resistance of the structure and load acting on the structure. Some parameters of these three elements are likely to be uncertain and its model are essential in order to perform the reliability assessment. Hence, this project will carry out the probability framework in order to perform the time dependent reliability assessment method. The framework will utilize probabilistic approach in order to obtain the robust result of probability failure of jacket platform.

The failure of mode in this study is base shear failure. The resistance of jacket platform is represented as global ultimate capacity and herein it will be denoted as base shear capacity. The corrosion of the structural members causes the degradation of global ultimate capacity of the structure. One of the reason of the degradation of the base shear capacity are thickness reduction due to corrosion. Hence, corrosion model should be referred from previous studies in order to determine the thickness reduction mathematical function.

Meanwhile, the load model should be referred from previous study in order to estimate the realistic load imposed on the structure. South China sea was selected as the subject of the study where the environmental load effect will consider the storm load.

1.2 Problem Statement

Reliability assessment method is used as a method to evaluate the safety of the offshore jacket platform. Typically, the resistance of offshore jacket platform is assumed to be constant during it design life. However, the resistance of offshore jacket platform will decrease as the time passes due to corrosion, fatigue, cracking, fracture and so on. Meanwhile, jacket platform will continuously resist the maximum load effect of ocean even though the resistance of the structure is decreased. Therefore, the resistance of the platform should not assume to be constant during its design life. This unrealistic assumption of the resistance will contribute to the failure of the platform. The occurrence of corrosion will reduce the thickness of structural members and eventually reduce its strength. At the same time, the extreme weather in South China Sea will definitely affect the jacket platform. The storm load that considered wind, wave and current and parameters is possibly acting on the jacket platform. Consequently, platform workers will face the huge risk of structural failure and devastated consequences to the environment are likely to occur. Besides, the production of oil will be affected and the losses could be huge. Hence, in this study, time dependent reliability assessment of offshore jacket platform that consider the reduction of resistance will be considered. This work will discuss the effect of corrosion on the resistance of the Malaysia's offshore jacket platform located in South China sea.

1.2 Objectives

The aim of this project is to perform reliability assessment of an offshore jacket platform using time dependent reliability assessment. In this regard, the resistance and load model are scrutinized in order to obtain the probability of failure. Hence, objectives of this study are as follow:

- To acquire the Reserve Strength Ratio(RSR) in different reference time.
- To obtain the probability of failure of Malaysia's offshore jacket platform for different reference time.

1.3 Scope of Study

The scope of study can be portrayed as listed below:

- The jacket platform which located in Malaysia water will be selected as a subject in order to obtain the result from the time dependent reliability assessment.
- The failure mode in this study is base shear failure.
- Finite element software such as SACS will be utilized to conduct the pushover analysis of the jacket platform.
- Computer software such as MATLAB and Microsoft Office Excel is to be used to compute the model and to perform typical computing task respectively.
- Probabilistic approach such as First Order Reliability Method (FORM) is to be practiced to determine the probability failure of the structure.
- Limit state design is exercised in this study to obtain the probability failure of the structure for different reference time and Finite Element Reliability Using MATLAB (FERUM) will be used to solve the limit state equation.

- The load model from the previous study is referred to satisfy the limit state function.
- Corrosion model from literature is to be used in this study in order to determine the thickness reduction of the structural members.
- The corrosion only applied to the splash zone and immersion zone in which the splash zone is +5.0 above mean sea level and -3.0 below mean sea level.
- The data of the platform model and metocean are provided by the owner.
- No changes are made in dead load and live load in the analysis of the platform.

CHAPTER 2

LITERATURE REVIEW

Reliability is defined as tendency of undesirable performance the structure (Ciampoli and Ellingwood, 2002). In this context, factors that influence the reliability of a structure are corrosion, fatigue and fractures. Ellingwood and Mori (1997) agreed that the severe service condition, aggressive environment as well as accident which are the structural aging of reinforced concrete structures may cause their strength and stiffness to decrease over time. Soom et al. (2015) stressed that as the structural integrity and reliability are concerned, the significant changes of platform loading were caused by major modification and fatigue. Braverman et al. (2004) insisted that the essential of knowledge of the effect of aging degradation on structures to ensure the structure maintained under all loading conditions. This is because the level of understanding of age-related degradation may affect the dynamic properties (stiffness, frequency, and damping), structural response, structural resistance/capacity, failure mode, and location of failure initiation is not well understood. Mori and Ellingwood (1993) emphasized that time-dependent effects on in-situ strength must be considered in assessing the effects of aging and possible structural deterioration of new or existing concrete structures. There are many studies regarding time dependent reliability assessment was conduct previously. Some researches of reliability has also been done on ships and offshore structures for example (Mohd et al., 2000). Studies on time dependent reliability assessment was conducted by Bai et al. (2015) and proper time dependent reliability model was developed. Besides, the time dependent reliability analysis model of ageing platform in ice zone was explained which the reliability of ageing platform in Bohai Bay was demonstrated by the time dependent reliability assessment (Chen and Chen,2010). This studies yielded the different results of reliability and failure rate changing over time. Ellingwood and Mori (1997) state that the probability failure of a structural member can be analyze over a function of time interval. However, this can be done if the probabilistic process determining the residual strength and probabilistic characteristics of the loads at any time are known.

Bai et al. (2015) claimed that the resistance of the structure decrease as the time being due to corrosion, fatigue and fractures. This statement was agreed by Chen and Chen (2010) that stated the structural member or system resistance will degrade due to ageing effects and the risk of failure of the structural will accelerate over time. Ciampoli and Ellingwood (2002) also emphasized that the strength and stiffness will deteriorate over time due to ageing effects. According to the authors, the loads imposed on the structure from its operations and environmental are uncertain. Stewart and Rosowsky (1998) stressed that probabilistic analysis is the useful assessment toll as it provides reliable criteria in order to compare the effectiveness of decisions taken under uncertainty. Similarly, the structural capacity of the structure was also uncertain in nature. Hence, in order to analyze these uncertainties rationally, the framework of probability theory was introduced. Bai et al. (2015) shared the same perception as the probability model of time dependent reliability assessment was demonstrated in their paper. In addition, probability model of resistance and load effects were presented in their paper. The time dependent probability model was presented and Bai et al. (2015) indicated that the resistance and load effect of the structure to N segments separately in assessment period. Then, through the mathematical transformation, the time dependent probability model was developed as the resistance and load effected were dependent to the probability model. The probability model of resistance of jacket platform was further explained in this studies.

According to Kameda and Koike (1975), structural resistance of the structure can be expressed as $R(t) = \phi(t)Ro$ as the $R(t)$ is the residual resistance, $\phi(t)$ is the degradation function and Ro is initial resistance. This mathematical expression has been agreed by Bai et al (2015) and Ciampoli and Ellingwood (2002) as well as Chen and Chen (2010). Bai et al. (2015) proposed PDS module of ANSYS software could be used in order to obtain the probability model of platform base shear capacity which the process of the PDS analysis is Monte Carlo simulation. Chen and Chen (2010) added that the initial resistance can simply be determined by studying the base shear force of the platform as the probabilistic characteristic is likely affected by the geometric and mechanical properties. However, Chen and Chen (2010) explained that offshore platform is indeterminate structure which consist high degree of freedom.

Hence, ANSYS PDS with Monte Carlo simulation method was utilized in order to determine the probability characteristic of resistance and load effects. Li (1995) emphasized that the only realistic way to deal with structural deterioration problem is Monte Carlo analysis. Stewart and Rosowsky (1998) emphasized the time-dependent actions which are corrosion affect and reliability can be quantified by Monte Carlo simulation analysis. Qin and Cui (2003) stated that marine corrosion can be divided into four categories which are immersion, splash zone, atmospheric and semi enclosed space. Meanwhile, Bai et al. (2015) concluded that the corrosion zone of jacket platform can be divided into three parts which are atmospheric zone, splash zone and full immersion zone. He also added that the corrosion rate is high in splash zone.

One of the important parameter in order to determine the residual resistance is degradation function and present corrosion model should be selected. The corrosion protection system (CPS) proposed by Qin and Cui (2003) was considered in the present corrosion model (Bai et al., 2015). Qin and Cui (2003) concluded in their report that the whole corrosion is break down into three parts; no corrosion, corrosion accelerating and corrosion slowing down. Chen and Chen (2010) implied that Weibull function will be used in order to describe the corrosion rate. Similarly, Bai et al. (2015) also agreed that the Weibull formulation will be used to describe the corrosion rate. He also added that four parameters of Weibull equations need to be determined. This equation will yield the corrosion rate and corrosion wastage of the structure. Due to corrosion of the structural member every year, the remaining diameter and thickness of the structural member was analyzed and finite element method(FEM) was used to calculate the base shear capacity (Bai et al., 2015). Then, numerical fitting method was used to determine the degradation function (Chen and Chen, 2010).

Chen and Chen (2010) stated that Weibull extreme distribution parameters will be used in order to fit the extreme value of the wind, wave and current parameters for typhoon. Bai et al. (2015) suggested that the Monte Carlo method was used in order to analyze the probability of the load effect. Similarly, Chen and Chen (2010) demonstrated the Monte Carlo simulation in order to determine the probability of load effects. For the determination of the degradation function, Chen and Chen (2010) utilized nonlinear collapse analysis method to calculate the base shear force of the platform in the ultimate limit state. Meanwhile, Bai et al. (2015) established the finite element model of the jacket's platform in order for the front part to get the base shear capacity. He also explained the methodology to obtain the initial base shear capacity in his studies. After getting the base shear capacity, the probability characteristic such as distribution type and distribution parameter was set as the input parameters. The output parameter was appointed, the output parameter is chosen and the solution is found. Finally, the probability characteristic could be acquired from the output report. Meanwhile, Chen and Chen (2010) utilized Latin Hypercube Sampling in order to perform thousand number of simulations of probabilistic analysis. The ratio of current base shear capacity and initial base shear capacity was tabulated and the graph and Weibull fitting was the appropriate equation for the degradation function of reliability assessment (Bai et al.,2015). However, Chen and Chen (2010) proposed three different degradation function which are polynomial model, exponential model and power model. In this case, authors concluded that power and exponential model are most suitable to fit the degradation function.

Bai et al. (2015) selected total of six parameters for wave and current conditions and 36 figure of base shear forces of the platform were obtained. Then, authors utilized surface fitting method to obtain the load effect function to determine the combination action between wave and current. The load effect equation of the wind also took account in the study. 139 m^2 is the figure considered as he windward area of the offshore jacket platform. The probability models illustrated three different model which are S data, generalized extreme value, extreme value and Weibull. Bai et al. (2015) implies the appropriate model for load effect equation was generalized extreme value. The result of the time dependent reliability model was also compared with the reliability of the platform that did not consider the resistance degradation and also different reference time (Bai et al.,2015). From the result, Bai et al. (2015) concluded that the failure probability of time dependent reliability assessment method is higher than the reliability assessment method.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

3.1.1 Jacket Platform Characteristics

Platform A located near shore of Bintulu, Sarawak is selected in this study. It located in Malaysia waters namely Sarawak Operations (SKO) and was installed in South China sea. Platform A was modelled and analyzed using the SACS and all the design model was provided by the owner. SACS is typically used to model and analyze the structural element of the jacket platform. No changes in geometric characteristics was made during this study. However, due to corrosion model in this study, the thickness and diameter of the platform in splash zone and immersion zone is reduced and the details will be delayed until section 3.1.3. Figure 3.1 showed the platform model that represented the platform in Malaysia water. Table 3.1 illustrated the details of the characteristic of the platform such as the location, water depth and number of legs.

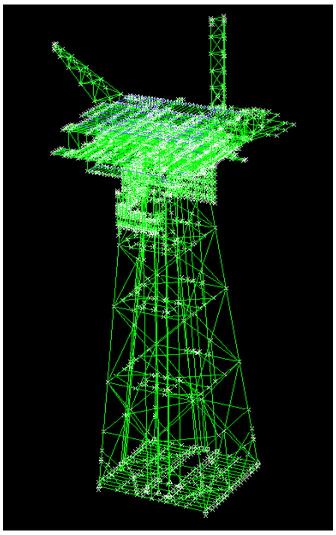


Figure 3.1: Platform Model

Table 3.1: Characteristic of Platform

Location	Water Depth (m)	No. of Legs
SKO	94.80	4

In this study, the platform metocean data was obtained from its design report. The metocean data is provided by the owner. The value of design wave in multi-directional of 100 year return period, current velocity profile and wind speed characteristics for 10 and 100 year return period are displayed in the table 3.2-3.4.

Table 3.2: Metocean (Wave Characteristic)

Direction(deg.)	100 Year Return Period Wave Characteristics	
	Wave Height, H_{max} (m)	Wave Period, T_{ass} (s)
NW-N-NE	11.7	10.6
W	10.2	10.0
E & SW	8.7	9.3
SE	6.3	8.0

Table 3.3: Metocean (Current Velocity)

Depth (D)	Current Velocity Collinear with Extreme Wave (cm/s)	
	10-Year Return Period	100-Year Return Period
1.00*D (Surface)	105.0	120.0
0.50*D (Mid Depth)	83.0	95.0
0.01*D (Near Seabed)	50.0	55.0

Table 3.4: (Wind Speed)

	Wind Speed (m/s)	
	10-Year Return Period	100-Year Return Period
1-hour mean	17.0	20.0
10-min mean	18.0	22.0
1-min mean	20.0	24.0
3-sec gust	22.0	26.0

Dead load and live load are acting on the platform and was considered during the analysis. In addition, the environmental load such as wind, current and wave are also considered. In this study, extreme weather such as storm might contribute to the huge amount of load on the platform. Thus, the storm load is considered the maximum load effect to the platform. The storm load might be acted on different load direction. Typically, the platform will be analyzed on eight different directions in which 0˚, 45˚, 90˚, 135˚, 180˚, 225˚, 270˚ and 315˚. The figure 3.2 show the eight direction of the storm load.

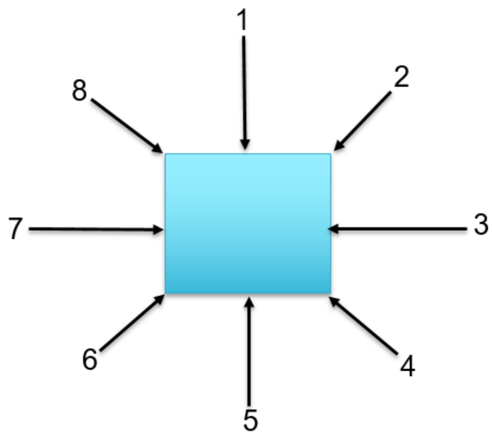


Figure 3.2: Load Directions

3.1.2 General Flowchart

This study initiated with the data collection of the platform model and metocean data. From this data, the structural reliability analysis is started by preparing the variables which are resistance and load model. These models then will be analyzed in limit state function in order to obtain the probability failure of platform in different reference time. Under a resistance variable circumstance, the present corrosion model known as corrosion protection system (CPS) is used in this study. This corrosion model will only start when the CPS has lost its effectiveness. The corrosion model based on the previous literature are referred to reduce the thickness of the structural member. Accordingly, static non linear collapse analysis/pushover analysis is performed to obtain the base shear capacity of the platform. The Reserve Strength Ratio (RSR) is expected as the outcomes of the static non linear collapse analysis. As for the load model, the response surface is used to obtain the coefficients and the function of the load effect. In this study, the load function and coefficients are obtained from the previous study. After preparing all the models, the limit state function is solved using First Order Reliability Method (FORM). Finite Element Reliability Using Matlab (FERUM) is utilized to perform the FORM. Figure 3.3 illustrates the study flowchart of this project.

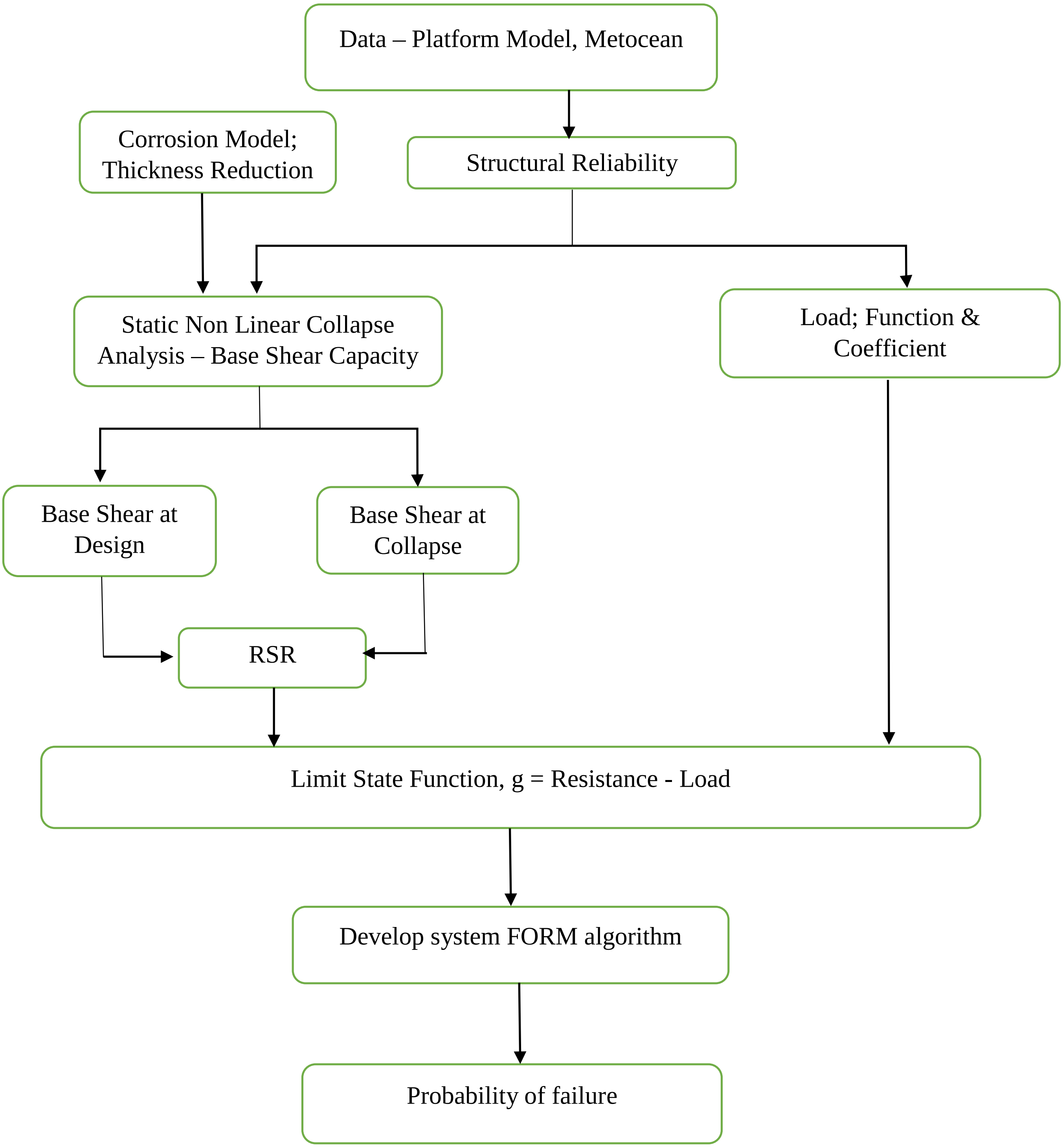


Figure 3.3: General Flow Chart of Study

3.1.3 Corrosion Model

The important part of under resistance model circumstances is degradation of the base shear capacity due to corrosion effect. The corrosion model in this project will cover the corrosion protection system (CPS) as the present corrosion model. Hence, the Weibull distribution is used to describe the corrosion growth over time and there are four parameters influence these Weibull equations namely *d, β, η,* and T_{st}. The equations are analyzed and all the parameters are determined. Therefore, it will lead to determination of the corrosion growth over time. The corrosion model following Weibull distribution can be described as follow (Bai et al.,2015);

$$d(t) = \begin{cases} 0 & 0 \le t < T_{\text{st}} \\ d\left\{1 - \exp\left[-\left(\frac{t - T_{\text{st}}}{\eta}\right)^{\beta}\right]\right\} & T_{\text{st}} \le t \le T_L \end{cases}$$

d constitutes the final corroded thickness. The value of *d* influences the final corroded thickness of the structure as the value of *d* is directly proportional to the value of final corroded thickness. The value of *d* is chosen from the literature which is 1.64 (Bai et al.,2015). *β and η* are the shape and scale parameters of the Weibull equation, valued at 1.99 and 9.19 respectively. These values are taken directly from the work of Bai et al. (2015). The T_{st} is the start time of the corrosion took place. The value of T_{st} has a greater influence on the starting point of the corrosion. It can be observed that the larger value of T_{st}, the later the corrosion will take place. According to Bai et al. (2015), the value of T_{st} is considered as 1.38. Hence, the corrosion growth over time can be described as

$$d(t) = \begin{cases} 0 & 0 \le t < 1.38 \\ 1.64\left\{1 - \exp\left[-\left(\frac{t - 1.38}{9.19}\right)^{1.99}\right]\right\} & 1.38 \le t \le T_L \end{cases}$$

The reference time of this study is taken until 50 years. From the equation, the graph of the corrosion growth vs time is plotted and shown below;

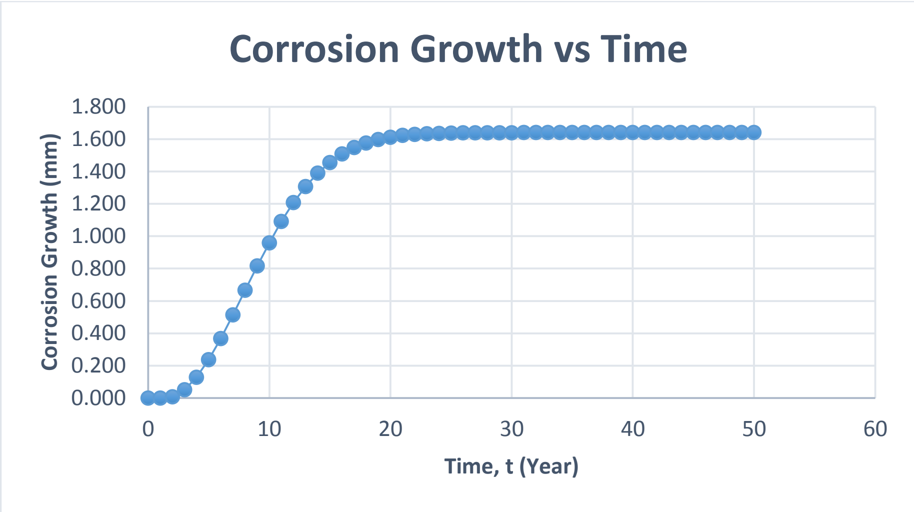


Figure 3.4: Graph of Corrosion Growth Vs Time

Typically, corrosion rates vary at different area of the platform. The corrosion zone can be classified into three different zone namely atmospheric zone, splash zone and immersion zone. Atmospheric zone is likely to affect the topside part and splash and immersion zone are mainly affect the jacket part (Bait et al.,2015). Generally, the splash zone is +5.0m above mean water level and -3.0m below mean sea level. All the corrosion zone should be assessed separately for the accurate analysis. However, in this project, splash zone and immersion zone are set to be same and only the jacket part is assessed for the simplicity of this study. Figure 3.5 shows the corrosion applied to the jacket part of the platform.

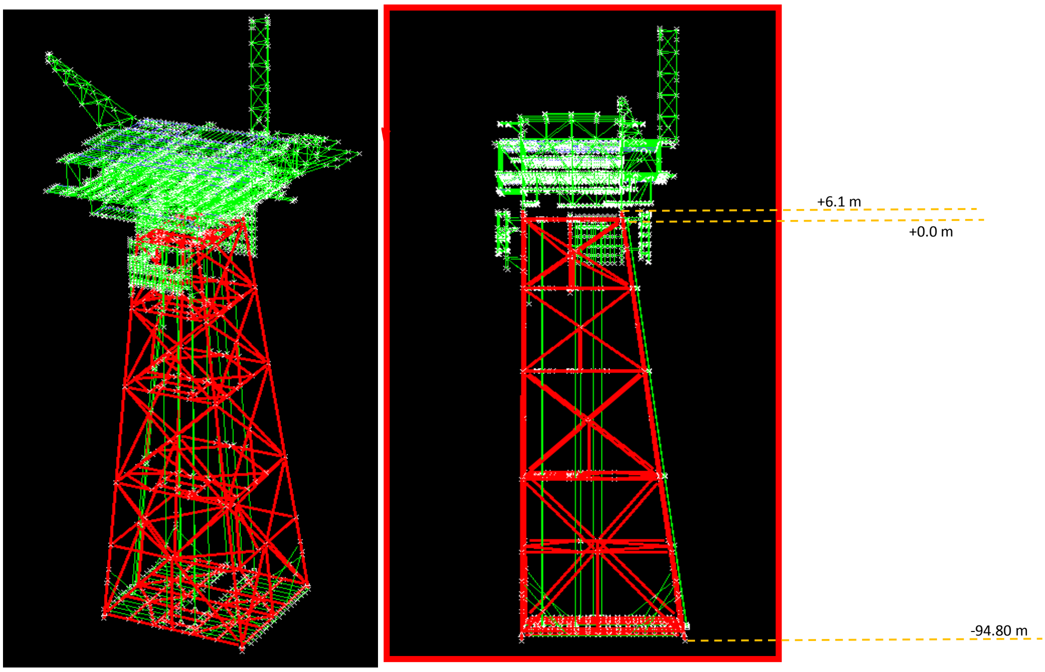


Figure 3.5: Different Views of Platform

3.1.4 Static Non Linear Collapse Analysis/Pushover Analysis

Finite element software such as SACS were utilized to conduct the pushover analysis in order to obtain the base shear capacity. The pushover analysis is conducted with nine different direction of the platform. The pushover analysis utilizes stiffness matrix method. Accordingly, the response of the structure is obtained. The base shear capacity is represented by Reserve Strength Ratio (RSR) in which the base shear at collapse is divided by base shear at design. The design load is calculated by 1.0 x Dead load + 1.0 x Live load + 1.0 x Storm load. The initial base shear capacity is determined using this analysis. The original platform model is analyzed and the base shear capacity is acquired without changing the thickness of the structure. The original diameter and thickness of the member that affected by corrosion can be referred in appendix section. As the corrosion model in different reference time has been developed, the corrosion growth of the member is determined. Hence, the original dimension of structural member has been reduced in an interval of 10 years until 50 years. The thickness of structural members under the splash and immersion zone are been reduced namely main tubular of the jacket, lateral and diagonal bracing of the jacket. The updated dimensions of the structure are then analyzed using pushover analysis in order to obtain the base shear capacity. To conclude, the base shear at collapse and base shear at design of the time assessing will be obtained and the RSR value is calculated. The red parts in Figure 3.6 shows the structural members that affected by the corrosion and the thickness of the members are been reduced.

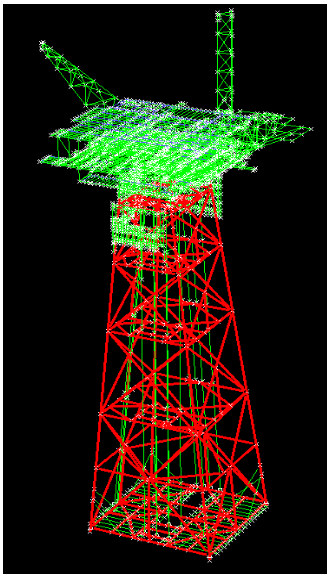


Figure 3.6: Structural Member that Affected by Corrosion

3.1.5 Reserve Strength Ratio (RSR)

Reserve Strength Ratio is the important parameter in the limit state function as it represented the resistance of the structure. RSR is the marginal safety of the structure in which the base shear at collapse is divided by base shear at design. In the pushover analysis, the dead load and live load are applied incrementally until the load factor is reached 1.0. Then, the storm load took place until the load factor of storm load is 1.0. At this point, the base shear capacity is recorded and denoted as base shear at design. Then, the load factor of storm load is continuously increased until the structure collapse. The base shear at collapse is recorded at the moment the structure collapsed. From here, the RSR value is obtained. These steps are repeated for nine different directions for each reference year. In this study, the reference time is started from 0 year until 50 years with an interval 10 years.

3.1.6 Limit State Function

Limit state function contains two vital variables which are resistance and load models. The limit state function also denoted as G function. This limit state function is a vital step in this study as it will indicate the failure of the structure. If the value of load model is greater than the value of resistance, then the structure is considered fail. Since some of the parameter in resistance and load models are uncertain, a large number of iterations is needed to calculate the limit state function. Herein, the FORM method is needed to calculate a large number of iteration of limit state function to obtain the probability of failure.

3.1.6.1 Resistance and Load Model

In this study, the limit state equation is based on the failure model which is base shear failure. The general limit state function can be portrayed as

$$G = R - L$$

Where, G is the limit state function, R is the resistance model and L is the load model. Herein, if the value of G is less than zero, the structure is considered fail as the value of load is greater than value of resistance. The probability of failure, P_f is used to describe the value of limit state function that less than zero and the equation is as follow;

$$P_f = [G(.) < 0]$$

3.1.6.1.1 Resistance Model

The resistance model is represented the capacity of the structure to resist the load applied to the structure. In this study, the resistance model is obtained from the literature and all parameters are obtained from the analysis. The resistance model will satisfy the limit state function in order to achieve the objective. The resistance model is also developed in nine different directions for each reference time. The resistance model was adopted from work of Ersdal, (2005) and shown below

$$R = \beta \times RSR\,[(C_1 \times H_{100}^2) + (C_2 \times H_{100}) + (C_3 \times U_{100}^2) + (C_4 \times U_{100}) + (C_5 \times W_{100}^2) + (C_6 \times W_{100}) + C_7]$$

Where, β is the uncertainty resistance model, RSR is the Reserve Strength Ratio from pushover analysis, H_{100} is the wave height of 100 year return period, U_{100} is the current velocity of 100 year return period, W_{100} is the wind speed of 1-min gust 100 year return period and C_1, C_2, C_3, C_4, C_5, C_6 and C_7 are the load coefficients. The values of H_{100}, U_{100} and W_{100} can be obtained from metocean data. However, the value of load coefficients is delayed until section 3.1.6.1.2. The value of β is adopted from literature and it is normally distributed with the value of mean is 1.0 and standard deviation is 0.10.

3.1.6.1.2 Load Model

At this point, load model acting on the jacket platform will be scrutinized. In this circumstances, the storm load in South China sea will be considered and there are three parameters that involve under storm load which are wave, current and wind. The Weibull extreme distribution parameter will be used to fitted this wave height parameter and the values of other parameters are adopted from the metocean. Then, the values of the scale and shape factors of the Weibull function are referred from work of Mubarak, (2016). The values of the scale and shape factors are 4.86 and 5.88. From the scale and shape factors, the mean and standard deviation can be obtained in which the values are 1.650 and 8.364 respectively. The load combination of the load model used in this study is wave height of 100 year return period + current velocity of 100 year return period + wind speed of 100 year return period (1 min gust). The load model is obtained from the work of Ersdal, (2005) and shown below

$$R = \alpha \text{ x } [(C_1 \text{ x } H_{100}^2) + (C_2 \text{ x } H_{100}) + (C_3 \text{ x } U_{100}^2) + (C_4 \text{ x } U_{100}) + (C_5 \text{ x } W_{100}^2) + (C_6 \text{ x } W_{100}) + C_7]$$

Where, α is the load uncertainty factor, H_{100} is the wave height, U_{100} is the current velocity of 100 year return period, W_{100} is the wind speed of 1-min gust 100 year return period and C_1, C_2, C_3, C_4, C_5, C_6 and C_7 are the load coefficients. The values of load coefficients are obtained from the response surface. However, in this study, the load coefficients are obtained from the work of Mubarak, (2016). Some of these parameters namely U_{100} and W_{100} can be acquired from metocean data. The table of the values of resistance and load model parameters are displayed in the table below;

Table 3.5: The Value of the Parameters

Model	Parameters	Algorithm Notation	Description	Values
Resistance	β	Bi	Resistance Uncertainty model	Normally Distributed • $\mu = 1.0$ • $\sigma = 0.10$
	U_{100}	Ub	Current Velocity	1.2 m/s
	W_{100}	Wb	Wind Speed	24 m/s
	H_{100}	Hd	Maximum Wave Height	11.7 m

	RSR	RSR	Reserve Strength Ratio	Obtain from Pushover analysis
Load	α	Ai	Load Uncertainty Model	Normally Distributed • μ = 1.0 • σ = 0.15
	U_{100}	Ua	Current Velocity	1.2 m/s
	W_{100}	Wa	Wind Speed	24 m/s
	H_{100}	Hs	Significant Wave Height	Weibull Distributed • μ = 1.650 • σ = 8.364
Load Coefficients	C_1, C_2, C_3, C_4, C_5, C_6, C_7	c1, c2, c3, c4, c5, c6, c7	Load coefficients	C_1 = 0.04232 C_2 = 0.09672 C_3 = 2.298 C_4 = 0.9034 C_5 = -0.04453 C_6 = 0.9760 C_7 = 0.2843

3.1.7 First Order Reliability Method (FORM)

Lastly, the final phase will be the time dependent reliability assessment of the jacket platform which the execution of the First Order Reliability Method (FORM) of the limit state function. The Finite Element Reliability Using MATLAB (FERUM) is utilized to conducted the analysis of limit state function. With all the model of resistance and load that satisfy the limit state function, the FORM algorithm is developed to conduct the analysis. The flow chart on how to conduct analysis in FERUM is shown below;

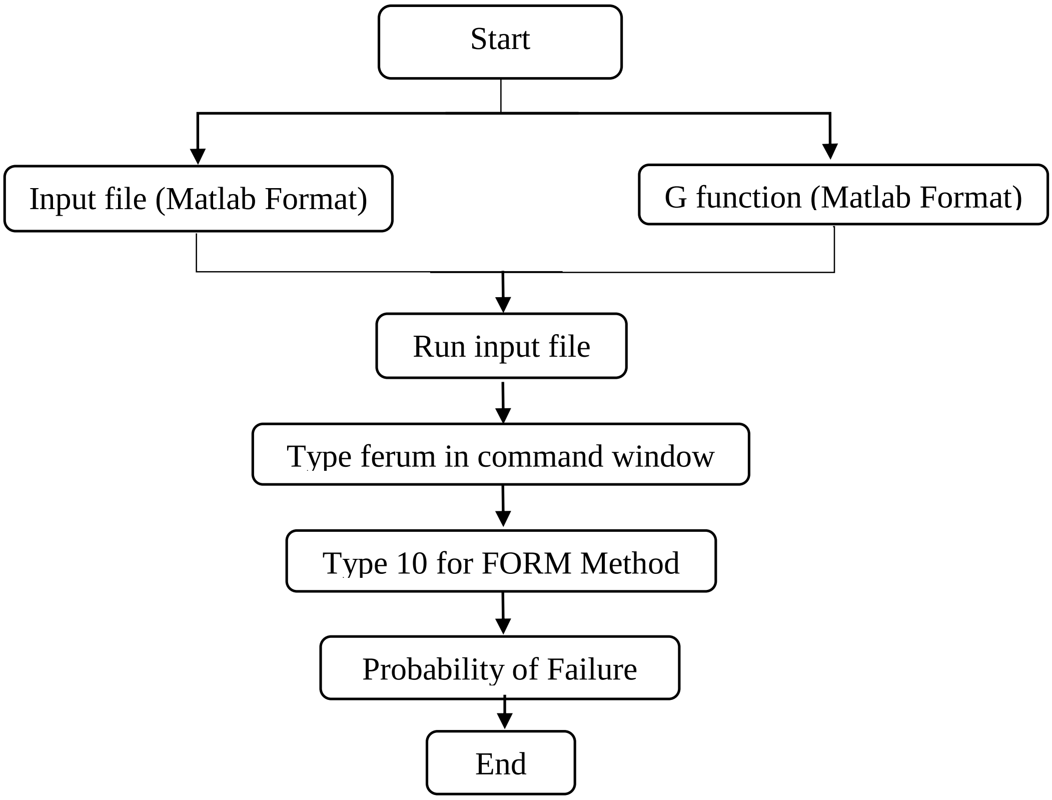


Figure 3.7: Flowchart of FORM Analysis in FERUM

The input file and g function algorithms are prepared according to limit state function. The formula of limit state function discussed in section 3.1.6 is written in the g function algorithm and all the deterministic values are defined. As for uncertain parameters, the type of distribution, mean and standard deviation is written in the input file algorithm in order to create the random number. Input file and g function algorithms must have similar name and must be placed in a same folder with other algorithms of the FERUM before started the analysis. The g function and input fie algorithms can be found in the appendix D. The probability of failure is expected at the end of the analysis.

3.2 Project Key Milestones

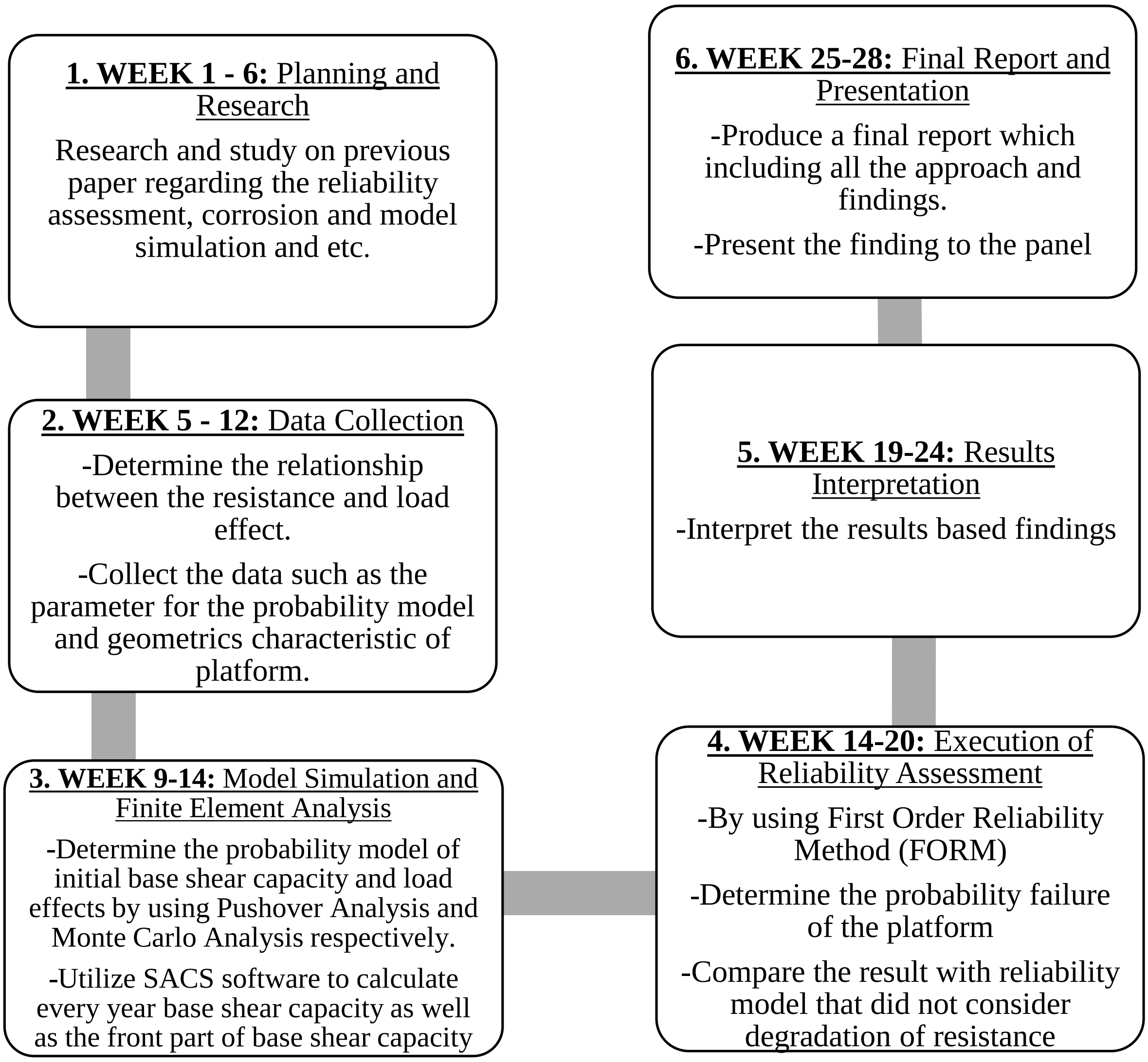


Figure 3.8: Project Key Milestone

3.3 Project Timelines

Project Task/Flow	FYP 1								FYP 2						
	1-2	3-4	5-6	7-8	9-10	11-12	13-14	Exam	15-16	17-18	19-20	21-22	23-24	25-26	27-28
Planning and Research															
Data Collection															
Model Simulation															
Static Non-Linear Collapse Analysis															
Reliability Assessment															
Results Interpretation															
Final Report and Presentation															

Figure 3.9: Gantt Chart

CHAPTER 4

RESULT AND DISCUSSION

4.1 Chapter Overview

In this chapter, the results of structural reliability analysis are presented. Firstly, the aim of this study is to acquire the RSR in different reference time and to obtain the probability failure of Malaysia's offshore jacket platform in different reference time. Hence, platform A which located at offshore Bintulu, Sarawak is selected for this time dependent reliability analysis and the water depth is 94.80 m. The results of static nonlinear collapse analysis are presented in this chapter. Base shear at collapse and base shear at design are the outcome of the pushover analysis. From the result of base shear at collapse and base shear at design, the Reserve Strength Ratio(RSR) can be calculated by dividing the base shear at collapse with the base shear at design. Hence, the result of Reserve Strength Ratio is presented in this section. Parameters of the resistance and load model has been prepared and necessary for a limit state function. Finite Element Reliability Using MATLAB is utilized in order to conduct the First Order Reliability Method. The probability of failure and reliability index of the jacket platform is obtained from the analysis and displayed in this section.

4.2 Static Nonlinear Collapse Analysis

As discussed in methodology section, the static nonlinear collapse analysis or pushover analysis is conducted in nine different directions by utilizing the SACS. The pushover analysis is conducted in every ten years until 50 years. Hence five sets of analysis are needed to obtain base shear capacities which are 10 years, 20 years, 30 years, 40 years and 50 years. The failure mode of this platform is base shear failure in which base shear capacity was represented as the resistance of the platform. The base shear capacity of the platform can be described as the (1) base shear at collapse and (2) base shear at design. In this case, option 1 in which platform is collapsed is took account to describe the failure of the platform. The pushover analysis of the platform A yielded the base shear capacity of the platform at each load step. Base shear at design is equal to 1.0 x Dead load + 1.0 x Live load + 1.0 x Storm load. As the one iteration of load step in SACS started with 0.2, fifteen iteration needed to obtain the base shear at design. The result of base shear at design is tabulated in Figure 4.1. For the base shear at collapse, the last iteration of load step of pushover analysis result is recorded and tabulated in the table. The Reserve Strength Ratio is calculated by dividing the base shear at collapse to base shear at design. Then, the result of the Reserve Strength Ratio (RSR) is presented in the table 4.1 below;

Table 4.1: Results of Pushover Analysis

Time	Load Direction	Base Shear at Collapse (KN)	Base Shear at Design (KN)	RSR
0	1	39780.12	8138.59	4.89
	2	45359.82	17960.14	2.53
	3	44012.08	8931.99	4.93
	4	45209.00	9246.80	4.89
	5	46707.62	9343.96	5.00
	6	44855.55	9180.07	4.89
	7	43972.82	9299.84	4.73
	8	42367.13	9299.26	4.56
10	1	39780.75	8145.57	4.88
	2	54088.50	17679.84	3.06
	3	44134.46	8924.03	4.95
	4	45178.36	9239.61	4.89
	5	46700.31	9336.53	5.00
	6	44823.57	9173.25	4.89
	7	40463.00	9292.41	4.35
	8	42028.58	9291.86	4.52
20	1	39783.11	8127.80	4.89
	2	54462.10	17937.31	3.04
	3	44207.09	8918.66	4.96
	4	45157.80	9234.75	4.89
	5	44861.64	9331.50	4.81
	6	44825.89	9168.65	4.89
	7	38461.18	9287.40	4.14
	8	38497.73	9286.88	4.15
30	1	39781.27	8127.56	4.89
	2	43506.72	17936.00	2.43

	3	44310.00	8918.38	4.97
	4	45154.68	9234.49	4.89
	5	44936.55	9331.24	4.82
	6	44827.32	9168.40	4.89
	7	38520.59	9287.14	4.15
	8	38481.51	9286.63	4.14
40	1	39781.27	8127.56	4.89
	2	43506.72	17936.00	2.42
	3	44310	8918.38	4.96
	4	45154.68	9234.49	4.89
	5	44936.55	9331.24	4.82
	6	44827.32	9168.4	4.89
	7	38520.59	9287.14	4.15
	8	38481.51	9286.63	4.14
50	1	39781.27	8127.56	4.89
	2	43506.72	17936.00	2.43
	3	44310.00	8918.38	4.97
	4	45154.68	9234.49	4.89
	5	44936.55	9331.24	4.82
	6	44827.32	9168.40	4.89
	7	38520.59	9287.14	4.15
	8	38481.51	9286.63	4.14

Table 4.1 shows the base shear capacity of the platform every 10 years until the 50 years. The reading showed that there some increment of value of base shear capacity as well as RSR. However, the trend line of base shear capacity illustrated that the value of base shear capacity is declined from initial year until fifty years. The same trend also can be seen in RSR value. The data in the table are then plotted in figure 4.1 until 4.3. Based on the table, the highest Reserve Strength Ratio (RSR) is from the load direction 5 in which the value of Reserve Strength Ratio is 5.00. It means that the platform can withstand well to counter all the load from load direction 5. Meanwhile, the lowest Reserve Strength Ratio (RSR) is 2.53 in which the load is from the direction 2. The reserve strength of platform to withstand the load from direction 2 is slightly less compared to reserve strength of platform of other direction. Thus, the critical load direction is from direction 2 whereas the Reserve Strength Ratio(RSR) is the lowest.

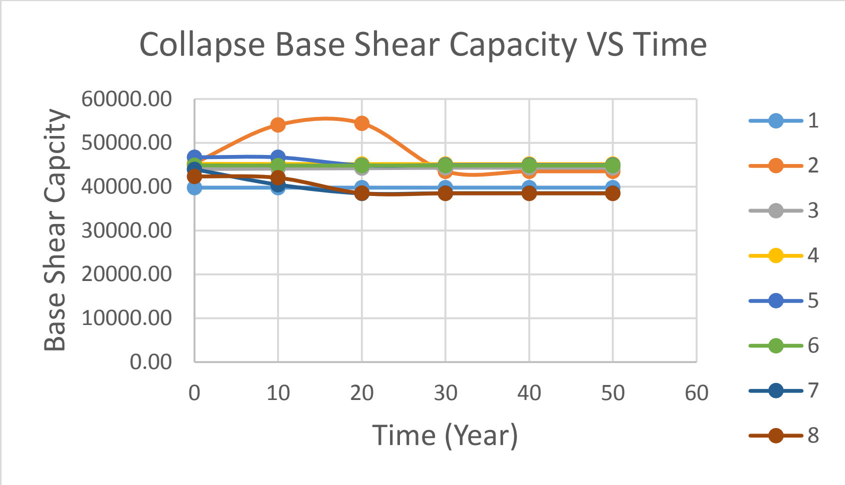


Figure 4.1: Graph of Collapse Base Shear VS Time

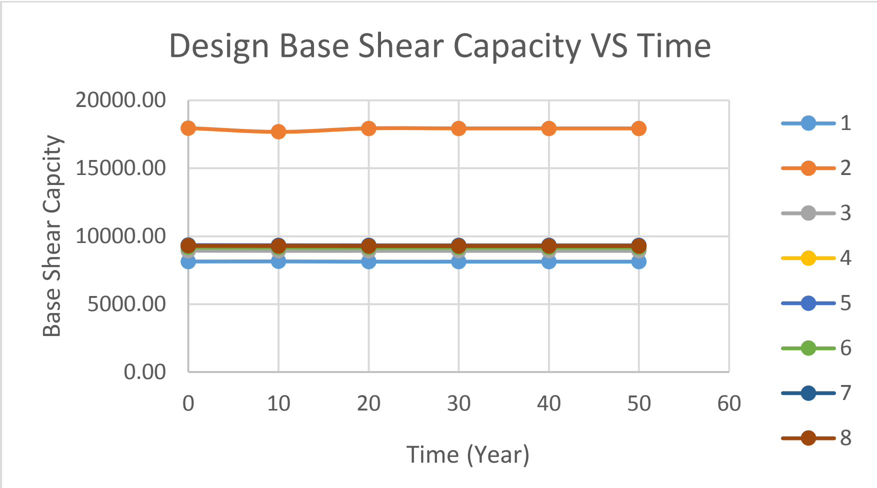


Figure 4.2: Graph of Design Base Shear VS Time

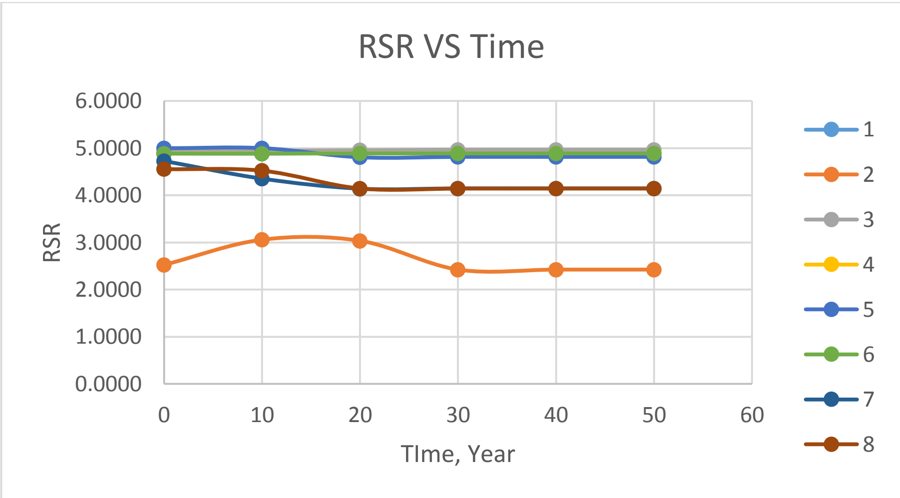


Figure 4.3: Graph of RSR VS Time

From the graph, it has been observed the collapse base shear capacity, design base shear capacity and Reserve Strength Ratio (RSR**)** show a downward trend as time passes. As the corrosion applied to the structure in different reference time, these results eventually proved that the resistance of the jacket platform decreased over time. The RSR is represent the marginal safety of the jacket platform and the data has been presented in different load direction. The graph shows that the critical RSR is at the load direction 2 as the lowest value of RSR is from load direction 2. With these results, the problem stated in this project is valid as the resistance of the structure decreased as time passes. Overall, all the RSR values of the load directions are decreased. However, for the RSR of load direction 2, the result is slightly increased before showing a downward trend. This show that the resistance of the structure to resist the load from direction 2 is higher at 20 years and decreased after 20 years. Assumption has been made to explain this unexpected variation. This non typical result may be induced in different failure mechanism. The load transfer may be shifted to the structural elements and the failure is happened in the structural elements rather than base shear.

4.3 Limit State Function

As stated in methodology, the limit state function is used to determine the safety of the jacket platform. It has been indicator in order to determine the failure of the structure. The formula that has been adopted is as below;

$$G = R - L$$

Where, R is the Resistance of the structure and L is the Load of the structure. If the load is higher than the resistance, the result may induce value less than zero which means the structure is failure. The probability of failure is given for the limit state value that less than zero.

$$P_f = [G(.) < 0]$$

4.3.1 Resistance Model

The resistance model has been obtained from the work of Ersdal, (2005). The metocean data and RSR value from pushover analysis has been utilized to satisfy the equation of resistance model. The resistance model can be referred in section 3.1.6.1.1 and all the parameter values can be obtained in section 3.1.6.1.1.

4.3.2 Load Model

The load model also has been obtained from the work of Ersdal, (2005). The load coefficients, load uncertainty factor and significant wave height are utilizing in this load model. The value of load uncertainty factor is obtained from the literature. The resistance model can be referred in section 3.1.6.1.2 and all the parameter values can be obtained.

4.4 Time Dependent Reliability Assessment

In time dependent reliability assessment, the jacket platform has been evaluated and the probability of failure of the jacket platform is expected. The limit state function is incorporated with First Order Reliability Method(FORM) to induce the result of probability of failure. The FERUM has been used to conducted the FORM. In this section, the RSR, probability of failure, P_f and Reliability Index, RI is presented. The RSR are obtained from the pushover analysis and tabulated in the table 4.2. The P_f and RI are the result from the FORM method and tabulated in the table 4.2. Probability of failure represent the tendency of the undesirable performance of the jacket platform. The results of the Probability of failure is shown below;

Table 4.2: Result of FORM Analysis

Time	Load Direction	RSR	Probability of Failure	Reliability Index
0	1	4.888	9.4369E-16	7.9469E+00
	2	2.526	8.3823E-09	5.6425E+00
	3	4.927	8.3267E-16	7.9671E+00
	4	4.889	9.4369E-16	7.9474E+00
	5	4.999	6.1062E-16	8.0036E+00
	6	4.886	9.4369E-16	7.9460E+00
	7	4.728	1.9429E-15	7.8603E+00
	8	4.556	4.2744E-15	7.7598E+00
10	1	4.884	9.9920E-16	7.9448E+00
	2	3.059	6.5153E-11	6.4268E+00
	3	4.946	7.7716E-16	7.9769E+00
	4	4.890	9.4369E-16	7.9479E+00
	5	5.002	6.1062E-16	8.0051E+00
	6	4.886	9.4369E-16	7.9460E+00
	7	4.354	1.1602E-14	7.6316E+00
	8	4.523	4.9960E-15	7.7397E+00
20	1	4.895	9.4369E-16	7.9506E+00
	2	3.036	7.9029E-11	6.3974E+00
	3	4.957	7.2164E-16	7.9825E+00
	4	4.890	9.4369E-16	7.9479E+00
	5	4.808	1.3323E-15	7.9043E+00
	6	4.889	9.4369E-16	7.9474E+00
	7	4.141	3.6526E-14	7.4823E+00
	8	4.145	3.5694E-14	7.4854E+00
30	1	4.895	9.4369E-16	7.9506E+00
	2	2.426	2.2719E-08	5.4683E+00
	3	4.968	6.6613E-16	7.9880E+00
	4	4.890	9.4369E-16	7.9479E+00
	5	4.816	1.2768E-15	7.9086E+00
	6	4.889	9.4369E-16	7.9476E+00
	7	4.148	3.5194E-14	7.4871E+00
	8	4.144	3.5971E-14	7.4842E+00
40	1	4.895	9.4369E-16	7.9506E+00
	2	2.426	2.2719E-08	5.4683E+00
	3	4.968	6.6613E-16	7.9880E+00
	4	4.890	9.4369E-16	7.9479E+00
	5	4.816	1.2768E-15	7.9086E+00
	6	4.889	9.4369E-16	7.9476E+00
	7	4.148	3.5194E-14	7.4871E+00
	8	4.144	3.5971E-14	7.4842E+00
50	1	4.895	9.4369E-16	7.9506E+00
	2	2.426	2.2719E-08	5.4683E+00
	3	4.968	6.6613E-16	7.9880E+00
	4	4.890	9.4369E-16	7.9479E+00

	5	4.816	1.2768E-15	7.9086E+00
	6	4.889	9.4369E-16	7.9476E+00
	7	4.148	3.5194E-14	7.4871E+00
	8	4.144	3.5971E-14	7.4842E+00

Table 4.2 showed the relationship between the RSR and time, Pf and Time as well as Reliability Index and time in every load direction. As discussed before, the RSR value is decreased over time and proved that the capacity of the jacket platform is degraded over time. Overall, based on the table 4.2, the probability of failure of the structure showed the upward trends in which the probability of failure increased over time. This proved that likelihood of the structure to fail is higher as the time passes. As the RSR value decreased over time, the P_f increased over time. Hence, the P_f is inversely related to the RSR. Figure 4.4 – 4.11 showed relationship between Pf and time in every different direction.

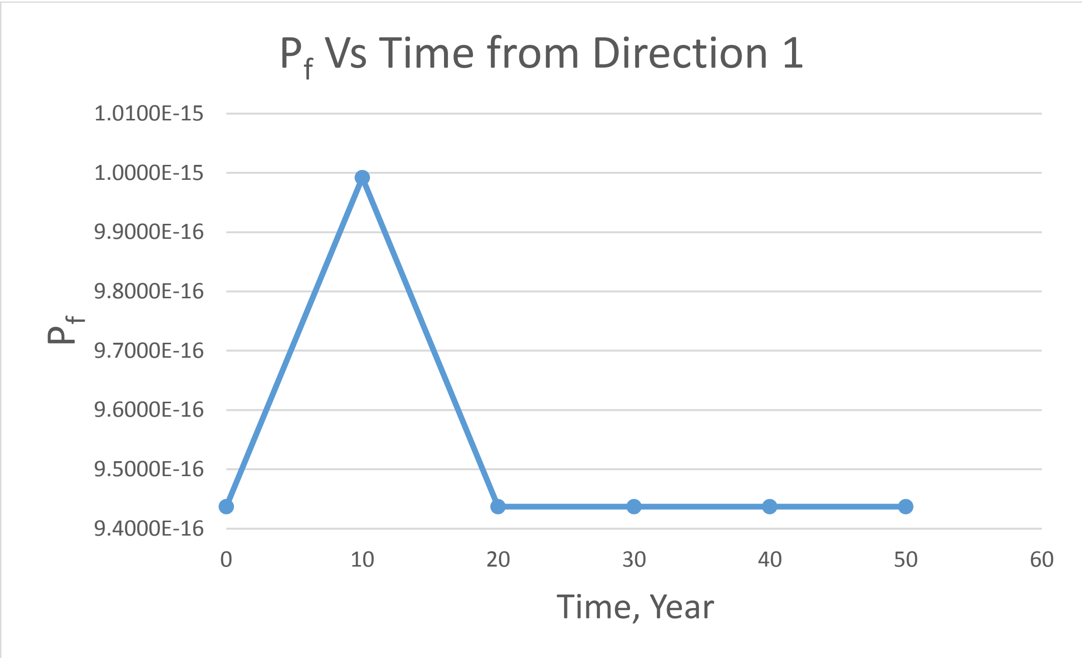


Figure 4.4: Graph of Pf Vs Time from Direction 1

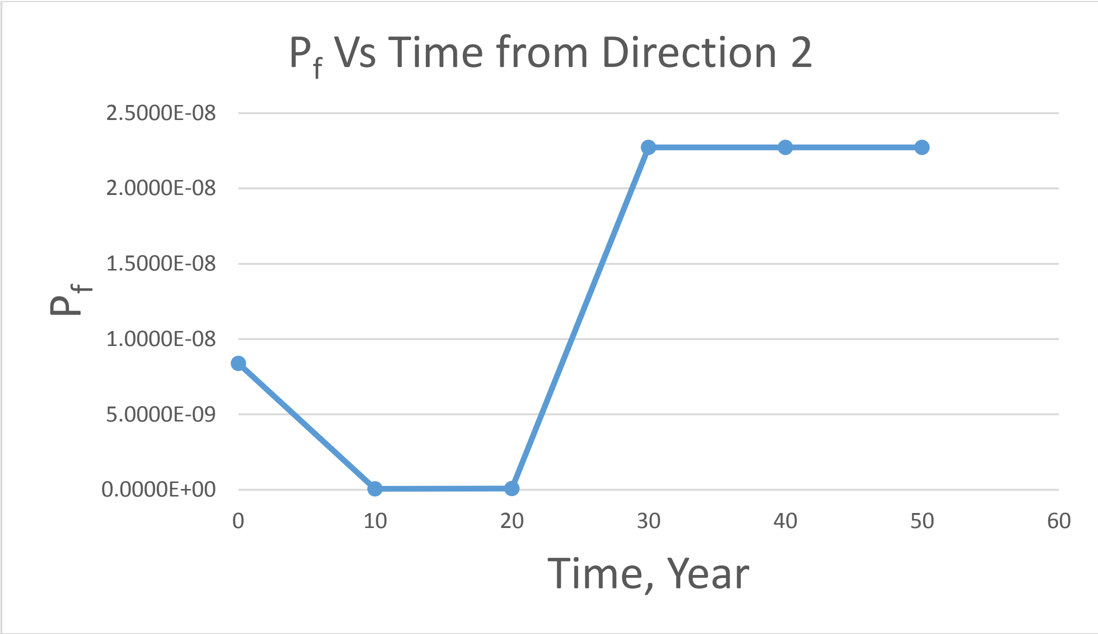


Figure 4.5: Graph of Pf Vs Time from Direction 2

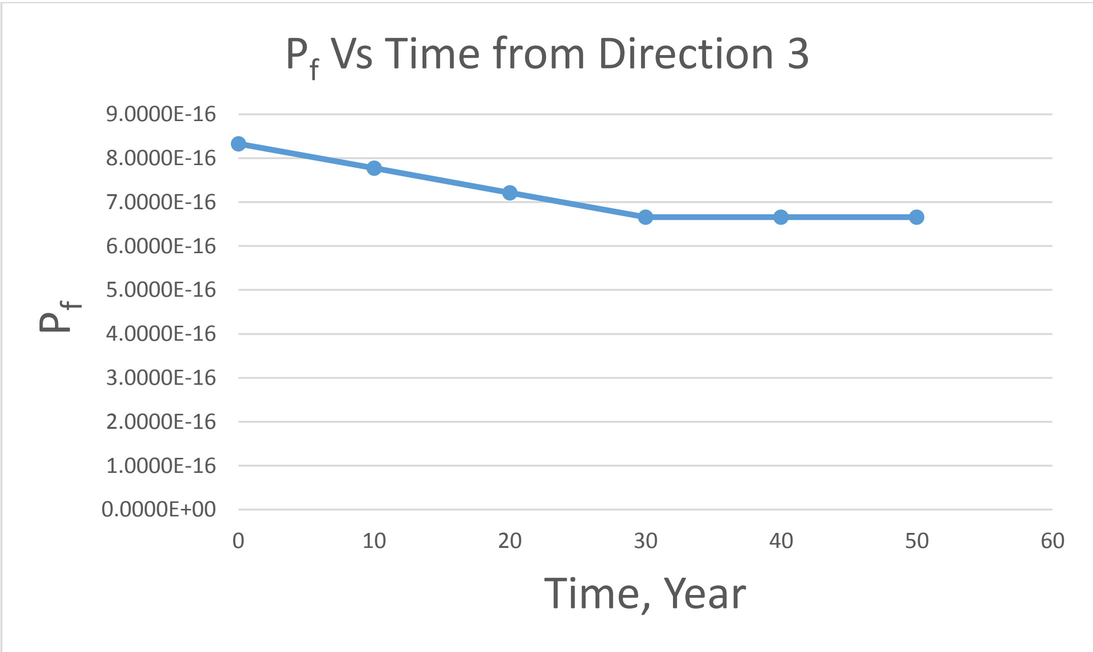


Figure 4.6: Graph of Pf Vs Time from Direction 3

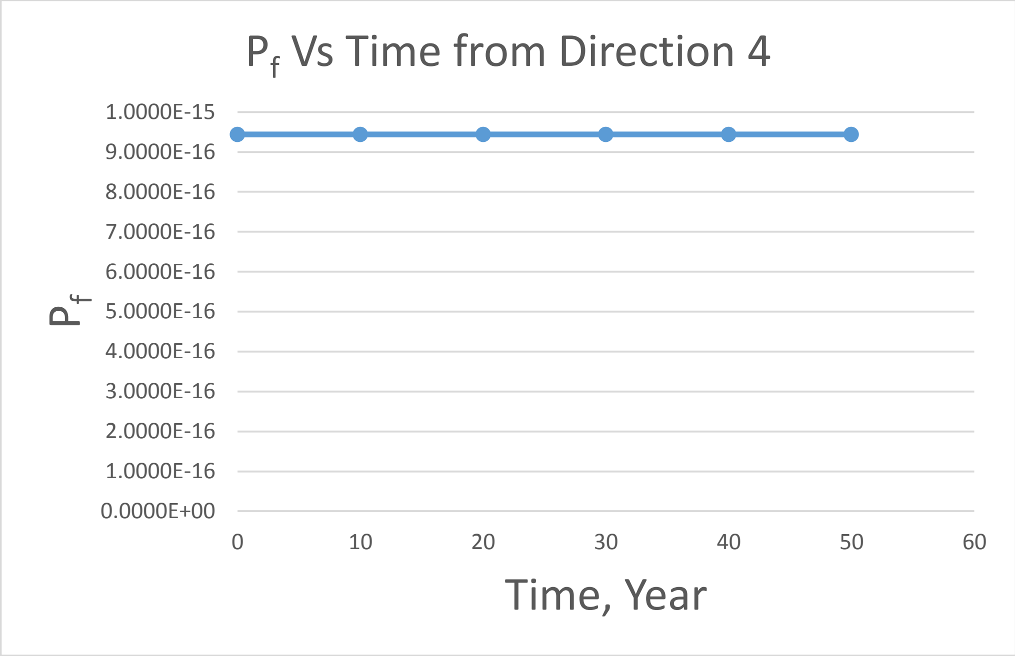


Figure 4.7: Graph of Pf Vs Time from Direction 4

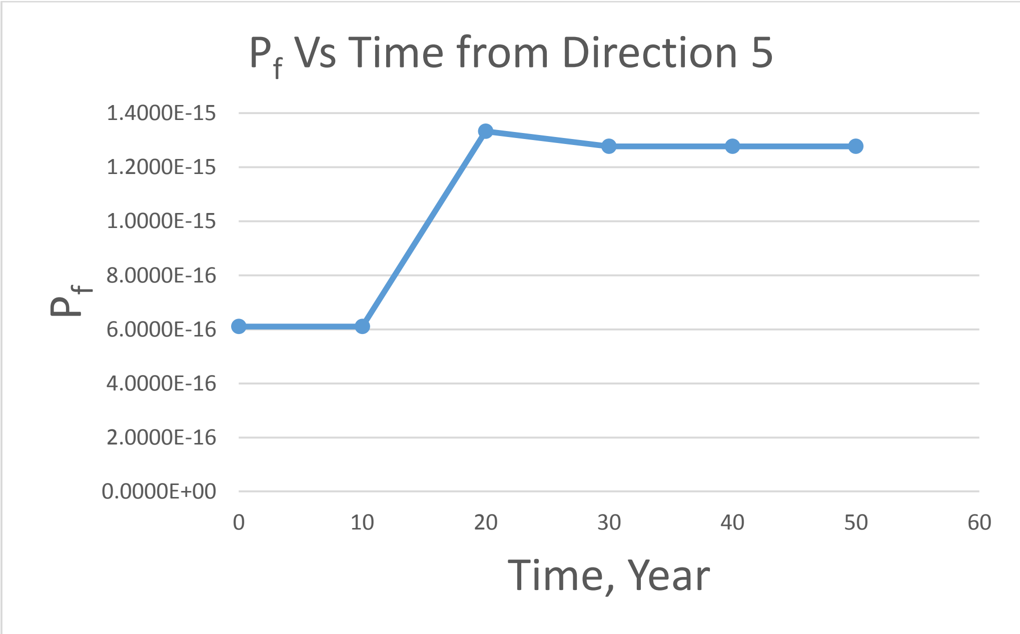


Figure 4.8: Graph of Pf Vs Time from Direction 5

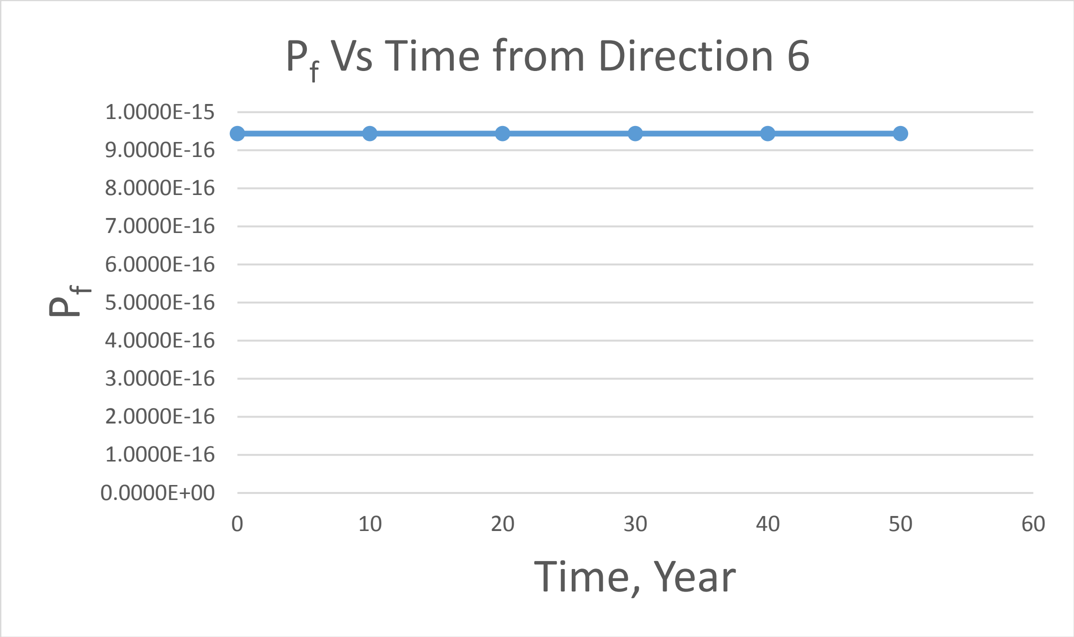


Figure 4.9: Graph of Pf Vs Time from Direction 6

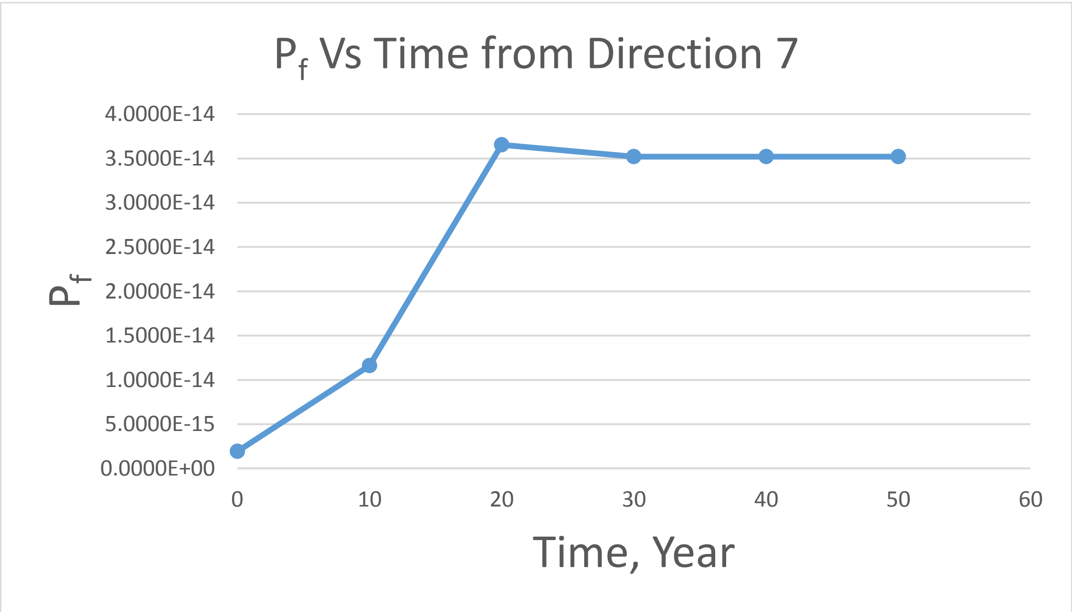


Figure 4.10: Graph of Pf Vs Time from Direction 7

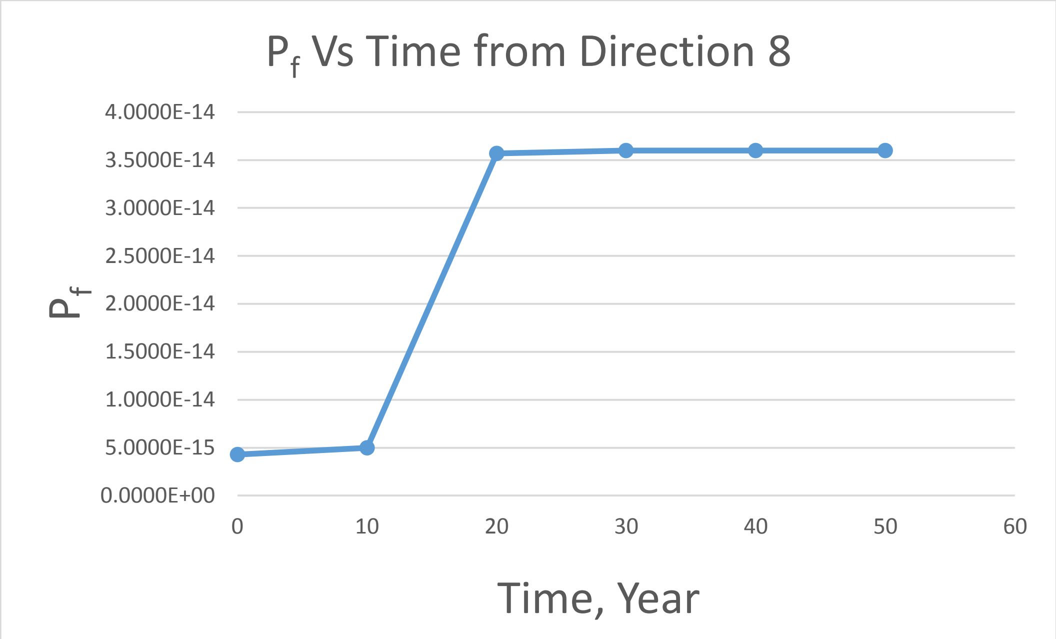
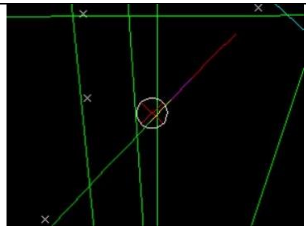
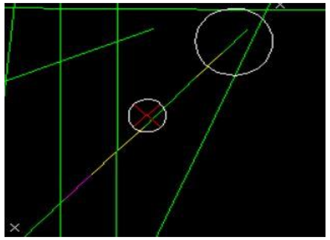
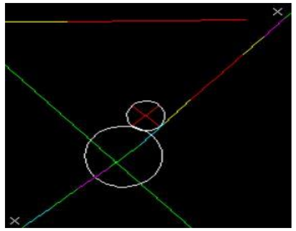
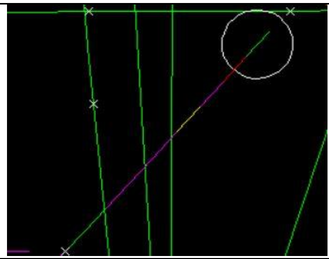
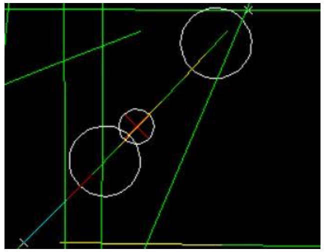
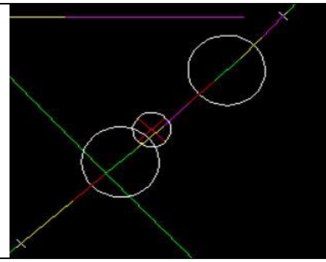
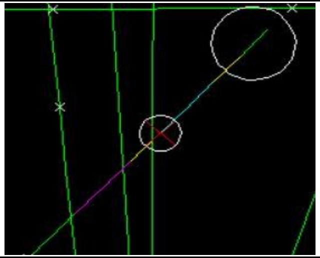
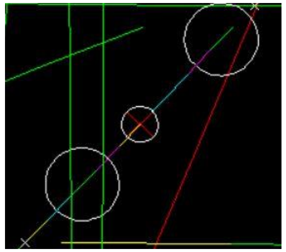
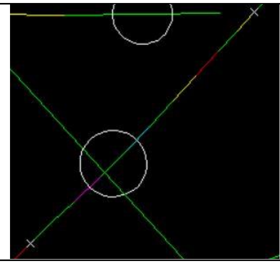
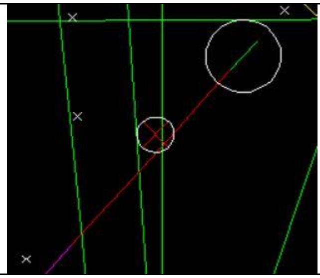
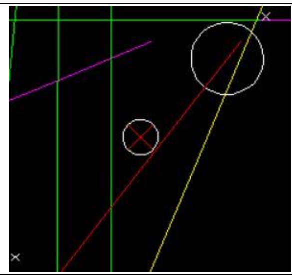
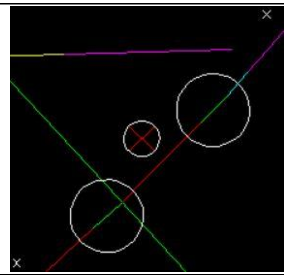
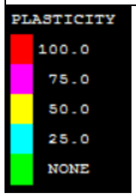


Figure 4.11: Graph of Pf Vs Time from Direction 8

Table 4.3: Failure of Member During Pushover Analysis

Load direction 2			
Member	534-528	530-524	528-518
0 year			
Load Factor	4.00 x Storm load	4.00 x Storm load	3.90 x Storm load
Length (m)	3.450	3.450	3.450
Displaced Length (m)	3.459	3.440	3.461
Diameter (m)	50.8	50.8	50.8
Thickness (m)	0.98	0.98	2.00
10 years			
Load Factor	4.00 x Storm load	4.00 x Storm load	3.90 x Storm load
Length (m)	3.450	3.450	3.450
Displaced Length (m)	3.447	3.438	3.434
Diameter (m)	50.608	50.608	50.608
Thickness (m)	0.854	0.854	1.904

20 years			
Load Factor	4.00 x Storm load	4.00 x Storm load	3.90 x Storm load
Length (m)	3.450	3.450	3.450
Displaced Length (m)	3.447	3.437	3.441
Diameter (m)	50.478	50.478	50.478
Thickness (m)	0.789	0.789	1.839
30 years			
Load Factor	4.00 x Storm load	4.00 x Storm load	3.90 x Storm load
Length (m)	3.450	3.450	3.450
Displaced Length (m)	3.473	3.435	3.459
Diameter (m)	50.472	50.472	50.472
Thickness (m)	0.786	0.786	1.836



Since the RSR and probability of failure of load direction 2 showed unexpected variation, assumption has been made to explain the undesirable result. Table 4.3 shows that the state of three members of the jacket platform before fail during pushover analysis. The three member denoted as 534-528, 530-524 and 528-518. The state of members is observed in 0 year, 10 years, 20 years and 30 years. The load factor for members of 534-528 and 530-524 are constant in which 4.00 x storm load. However, the load factor for member 528-518 is 3.90 x storm load as the member is completely failed before reach load factor 4.00 x storm load. The length of the members observed is constant in which 3.450m. The red part of the member shows that the segment of the member is 100% in plastic state which the member is completely yielded. The purple part illustrates the segment of the member 75% in plastic state. The yellow part displays that the member is 50% yielded, the blue part shows that the segment of the member is 25% in plastic state whereas the green part displays that the member is still in elastic state. For the member 534-528 in 0 year, some of the segments of the whole length of member is completely yielded or in plastic state. However, the same segments of member analyzed in 10 and 20 years illustrated green color which the segments are not yield. The same pattern also can be seen in member 528-518. The certain segments are completely yielded in 0 year during pushover analysis. However, the same segments analyzed in 10 and 20 years displayed different results compared the analysis in 0 year. These segments illustrated the member is still in elastic state or only in 50% plastic state. These results proved that the failure mechanism of the member is random and likely to affect the RSR and probability of failure results. The load transfer to the member parts are random since the failure of the members are random. Assumption made in previous results that the results may induced by different failure mechanism is relevant with this observation of specific members. This assumption may lead to the unexpected variation of the RSR and probability of failure of load direction 2.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

The aim of this project is to acquire the RSR in different reference time. In order to achieve this objective, the static nonlinear collapse analysis is being used to determine the RSR. The RSR is important value for resistance of the structure and the analysis in different reference time is needed. The thickness of structural member platform is adjusted suit to the corrosion model and analysis is took place in different reference time. From the findings, The RSR value from load direction 2 induce a critical result as the lowest RSR compared with other load direction. However, by interpreting all the results from the load direction, it can be concluded that the RSR value decreased over time. The results proved that the capacity of jacket platform is degrade as time passes. Hence, these results validate the problem statement in this project. Then, the RSR value will be used to satisfy the limit state function in term of resistance. The value that exceeded the limit state is considered fail. In this regard, resistance and load model is prepared and the analysis is conducted utilizing FORM method. The storm load is considered in this study and 100 year return period data is utilized. The probability of failure has been predicted until 50 years based on the corrosion model. From the overall result, the probability of failure of jacket platform is considered increasing over time. This proved that as time passes, the tendency of the undesirable performance of the structure become higher. With the result of probability of failure, the objectives of this study are achieved. To conclude, the resistance or capacity of the platform degraded and probability of failure of the platform increased as time passes. Hence, the relationship between RSR and probability of failure of the platform has been made as the probability of failure of the platform is inversely related to RSR. As for the recommendation, this study can be extended with the analysis on the component members of the structure and not only limited to structural system and other failure mode such as buckling and member internal stress will be considered. Besides, as the corrosion applied in this structure is limited to splash and immersion zone, the study can be continued with consider the atmospheric zone. Since the probability of failure showed small reduction, the explanation has been made. The corrosion model is the most vital part in this study. In 50 years, the total corrosion growth is approximately 1.60mm in which the reduction of thickness of the members is very less. The critical corrosion growth is critical during year 1.38 until year 20. At this point, the members of the platform are maintained in which the corrosion protection is starting to be applied to the structure. This small reduction of the thickness is likely to affect the probability of failure. Hence, the reduction probability of failure is likely to be less. As for recommendation for this situation, the other corrosion model can be used. The latest corrosion model should take into account in order to perform the reliability assessment method.

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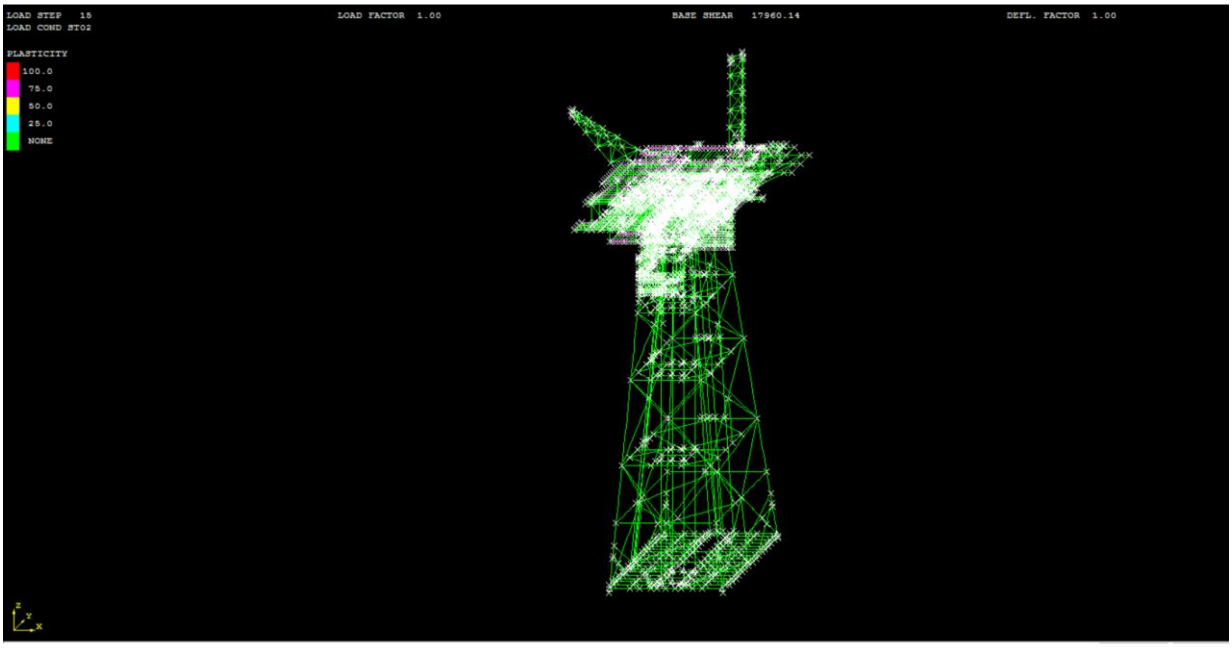
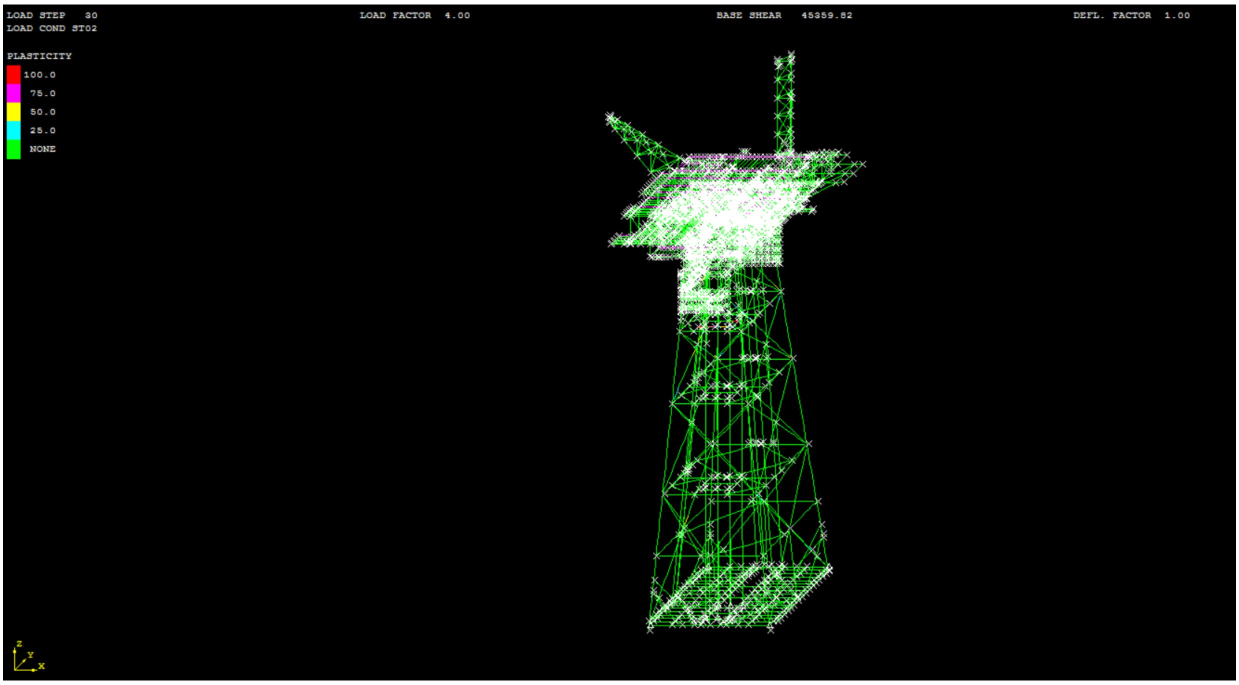
APPENDICES

Appendix A – Result from Pushover Analysis

Design Base Shear of jacket platform from direction 2



Collapse Base Shear of jacket platform from direction 2



Appendix B – Corrosion Growth

The details of the corrosion growth are shown as follows

t	t-tst	Weilbull CDF	d	CDF
0	-1.38	#NUM!	1.64	#NUM!
1	-0.38	#NUM!	1.64	#NUM!
2	0.62	0.004664946	1.64	0.008
3	1.62	0.031123562	1.64	0.051
4	2.62	0.079008198	1.64	0.130
5	3.62	0.144966457	1.64	0.238
6	4.62	0.224674084	1.64	0.368
7	5.62	0.313272589	1.64	0.514
8	6.62	0.40583988	1.64	0.666
9	7.62	0.49782119	1.64	0.816
10	8.62	0.585367467	1.64	0.960
11	9.62	0.665550144	1.64	1.092
12	10.62	0.736444283	1.64	1.208
13	11.62	0.797092693	1.64	1.307
14	12.62	0.847378451	1.64	1.390
15	13.62	0.887840695	1.64	1.456
16	14.62	0.919468879	1.64	1.508
17	15.62	0.943505221	1.64	1.547
18	16.62	0.961276403	1.64	1.576
19	17.62	0.974065843	1.64	1.597
20	18.62	0.983029152	1.64	1.612
21	19.62	0.989148858	1.64	1.622
22	20.62	0.993220571	1.64	1.629
23	21.62	0.995861322	1.64	1.633
24	22.62	0.997531202	1.64	1.636
25	23.62	0.998560971	1.64	1.638
26	24.62	0.999180369	1.64	1.639
27	25.62	0.999543821	1.64	1.639
28	26.62	0.999751901	1.64	1.640
29	27.62	0.999868147	1.64	1.640
30	28.62	0.999931524	1.64	1.640
31	29.62	0.999965249	1.64	1.640
32	30.62	0.999982766	1.64	1.640
33	31.62	0.999991648	1.64	1.640
34	32.62	0.999996045	1.64	1.640
35	33.62	0.999998169	1.64	1.640
36	34.62	0.999999172	1.64	1.640
37	35.62	0.999999634	1.64	1.640
38	36.62	0.999999842	1.64	1.640
39	37.62	0.999999933	1.64	1.640
40	38.62	0.999999972	1.64	1.640

41	39.62	0.999999989	1.64	1.640
42	40.62	0.999999996	1.64	1.640
43	41.62	0.999999998	1.64	1.640
44	42.62	0.999999999	1.64	1.640
45	43.62	1	1.64	1.640
46	44.62	1	1.64	1.640
47	45.62	1	1.64	1.640
48	46.62	1	1.64	1.640
49	47.62	1	1.64	1.640
50	48.62	1	1.64	1.640

Appendix C – Original Dimension of Platform Structural Members

The original dimension of the structural members of the platform A are shown below. The data was extracted from the original platform model. All the dimensions of the structural members are then reduced by subtracting the value of corrosion growth in every 10 years until 50 years.

Main Tubular		
Section	Outside Diameter	Wall thickness
G02	170.00	5.00
G03	168.60	4.30
G04	164.00	2.00
G07	171.00	5.50
G08	165.20	2.60

Diagonal Bracing of the Jacket		
Section	Outside Diameter	Wall Thickness
GRUP V1A	81.30	1.59
GRUP V1B	81.30	1.59
GRUP V1C	76.20	1.59
GRUP V1D	81.30	1.59
GRUP V1E	76.20	1.59
GRUP V1F	66.00	1.59
GRUP V1F	66.00	2.54
GRUP V1G	66.00	2.54
GRUP V1G	66.00	1.59
GRUP V1H	66.00	1.59
GRUP V1I	66.00	1.59
GRUP V1N	50.80	1.59
GRUP V1Q	76.20	1.59
GRUP V1R	76.20	1.59
GRUP V1S	76.20	1.59
GRUP V1S	76.20	2.54
GRUP V1T	76.20	2.54
GRUP V1T	76.20	1.59
GRUP V1U	91.40	1.59
GRUP V1U	91.40	3.18
GRUP V1V	91.40	3.18
GRUP V1V	91.40	1.59
GRUP V3A	81.30	1.59
GRUP V3B	81.30	1.59
GRUP V3C	76.20	2.00
GRUP V3D	81.30	1.59
GRUP V3E	91.40	1.59
GRUP V3E	91.40	3.18
GRUP V3F	66.00	1.59

GRUP V3F	66.00	2.54
GRUP V3G	66.00	2.54
GRUP V3G	66.00	1.59
GRUP V3H	66.00	1.59
GRUP V3I	66.00	1.59
GRUP V3J	91.40	1.59
GRUP V3M	61.00	1.27
GRUP V3M	61.00	3.18
GRUP V3N	50.80	1.59
GRUP V3Q	76.20	2.54
GRUP V3R	76.20	2.54
GRUP V3S	76.20	2.54
GRUP V3S	76.20	3.50
GRUP V3T	76.20	3.50
GRUP V3T	76.20	2.54
GRUP V3X	58.60	1.34
GRUP V3X	58.60	1.98
GRUP V3Y	58.60	1.34
GRUP V3Z	61.00	2.54
GRUP V3Z	61.00	1.27
GRUP VA1	32.40	1.27
GRUP VA2	121.90	2.00
GRUP VA2	121.90	3.50
GRUP VA3	121.90	3.50
GRUP VA3	121.90	2.00
GRUP VA4	40.60	1.27
GRUP VA6	121.90	3.50
GRUP VAA	81.30	2.00
GRUP VAB	81.30	2.00
GRUP VAC	81.30	2.00
GRUP VAD	81.30	1.59
GRUP VAE	81.30	1.59
GRUP VAR	50.80	1.59
GRUP VAS	76.20	1.59
GRUP VAY	76.20	1.59
GRUP VAY	76.20	3.50
GRUP VAZ	76.20	3.50
GRUP VAZ	76.20	1.59
GRUP VB1	40.60	1.27
GRUP VB2	121.90	2.00
GRUP VB2	121.90	3.50
GRUP VB3	121.90	3.50
GRUP VB3	121.90	2.00
GRUP VB4	32.40	1.27
GRUP VB5	58.60	1.34
GRUP VB5	58.60	1.98

GRUP VB6	58.60	1.34
GRUP VB7	119.50	2.30
GRUP VB7	119.50	0.80
GRUP VB8	121.90	3.50
GRUP VB9	119.50	0.80
GRUP VB9	119.50	2.30
GRUP VBA	81.30	2.00
GRUP VBB	81.30	2.00
GRUP VBC	81.30	2.00
GRUP VBD	71.10	1.27
GRUP VBD	71.10	2.54
GRUP VBE	61.00	2.00
GRUP VBF	71.10	1.27
GRUP VBG	71.10	1.27
GRUP VBG	71.10	2.54
GRUP VBH	61.00	2.00
GRUP VBH	61.00	3.18
GRUP VBI	61.00	2.00
GRUP VBJ	71.10	1.27
GRUP VBJ	71.10	3.18
GRUP VBK	71.10	1.27
GRUP VBK	71.10	3.18
GRUP VBR	50.80	1.59
GRUP VBS	81.30	1.59
GRUP VBW	76.20	1.59
GRUP VBW	76.20	3.50
GRUP VBX	76.20	1.59
GRUP VBX	76.20	3.50
GRUP VBY	76.20	1.59
GRUP VC1	119.50	0.80
GRUP VC2	121.90	3.50
GRUP VC2	121.90	2.00
GRUP VC2	121.90	3.50
GRUP VC3	121.90	3.50

Lateral Bracing of the Jacket		
Section	Outside Diameter	Wall Thickness
GRUP 1A1	61.000	2.540
GRUP 1A1	61.000	1.590
GRUP 1A2	61.000	2.540
GRUP 1A2	61.000	1.590
GRUP 1A3	61.000	1.590
GRUP 1A3	61.000	2.540
GRUP 1A4	61.000	2.540
GRUP 1A6	61.000	2.540

GRUP 1A6	61.000	1.590
GRUP 1A7	61.000	2.540
GRUP 1A7	61.000	1.590
GRUP 1A8	61.000	2.540
GRUP 1A8	61.000	1.590
GRUP 1A9	61.000	2.000
GRUP 1A9	61.000	2.540
GRUP 1AH	40.600	1.270
GRUP 1B1	61.000	2.540
GRUP 1B1	61.000	1.590
GRUP 1B2	61.000	1.590
GRUP 1B2	61.000	2.540
GRUP 1B3	61.000	1.590
GRUP 1B3	61.000	2.540
GRUP 1B5	61.000	2.540
GRUP 1B6	61.000	2.000
GRUP 1B7	61.000	2.540
GRUP 1CH	61.000	2.540
GRUP 1CH	61.000	1.590
GRUP 1DH	61.000	2.540
GRUP 1EH	61.000	2.540
GRUP 1EH	61.000	1.590
GRUP 1FH	61.000	2.540
GRUP 1FH	61.000	1.590
GRUP 1FH	61.000	2.540
GRUP 1GH	61.000	2.540
GRUP 1GH	61.000	1.590
GRUP 1GH	61.000	2.540
GRUP 1HH	61.000	2.540
GRUP 1HH	61.000	1.590
GRUP 1IH	61.000	2.540
GRUP 1IH	61.000	1.590
GRUP 1JH	61.000	2.540
GRUP 1JH	61.000	1.590
GRUP 1JH	61.000	2.540
GRUP 1KH	61.000	2.540
GRUP 1KH	61.000	1.590
GRUP 1MH	61.000	1.590
GRUP 1MH	61.000	2.540
GRUP 1NH	61.000	1.590
GRUP 1NH	61.000	2.540
GRUP 1OH	61.000	1.590
GRUP 1OH	61.000	2.540
GRUP 1RH	61.000	1.590
GRUP 1UH	40.600	1.270
GRUP 1XH	61.000	2.540

GRUP 1XH	61.000	1.590
GRUP 2A4	61.000	2.000
GRUP 2A4	61.000	2.540
GRUP 2AH	35.600	1.270
GRUP 2BH	45.700	1.590
GRUP 2CH	50.800	0.950
GRUP 2CH	50.800	2.000
GRUP 2DH	50.800	2.000
GRUP 2DH	50.800	0.950
GRUP 2DH	50.800	2.000
GRUP 2EH	50.800	2.000
GRUP 2EH	50.800	0.950
GRUP 2FH	61.000	2.540
GRUP 2FH	61.000	2.000
GRUP 2FH	61.000	2.540
GRUP 2GH	50.800	0.950
GRUP 2HH	61.000	2.000
GRUP 2HH	61.000	2.540
GRUP 2JH	61.000	2.540
GRUP 2JH	61.000	2.000
GRUP 2KH	61.000	2.000
GRUP 2KH	61.000	2.540
GRUP 2LH	61.000	2.540
GRUP 2LH	61.000	2.000
GRUP 2MH	61.000	2.540
GRUP 2MH	61.000	2.000
GRUP 2OH	61.000	2.000
GRUP 2OH	61.000	2.540
GRUP 2PH	61.000	2.000
GRUP 2PH	61.000	2.540
GRUP 2QH	61.000	1.270
GRUP 2QH	61.000	2.000
GRUP 2SH	61.000	2.000
GRUP 2SH	61.000	2.540
GRUP 2TH	61.000	2.540
GRUP 2TH	61.000	2.000
GRUP 2UH	50.800	0.950
GRUP 2VH	61.000	2.540
GRUP 3A3	61.000	2.000
GRUP 3A4	61.000	2.540
GRUP 3A5	50.800	0.950
GRUP 3A5	50.800	2.000
GRUP 3A6	50.800	2.000
GRUP 3A7	61.000	2.000
GRUP 3A7	61.000	1.590
GRUP 3A8	61.000	2.540

GRUP 3A9	61.000	2.000
GRUP 3A9	61.000	2.540
GRUP 3AH	35.600	1.270
GRUP 3BH	45.700	1.590
GRUP 3CH	50.800	0.950
GRUP 3CH	50.800	2.000
GRUP 3DH	50.800	2.000
GRUP 3DH	50.800	0.950
GRUP 3DH	50.800	2.000
GRUP 3EH	50.800	2.000
GRUP 3EH	50.800	0.950
GRUP 3FH	61.000	2.000
GRUP 3FH	61.000	2.540
GRUP 3GH	50.800	0.950
GRUP 3JH	61.000	2.000
GRUP 3JH	61.000	1.590
GRUP 3KH	61.000	1.590
GRUP 3KH	61.000	2.000
GRUP 3LH	61.000	2.540
GRUP 3LH	61.000	2.000
GRUP 3MH	61.000	2.540
GRUP 3MH	61.000	2.000
GRUP 3MH	61.000	2.540
GRUP 3NH	61.000	2.000
GRUP 3PH	61.000	2.540
GRUP 3PH	61.000	2.000
GRUP 3PH	61.000	2.540
GRUP 3QH	61.000	2.000
GRUP 3QH	61.000	2.540
GRUP 3TH	61.000	2.000
GRUP 3TH	61.000	1.270
GRUP 3VH	61.000	2.000
GRUP 3VH	61.000	1.590
GRUP 3WH	50.800	0.950
GRUP 3XH	61.000	2.000
GRUP 3ZH	61.000	1.590
GRUP 4A1	50.800	2.000
GRUP 4A1	50.800	2.540
GRUP 4A3	50.800	2.540
GRUP 4A5	45.700	1.900
GRUP 4A6	45.700	1.900
GRUP 4A6	45.700	1.590
GRUP 4A7	50.800	2.540
GRUP 4A8	61.000	3.000
GRUP 4A8	61.000	2.000
GRUP 4A9	61.000	2.540

GRUP 4A9	61.000	1.590
GRUP 4A9	61.000	3.000
GRUP 4AH	35.600	1.270
GRUP 4B1	61.000	3.000
GRUP 4B1	61.000	1.590
GRUP 4B1	61.000	3.000
GRUP 4B3	61.000	2.000
GRUP 4B6	50.800	2.000
GRUP 4B6	50.200	2.240
GRUP 4B7	61.000	3.000
GRUP 4B8	61.000	2.540
GRUP 4B8	61.000	1.590
GRUP 4BH	45.700	2.000
GRUP 4CH	61.000	2.000
GRUP 4DH	45.700	1.590
GRUP 4EH	45.700	2.540
GRUP 4FH	45.700	1.590
GRUP 4FH	45.700	2.540
GRUP 4GH	45.700	1.270
GRUP 4HH	61.000	2.540
GRUP 4IH	61.000	2.540
GRUP 4JH	61.000	2.540
GRUP 4JH	61.000	2.000
GRUP 4KH	61.000	1.590
GRUP 4KH	61.000	3.000
GRUP 4LH	61.000	2.000
GRUP 4LH	61.000	3.000
GRUP 4MH	50.800	1.270
GRUP 4MH	50.800	2.540
GRUP 4NH	61.000	2.000
GRUP 4OH	45.700	2.540
GRUP 4OH	45.700	1.590
GRUP 4PH	45.700	1.590
GRUP 4QH	45.700	2.540
GRUP 4RH	61.000	2.000
GRUP 4RH	61.000	2.540
GRUP 4SH	61.000	2.000
GRUP 4UH	45.700	1.590
GRUP 4VH	76.200	2.540
GRUP 4XH	21.900	0.790
GRUP 4YH	61.000	2.000
GRUP 4ZH	50.800	2.000
GRUP 4ZH	50.800	2.540
GRUP 5A2	61.000	1.590
GRUP 5A2	61.000	2.000
GRUP 5A3	61.000	2.000

GRUP 5A3	61.000	1.590
GRUP 5A3	61.000	2.000
GRUP 5A5	61.000	2.000
GRUP 5A5	61.000	1.590
GRUP 5A6	61.000	1.590
GRUP 5AH	35.600	1.270
GRUP 5BH	45.700	1.590
GRUP 5CH	50.800	0.950
GRUP 5CH	50.800	2.000
GRUP 5DB	76.200	1.270
GRUP 5DH	50.800	2.000
GRUP 5DH	50.800	0.950
GRUP 5DH	50.800	2.000
GRUP 5EH	50.800	2.000
GRUP 5EH	50.800	0.950
GRUP 5FH	61.000	2.000
GRUP 5FH	61.000	1.590
GRUP 5FH	61.000	2.000
GRUP 5GH	50.800	0.950
GRUP 5HH	61.000	1.590
GRUP 5HH	61.000	2.000
GRUP 5JH	61.000	1.590
GRUP 5JH	61.000	2.000
GRUP 5KH	61.000	2.000
GRUP 5KH	61.000	1.590
GRUP 5LH	61.000	2.000
GRUP 5LH	61.000	1.590
GRUP 5MH	61.000	2.000
GRUP 5MH	61.000	1.590
GRUP 5MH	61.000	2.000
GRUP 5NH	61.000	2.000
GRUP 5NH	61.000	1.590
GRUP 5NH	61.000	2.000
GRUP 5QH	61.000	1.590
GRUP 5QH	61.000	2.000
GRUP 5RH	61.000	1.590
GRUP 5RH	61.000	2.000
GRUP 5SH	61.000	2.000
GRUP 5SH	61.000	1.590
GRUP 5TH	61.000	2.000
GRUP 5TH	61.000	1.590
GRUP 5UH	61.000	2.000
GRUP 5UH	61.000	1.590
GRUP 5VH	50.800	1.270
GRUP 5YH	61.000	2.000

Appendix D – Matlab Algorithm

Random Variables Input File

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% DATA FIELDS IN 'PROBDATA' %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Names of random variables. Default names are 'x1', 'x2', ..., if
not explicitely defined.
% probdata.name = { 'name1' 'name2' ... } or { 'name1'
'name2' ... }'
%>>> Tubular Joint Input Variables <<<<
probdata.name = { 'Bi'
                  'Hs'
                  'Ai'};
% Marginal distributions for each random variable
% probdata.marg = [ (type) (mean) (stdv) (startpoint) (p1) (p2) (p3)
(p4) (input_type); ... ];
probdata.marg = [ 1 1.000 0.100 1.000 nan nan nan nan 0 ;
                 16 8.364 1.650 8.364 nan nan nan nan 0 ;
                  1 1.000 0.150 1.000 nan nan nan nan 0 ;];
% Correlation matrix
probdata.correlation = eye(3); %Non-Correlated variables, function
eye(n) displays the identitiy matrix
probdata.transf_type = 3;%Natal Joint Distribution - Transformation
matrix
probdata.Ro_method = 1;%Method for computation of Nataf Corr Matrix
- Solved numerically
probdata.flag_sens = 1;%Computation of sensitivities w.r.t - all
sensitivities assessed
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% DATA FIELDS IN 'ANALYSISOPT' %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
analysisopt.multi_proc = 1; % 1: block_size g-calls sent
simultaneously
% - gfunbasic.m is used and a vectorized version of
gfundata.expression is available.
% The number of g-calls sent simultaneously (block_size) depends on
the memory
% available on the computer running FERUM.
% - gfunxxx.m user-specific g-function is used and able to handle
block_size computations
% sent simultaneously, on a cluster of PCs or any other
multiprocessor computer platform.
% 0: g-calls sent sequentially
analysisopt.block_size = 100; % Number of g-calls to be sent
simultaneously
% FORM analysis options
analysisopt.i_max = 1000; % Maximum number of iterations allowed in
the search algorithm
analysisopt.e1 = 1e-5; % Tolerance on how close design point is to
limit-state surface
analysisopt.e2 = 1e-5; % Tolerance on how accurately the gradient
points towards the origin
analysisopt.step_code = 0; % 0: step size by Armijo rule, otherwise:
given value is the step size
analysisopt.Recorded_u = 1; % 0: u-vector not recorded at all
iterations, 1: u-vector recorded at all iterations
```

```
analysisopt.Recorded_x = 1; % 0: x-vector not recorded at all
iterations, 1: x-vector recorded at all iterations
% FORM, SORM analysis options
analysisopt.grad_flag = 'ffd'; % 'ddm': direct differentiation,
'ffd': forward finite difference
analysisopt.ffdpara = 1000; % Parameter for computation of FFD
estimates of gradients - Perturbation = stdv/analysisopt.ffdpara;
% Recommended values: 1000 for basic limit-state functions, 50 for
FE-based limit-state functions
analysisopt.ffdpara_thetag = 1000; % Parameter for computation of
FFD estimates of dbeta_dthetag
% perturbation = thetag/analysisopt.ffdpara_thetag if thetag ~= 0 or
1/analysisopt.ffdpara_thetag if thetag == 0;
% Recommended values: 1000 for basic limit-state functions, 100 for
FE-based limit-state functions
% Simulation analysis (MC,IS,DS,SS) and distribution analysis
options
analysisopt.num_sim = 1000000; % Number of samples (MC,IS), number
of samples per subset step (SS) or number of directions (DS)
analysisopt.rand_generator = 1; % 0: default rand matlab function,
1: Mersenne Twister (to be preferred)
% Simulation analysis (MC, IS) and distribution analysis options
analysisopt.sim_point = 'origin'; % 'dspt': design point, 'origin':
origin in standard normal space (simulation analysis)
analysisopt.stdv_sim = 1; % Standard deviation of sampling
distribution in simulation analysis
% Simulation analysis (MC, IS)
analysisopt.target_cov = 0.05; % Target coefficient of variation for
failure probability
analysisopt.lowRAM = 0; % 1: memory savings allowed, 0: no memory
savings allowed
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% DATA FIELDS IN 'GFUNDATA' (one structure per gfun) %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Type of limit-state function evaluator:
% 'basic': the limit-state function is defined by means of an
analytical expression or a Matlab m-function,
% using gfundata(lsf).expression. The function gfun.m calls
gfunbasic.m, which evaluates gfundata(lsf).expression.
% 'xxx': the limit-state function evaluation requires a call to an
external code. The function gfun.m calls gfunxxx.m,
% which evaluates gfundata(lsf).expression where gext variable is a
result of the external code.
gfundata(1).evaluator = 'basic';
gfundata(1).type = 'expression'; % Do no change this field!
% Expression of the limit-state function:
gfundata(1).expression = 'gfun_testA(Bi,Hs,Ai)';
% Flag for computation of sensitivities w.r.t. thetag parameters of
the limit-state function
% 1: all sensitivities assessed, 0: no sensitivities assessment
gfundata(1).flag_sens = 0;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% DATA FIELDS IN 'FEMODEL' %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
femodel = [];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% DATA FIELDS IN 'RANDOMFIELD' %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
randomfield = [];
```

Limit State Function File

```
function g = gfun_testA(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 = 0.000;
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);
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATA FIELDS IN 'Load Model' %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Environmnetal Load Model
%Hc = 4.8600; %scale parameter from weibull distribution
%r = 5.8849; %shape parameter from weibull distribution
Ua = 1.20;
Wa = 24.00;
Load =
Ai.*((c1.*(Hs.^2))+(c2.*Hs)+(c3.*(Ua.^2))+(c4.*Ua)+(c5.*(Wa.^2))+(c6
.*Wa)+c7);
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATA FIELDS IN 'lIMIT STATE FUCTION'(gfun) %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Limit State Function
g = (Resistance - Load);
```