System Reliability of an Existing Jacket Platform
(Failure Paths and System Reliability Index)

By

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CERTIFICATION OF APPROVAL

SYSTEM RELIABILITY OF AN EXISTING JACKET PLATFORM (FAILURE PATHS AND SYSTEM RELIABILITY INDEX)

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Approved by,

____
Prof. Dr. Kurian V. John

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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 has not been undertaken or done by unspecified sources or persons.

THEA SOKHEANG

ABSTRACT

The objective of the project is to determine the reliability of an existing jacket platform in Malaysia. This can be achieved by determining the system probability of failures as well as the accompanied system reliability index. Those two parameters are important indicators for assessing the integrity and reliability of the platform, and will point out whether the platform is strong enough for continued and prolonged operation. A lot of studies in the past have been focusing on component reliability which does not necessarily indicate the robustness of the platform as a whole. Thus, this project assess the whole system reliability by determining possible failure paths of the structure, the system probability of failures and its related system reliability index. In order to do that, first, the probability of failure of each component needs to be determined. From that, the probability of failure of each failure path and the probability of failure of the system can be calculated using the bounding formulae (Simple Bound). For component reliability, response surface method will be used to determine the global response as well as the local response of the structure. Those surfaces will be the input for the limit state functions. The probability of failure of each component can then be determined from the function using FORM method. Pushover analysis and the bounding formulae will used to determine most probable failure paths, the system probability of failures and corresponding reliability index. From the study, three probable failure paths have been determined, and it is found that the system reliability index of the structure is $\beta = 9.23$ with corresponding failure probability, P_f =1.36E-20 . With this, it can be assumed that the platform is robust and the probability of the collapse is very small.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The Oil and Gas Industries in Malaysia has been growing substantially since the 1990s. As the industries expanded, so do the number of supporting platforms. So far there are approximately 200 platforms (Potty & Akram, 2009). Many of those are located offshore.

In offshore industries, there are two categories of platforms: fixed offshore platform and floating offshore platform. The most commonly used fixed offshore platform is jacket structures. In Malaysia, the design life of fixed offshore is 30 years (PETRONAS, 2010) with the general practice of only for 25 years. Currently, they have been a lot of efforts to conduct the integrity and safety check on those platforms since as many as 90 platforms have exceeded their intended design life and are still in operation (Potty & Akram, 2009).

In order to ensure that the platforms are still safe to operate, several methods have been developed to assess the integrity and reliability of the platform. One of the methods is Reliability Analysis of the structures. In this method, the probability of failures of structural systems are determined, and the structural reliability index can be then obtained from the probability. These two parameters along with other factors acts as the basis and benchmark for further decision making and inspections.

The platform chosen for this project is F9JT-A. It is 4 pile leg gas producing platform in the Kumang Cluster, off the coast of Bintulu, Sarawak with a water depth of 94.6m.

Figure 1-1 F9JT-A

1.2 Problem Statement

1.2.1 Problem Identification

As mentioned above, there have been several methods to assess the safety and robustness of the existing platform. The analysis can be done either on the component level or system level. At component level, the analysis measures only the strength ratio or the failure probability of the component, and thus it does not show the integrity of the system as a whole. At system level, the integrity and safety of the system are considered. For example, the Reserve Strength Ratio (RSR) which is the ratio of the ultimate load at collapse and the design strength of the structures measures the excess load that the platform can take.

The system reliability analysis is employed to determine dominant failure paths, the probability of each failure paths, and the combined probability of failures of those failure paths. The reliability index can then be obtained from the system probability of failures.

1.2.2 Significant of the Project

The project aims to determine the reliability index as well as the failure probability of system. Those two indicators will be the basis to determine whether the jacket can still be used, or require necessary reimbursement. It will also point out dominant failure paths and their associated probability of failures. Knowing that will allow easier maintenance and inspection. The project will also provide useful methodologies that may be able to apply to other jacket platforms to assess their reliability.

1.3 Objectives and Scope of Study

1.3.1 Objectives

Main Objective:

- Reliability index and system probability of failure of an existing jacket platform

Sub Objectives:

- Determine dominant failure paths
- Determine the failure probability of each failure path

1.3.2 Scope of Study

The project covers only the objectives mentioned above. Other parameters to determine the integrity of the structural systems and system effects such as Reserved Strength Ratio, and Residual Strength are not considered.

1.4 Relevancy of the Project

1.4.1 Scope Feasibility

The project focuses on the determining failure paths and the related reliability index only. The analysis of the load, and resistance will not be conducted extensively due to time constraint. Thus, the scope is small enough to cover the period of two semesters.

1.4.2 Schedule Feasibility

The schedule of the project is shown as Gantt chart in the methodology section of the proposal. Since this project is carried out for two semesters, it is divided into two stages. The first stage will be mostly involved researches for literatures and methodologies as well as initial analysis and understanding. It will focus on determining the load and resistance condition, mathematical formulations, and refinement of the method. The second stage will focus more on the analysis part to determine possible failure paths, probability of failures and its related index.

1.4.3 Technical Feasibility

Essential software and tools for the completion of the project are readily available at UTP. UTP have obtained licenses for SACS software, which are installed in computer laboratory. Mathematical programming such as Matlab and Microsoft Excel are also installed on the author’s notebook.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will first introduce the concept and method of structural reliability, before moving on to system reliability. The literature on searching and determining failure modes, and some previous studies on the reliability of offshore platforms in Malaysia are also discussed.

2.2 Method of Structural Reliability

In general sense, reliability of a structure can be referred to as the ability to fulfill its design purpose for s specified time and under specified conditions. For narrower definition, it is described as the probability of the survival of the structure under a specific limit state (ultimate or serviceability) during a specified reference period (Chakrabarti, 2005).

The basis of reliability assessment depends on the probability of structural failure, P_f, by determining whether or not the limit-state functions are exceeded (Choi, Grandhi, & Canfield, 2007). Generally, limit-state can be grouped into two categories:

- **Ultimate limit-state:** collapse or failure of part or all of the structures. Some examples includes corrosion, fatigue, and fire. This kind of limit state should have a very low probability of occurrence since it presents the risk of life and finance.
- **Serviceability limit-state:** disruption of normal use of the structure. Some examples are excessive deflection and vibration. For this limit-state, higher tolerance can be applied since there is less danger.

The limit-state function is generally given as the difference between the resistance and the load of the structures. The limit-state function $g(X)$ and probability of failure P_f can be defined as:

$$g(X) = R(X) - S(X) \qquad (1)$$

$$P_f = P[g(X) < 0] \tag{2}$$

Where R and S are the resistance and loading of the system respectively. They are both the function of random variables, X.

The region where $g(X) < 0$ is called “failure region”, while $g(X) = 0$ and $g(X) > 0$ are called “failure surface” and “safe region” respectively.

The mean and variance of $g(X)$ are given by:

$$\mu_g = \mu_R - \mu_S \tag{3}$$

$$\sigma_g = \sqrt{\sigma_R^2 + \sigma_S^2 - 2\rho_{RS}\sigma_R\sigma_S} \tag{4}$$

Where μ_R and σ_R are the mean and standard deviation of resistance, μ_S and σ_S are the mean and standard deviation of load, and ρ_{RS} is the correlation coefficient between R and S.

The reliability index, β can be determined by:

$$\beta = \frac{\mu_g}{\sigma_g} \tag{5}$$

For special case where R and S are normally distributed and uncorrelated, and when $g(X) = 0$, the probability of failure P_f is given by:

$$P_f = 1 - \phi(\beta) = \phi(-\beta) \tag{6}$$

, where $\phi(\cdot)$ is the standard normal distribution function.

The reliability index, β, can be then determined by:

$$\beta = -\phi^{-1}(P_f) \tag{7}$$

Equation (6) and Equation (7) presents the relationship between probability of failure, P_f and reliability index, $\phi(\beta)$.

In general, the probability of failure, P_f, is given by the integral:

$$P_f = \int \dots \int_{g(\cdot)<0} f_x(x_1, x_2, \dots, x_n) dx_1 dx_2 \dots dx_n \tag{8}$$

, where $f_x(x_1, x_2, \dots., x_n)$ is the joint probability density function for the basic random variables, $X_1, X_2, \dots, X_n$ and the integration is conducted over the failure region, $g(\cdot) < 0$.

Since the direction integration of Equation (8) is extremely complicated, the method such as FORM (First-Order Reliability Method) is used to evaluate when the limit state function is a linear function or uncorrelated normal variables or when the non-linear limit state function is represented by a first order (linear) approximation with equivalent normal variables. In this study, FORM will be employed to determine the probability of failures of the component by using FERUM Program.

2.3 System Reliability

System Reliability analysis is a relatively new area with an extensive ongoing researches in the field. For statistically determinate structures, in some instances the reliability of individual members are sufficient since the failure of one member will lead to the whole structure failure. However, this is not the case for a highly redundant structures. The failure of one or few members does not necessarily result in the collapse of the system. In that sense, the system will contain numerous failure modes or failure paths. According to the random nature of load and resistance distributions, some failure paths are more likely to occur than other. The probability of those failure modes and their method of determinations are the basis of system reliability analysis.

2.3.1 Structural System Idealization

In real life, a structural system is usually very complicated. Direct exact calculation is therefore impossible. The system is then to be idealized to simplify the process. However, this needs to be chosen carefully so that the model still reflects the real structure properties and at the same time reduce calculation difficulties. The total reliability of the system can be then estimated by taking into account a specific number of failure modes or failure paths, and combine them in complex reliability system (Christensen, 2005).

A structural system usually can be modelled as a series system, parallel system or combination of both. A series system (Christensen, 2005) is a system in which failure in a structural element will lead the whole system collapse. For parallel system (Figure 2-2), failure in a member does not usually lead to total system collapse. For complex structures (Figure 2-3), it is assumed that the structural system is a series of parallel systems, in which each parallel system represent a failure mode.

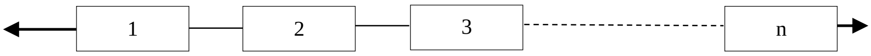


Figure 2-1 Series system with n elements

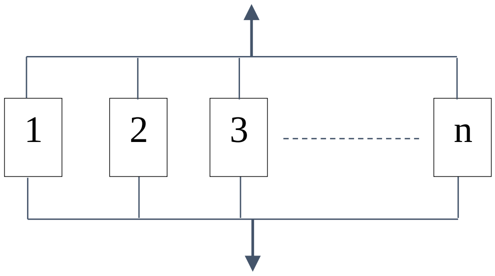


Figure 2-2 Parallel system with n elements

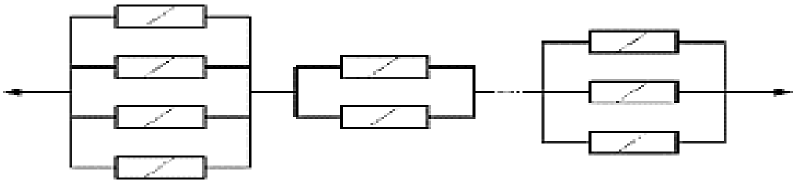


Figure 2-3 Hybrid System

Thus, the system event can then be given by (Kim, Ok, Song, & Koh, 2013):

$$E_{sys} = \bigcup_{k=1}^{N_{cut}} C_k = \bigcup_{k=1}^{N_{cut}} \left[\bigcap_{i \in I_{C_k}} E_i \right] \tag{9}$$

Where:

- C_k represents each failure mode
- N_{cut} is the number of failure modes
- E_i represents the each failure element in each failure modes
- $I_{C_k}$is the index set of components that exist in C_k

In order to determine the system probability and reliability index, the probability of failure of each component in each failure path (parallel system) are first determined. The probability of each failure mode are then evaluated before proceeding to the total system probability of failure as shown in Equation (9).

2.3.2 Reliability Bounds

In order determine the probability of the system in Equation (9), approximate techniques or bounding techniques must be used. Simple Bounds and Ditlesven Bounds are described below.

2.3.2.1 Simple Bounds

For convenience, Boolean variables are used. Let S be a system with n failure elements $E_1, \ldots, E_i, E_{i+1}, E_n$. For each failure element $E_i, i = 1, \ldots, n$, a Boolean variable e_i is defined by:

$$e_i = \begin{cases} 1, & if\ the\ failure\ element\ is\ in\ a\ nonfailure\ state. \\ 0, & if\ the\ failure\ element\ is\ in\ a\ failure\ state. \end{cases}$$

For series system, the simple bounds is given by:

$$\max_{i=1,\ldots,n} P(e_i = 0) \leq P_{fs} \leq 1 - \prod_{i=1,\ldots,n} (1 - P(e_i = 0)) \qquad (10)$$

The lower bound in Equation (10) is equal to the exact value of P_{fs} if there is full dependence between all elements and the upper bound correspond to no dependence between any pair of elements. When the probability of failure of one element is predominant in relation to the other failure elements then the probability of failure of series system is approximately equal to the predominant probability of failure and the gap between the upper bound and lower bound is narrow. However, when the probabilities of failure are in the same order the simple bounds are wide.

For parallel system, the simple bound formula is given by:

$$\prod_{i=i,\ldots,n} P(e_i = 0) \leq P_{fp} \leq \min_{i=1,\ldots,n} P(e_i = 0) \qquad (11)$$

The lower bound in Equation (11) is equal to the exact value of P_{fp} if there is no dependence between any pair elements and the upper bound corresponds to full dependence between all elements.

2.3.2.2 Ditlesven Bounds

Since the bound provided by the simple bound can be very wide, Ditlesven Bounds provides a narrower ones.

For series systems, it is given by:

$$P_{fs} \leq \sum_{i=1,\ldots,n} P(e_i = 0) - \sum_{i=2,\ldots,n} \max_{i<j} P(e_i = 0 \cap e_j = 0) \qquad (12)$$

$$P_{fs} \geq \ P(e_1 = 0) + \max_{i=2,\ldots,n} P(e_i = 0) - \sum_{j=1,\ldots,i-1} P(e_i = 0 \cap e_j = 0{,}0) \qquad (13)$$

The gap given by Equation (12) and Equation (13) are usually much smaller than the gap between the simple bound. Nonetheless, they require the calculation of the joint probabilities, and these calculation are not trivial, usually requiring numerical technique.

For this reason, simple bound is used in the study. Even though the gap may be wide, it also can provide some indication of the reliability of the platform.

2.4 Methods to Determine Failures Modes and System Reliability Index

As mentioned earlier, a structure especially for complex one can contains a large number of possible failure modes. Including all the possible failure modes in the analysis is an infeasible and inefficient, since many of the failure modes have a very low probability of occurrence. Thus, many of the methods to determine the system reliability are developed to consider dominant failure modes with higher probability in an event tree (Kim, Ok, Song, & Koh, 2013). An event tree is a diagram showing dominant possible paths of failure, which include sequence of structural member failures with their probability of failures.

Shao and Murostu (1999) discusses a varieties of methods to determine dominant failure modes. They categorize the methods into three: “Enumeration Approach”, “Plasticity Based Approach” and “Simulation Based Approach”. In “Enumeration Approach”, failure trees are generated by extending the sequence of element failures step by step until the system collapses. Some examples of the approaches are incremental loading method (pushover) and branch-and-bound method. In incremental loading method, the failure modes are generated by incrementally factoring the load to cause sequence of member failures. The method is deterministic, and can obtain crucial failure paths with few repetitions of structural analysis. However, with this method not all dominant failure paths can be determined. The brand-and-bound method, on the other hand, employs probabilistic search algorithm. It searches possible failures mode by considering their probabilities of occurrences. Even though the branch and bound method is theoretically rigorous, the required computing power can be very high.

“Plasticity-based Approach” is based the assumption of plastic behavior in the material. The analytical formulation of plastic mechanism can determined by lower-bound and upper-bound theorem (Shao & Murotsu, 1999). Some of the methods using this approach is β-unzipping method and linear programming (LP).

“Simulation-based Approach” uses simulation methods such as Monte Carlo to generate possible failure modes. However, this method can be computationally expensive.

Shao and Murotsu (1999) also proposed a method “Selective Searching Technique” which is a compromise between deterministic and probabilistic approach. They used Genetic Algorithm (GA) to search for dominant failure paths. β-value is used to determine search directions and fitness function. Kim et al. (2013) further improve the method by eliminating the use of fitness function, and introducing outward searching techniques to determine dominant failure modes. In this way, all critical failure paths can be identified without eliminating potential chromosomes that may lead to system collapse.

2.5 Previous Studies on System Reliability of Fixed Malaysian Offshore Platforms

There have been few studies on the system reliability of Malaysian fixed offshore platform. A variety of methods are employed including failure paths, reserved strength ratios, component and joint reliability analysis.

Leng (2005) did an extensive studies on a jacket platform. She worked on both component reliability analysis as well as structural system analysis. For the system reliability analysis, in order to determine the system reliability index pushover method was used. The search for failure modes was done manually. In the way, only four failure paths were determined, with one for each direction. The probability of failure were carried out using the simple bound method, which gives the reliability index of 10.91.

Tan (2012) determined the RSR (Reserved Strength Ratio) of an existing jacket platform in Sarawak, Malaysia by using the pushover analysis. He did not consider the probability of failures, and found the RSR of 2.64.

Cossa, Potty, Liew and Idrus (2011) compared the different design code (API RP2A, WSD and ISO 19902) by using reliability analysis on tubular joints of fixed platform. First Order Reliability Method (FORM) coded in Matlab was employed to determine the reliability index. The reliability index based on ISO design code was found to be approximately 3.0.

Malaysian Environmental Load Factors are also established by using reliability analysis of the jacket platform (Cossa N. J., Potty, Idrus, Hamid, & Nizamani, 2012). Monte Carlo Simulation (MSC) is employed to generate random variables based on the predetermined probability distribution function. Their goals is to determine the environment load factors; however, in the same process the component reliability index is obtained based on API RP2A-WSD. The index of 3.26 and 3.44 were found for brace members and leg members respectively.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter presents the methodologies employed in the studies. It includes loading and resistance criteria; analysis method; failure tree generation and reliability; FERUM 4.1 Program description; project activities, Gantt chart and key milestones; and development tools.

3.2 Load and Resistance Parameters

3.2.1 Environmental Loading Criteria

The metocean data for the study will be taken from the data provided by PETRONAS specifically for the Kumang Cluster and F9JT-A. In this study, only three directions of environmental loads are considered, which are 0 degree, 270 degrees and 315 degrees relative to platform north.

3.2.1.1 Wave

The wave data used in this analysis are listed in table below.

Table 3-1 Significant Wave Height for 0, 270 and 315 Degrees Storm

Return Period, Tr (years)	H_s (m)	T_z (s)
1	4.9	7.4
10	5.6	7.85
50	6.1	8.05
100	6.3	8.2

From the data above, Weibull distribution is used to fit to obtain shape and scale parameters. Those parameters will later be used to generate random wave data for the analysis. The tables below list those parameters.

Table 3-2 Wave Height Distribution Parameters for 0, 270 and 315 Degrees Storm

Type of Distribution	Weibull
Shape Parameter	5.88
Scale Parameter	4.86

Table 3-3 Wave Height Distribution for 45 Degrees Wave

Type of Distribution	Weibull
Shape Parameter	5.09
Scale Parameter	4.07

In order to determine, maximum wave height, $Hmax$, it is assumed that

$$Hmax = 1.8 * Hs \tag{14}$$

The relationship between zero-crossing period, Tz and Hs is given by Equation (15).

$$Tz = aH_s^b \tag{15}$$

Tz, is fitted against Hs to by using the data given in Table 3-1 to find the coefficient a and b.

The associated wave period, $Tass$ is determined from Tz through the relationship

$$Tass = 1.31 * Tz \tag{16}$$

3.2.1.2 Current

The current velocity at surface are given in Table 3-4.

Table 3-4 Current Velocity

Return Period, Tr (years)	Vc (m/s)
1	0.85
10	1.05
50	1.15
100	1.2

Weibull distribution is also used to fit the data to determine shape and scale parameters, which will later be used to generate random variables. The parameters are given in Table 3-5.

Table 3-5 Current Velocity Distribution

Type of Distribution	Weibull
Shape Parameter	5.19
Scale Parameter	0.89

In order to determine the current velocity profile at mid-depth (0.5*d) and near-bottom (0.1*d), the 1/3 power law is used.

$$V_{@d} = \left(\frac{d}{D}\right)^{\frac{1}{3}} * V_c \tag{17}$$

It should also be noticed that current velocity is independently generated from the wave height. The justification of this is that due to the random nature of the sea, wave height and current velocity is not always correlated.

3.2.1.3 Wind

In the platform studied, wind is determined as static point load and applied at the topside. In this study, wind is assumed to be deterministic and not a random parameter. The wind velocity for storm condition is 24 m/s.

3.2.2 Resistance Variables

The resistance parameters used in this study is based on the survey and study in Malaysia by Zafarullah (2013). The parameters used here are diameter, wall thickness, and yield strength.

Table 3-6 Resistance Variables

Type of Variability	Statistical Parameter	Leg> 1000mm	Brace <1000mm
Diameter	Distribution	Normal	Normal
	Mean Coefficient	1.001	0.9993
	Variance Coefficient	0.0014	0.0018
Wall Thickness	Distribution	Normal	Normal
	Mean Coefficient	1.024	
	Variance Coefficient	0.016	
Yield Strength	Distribution	Normal	
	Mean Coefficient	1.23	
	Variance Coefficient	0.05	

The axial resistance, F_a, and bending resistance, F_b, of the tubular component are given in API RP 2A-WSD code. The random parameters listed in Table 3-6 are used to determine both F_a and F_b which will be the inputs of the limit state functions.

3.3 Analysis Method

3.3.1 Pushover Analysis

Pushover analysis is the industry standard analysis to determine the excess strength of the platform. It is based on the non-linear collapse module in SACS. The load will be incrementally factored until the whole structure collapse. The sequence of applying the incremental factor are dead load, followed by live load and environmental load. The load factor for dead load and live load are usually from 0 to 1, while that for environmental load are factored until the structure collapse. While the structure is incrementally loaded, the component of the platform will also be loaded beyond its yielding point. The plastic behavior of element are closer to the real response of the component, since in real situation each member will be more likely to fail beyond their yielding point. The pushover analysis stops when the platform undergoes large deflection or collapses.

3.3.2 Component Post-Failure Behavior

In order to accurately determine failure paths, post-failure behavior of the component needs to be modelled correctly. The failure element can be regarded as perfect brittle element or perfect ductile element. For brittle element, it will become ineffective after failure; that is, it lost its load-bearing capacity after it failed. However, if the element is ductile, it still can carry the load.

In this study, semi-brittle model is used as shown in Figure 3-1. The member force increases elastically to the member capacity or resistance. After failure, that is, if the axial deformation in the element is increased beyond its failure value, the element force abruptly drops to a fraction, φ , of its unfailed capacity. For this application a deterministic value of $\varphi = 0.4$ was used for members failing in compression and $\varphi = 1.0$ for tension failure. In other words we assumed ductile tension failure behavior, maintaining the failure load, and an abrupt drop to 40 % capacity when failing in compression.

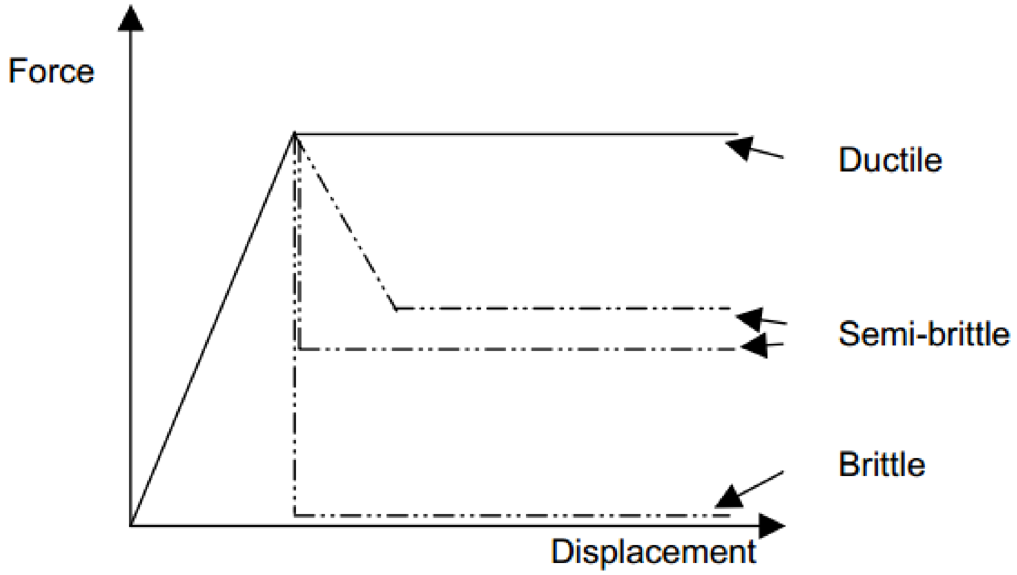


Figure 3-1 Semi-Brittle Model

The loading bearing capacity of the component is given by AISC formula with safety factor removed. The resistance is also reduced by 15% to account for the neglected moments induced by frame action (Nordal, Cornell, & Karamchandani, 1987).

For compression capacity, it is given in Equation (18).

$$R_c = 0.85 f_y A_x \left(1 - \frac{\left(\frac{kl}{r}\right)^2}{2C_c^2}\right) \quad (18)$$

Where,

$$C_c = \sqrt{\frac{2\pi^2 E}{fy}}$$

$$r = \frac{\sqrt{d_o^2 + d_i^2}}{4}$$

For tension capacity, it is given in Equation (19).

$$R_T = 0.85 f_y A_x \quad (19)$$

In order to represent the true capacity of the member especially in a probabilistic context, the random member properties are described by a mean resistance since the design capacities take from the codes include some conservatism. In other words, mean resistances are the best estimates of the real capacity.

In this study, f_y in Equation (18) and Equation (19) is taken as mean value which equals to nominal value multiplied by MC given in Table 3-6. A_x is still taken as nominal value since it is not very significant.

3.3.3 Response Surfaces

Response Surfaces method will be employed to perform the reliability analysis. This approach can reduce the number of structural analysis required for probabilistic analysis. It is divided into two stages which are “Global Response Surfaces” and “Local Response Surfaces.”

3.3.3.1 Global Response Surfaces

The global response surfaces relate the environmental load to the global response of the structure. The environmental load considered for the global response surfaces in this study is, maximum wave height, $H_{max,}$ and current velocity, V_c, while the global response of the structure is the base shear. Overturning moment is not taken as one of the global response to simplify the model, and due to that base shear can be fitted with H_{max} and V_c very well. The wind speed is not also taken one of the variable since in this study it is considered as deterministic, and its contribution to the load is not very significant.

We take the function G as the global response:

$$G = f(Wave, Current) \tag{20}$$

To be more specific, BS (Base Shear) is against H_{max} and V_c in the Equation (21).

$$BS = aH_{max}^2 + bH_{max} + cV_c^2 + dV_c + e \tag{21}$$

In order to determine the response of the structure (base shear), 20 sets of environmental load (H_s and V_c) are generated based on Weibull distribution base on the parameter in Table 3-2 and Table 3-5. H_{max} and T_{ass} can then be determined from Equation (14) and Equation (16).

Structural analysis are then carried out by using SACS. From the analysis, 20 sets of global structure response are obtained. The relationship between the environmental load and structure response is represented by Equation (21). The coefficients $a, b, c, d\ and\ e$ are determined by using Matlab Curve Fitting Tool.

3.3.3.2 Local Response Surfaces

The local response surfaces relate the global response of the structure to the local response of each member, g (axial stresses, $\mathrm{f_a}$, and bending stresses, f_b). Second-degree polynomial equation is used.

$$g = f(Base\ shear\ at\ mudline) \tag{22}$$

$$f_a = aBS^2 + bBS + c \tag{23}$$

$$f_b = aBS^2 + bBS + c \tag{24}$$

The procedure is the same as the global response surfaces .The local response surfaces will be used in the Limit State Function to determine the probability of failure of the component.

The step by step procedure to determine the response surfaces are given below:

1. Generate environmental loading conditions using Weibull Distribution (Significant Wave Height, H_s, and Current Velocity, V_c)
2. Structural analysis (SACS) are conducted using the generated environmental loads. Base shear at mudline can be obtained.
3. Using the Curve Fitting Tool in Matlab, global response surfaces as a function of H_{max} and V_c can be obtained.
4. Local response surfaces are obtained from the global response using the similar procedure.

3.3.4 Limit State Function

The reliability index and probability of failure are obtained from the limit state function. Thus, it is important to correctly determine types of failures, choices of interaction equations as well as random variables. In this study, the limit state functions are based on the utilization ratio from the codes of professional practice, API-RP2A working stress design (2007).

For cylindrical members subjected to combined compression and bending, a general utilization ratio should be:

$$\frac{f_a}{F_a} + \frac{f_b}{F_b} \leq 1.0 \qquad (25)$$

The general limit state can be then derived as:

$$g(\cdot) = 1.0 - (\frac{f_a}{F_a} + \frac{f_b}{F_b}) \qquad (26)$$

Where:

- f_a and f_b are axial stress and bending stress respectively. They are obtained from the local response of the structure, which are from SACS structural analysis.
- F_a and F_b are the resistance parameters determined from API RP 2A-WSD equation with the random variables in Table 3-6.

The limit state function divides the surface into two different regions which are safe region and unsafe region, which can be observed from Figure 3-2.

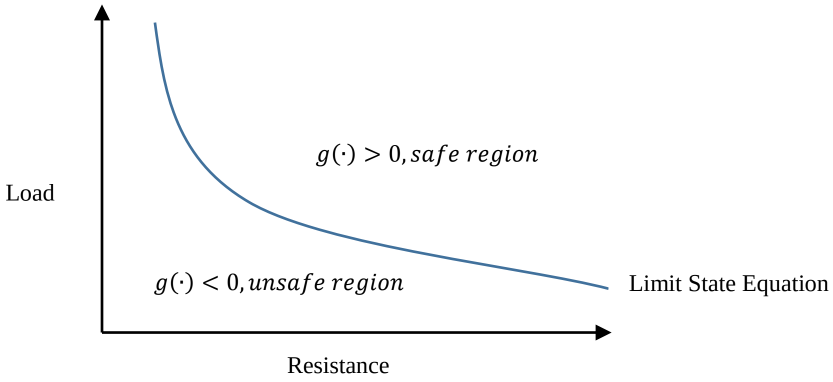


Figure 3-2 Limit State Function

3.4 Failure Tree Generation and Reliability

In order to determine the most probable failure path, pushover analysis is employed. The analysis will be conducted from three directions (0 degree, 270 degrees and 315 degrees), which are chosen based on the criticality of the environmental loading. In this method, only one failure path can be generated for each direction, totaling in three paths for the system reliability index.

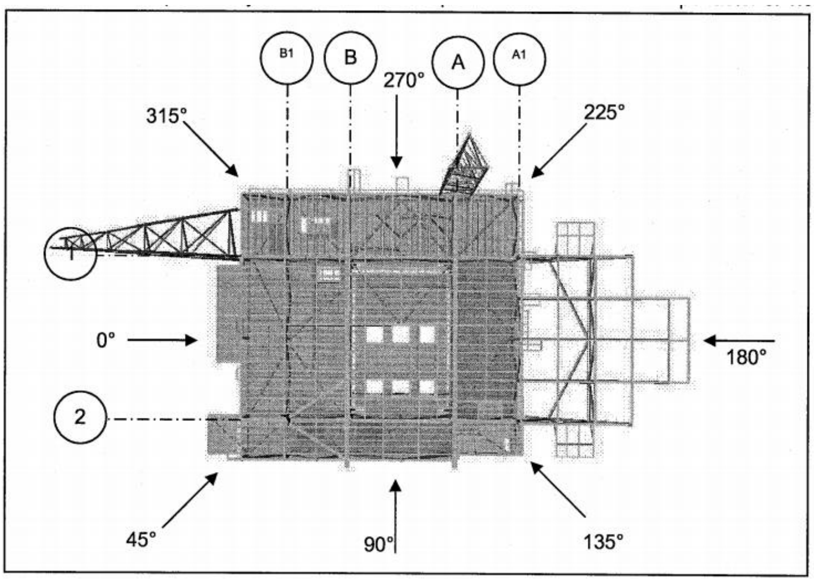


Figure 3-3 Directions of Storm

Using SACS non-linear collapse module, the structure and member are incrementally loaded beyond yielding spot. At the point where a member will be no longer be able to sustain the load, it will buckle or fracture. The first member that fails in that way is recorded. Thus, the first failure element is determined.

In order to choose the second failure element, the first member needs to be removed and replaced with fictitious load as discussed in Section 3.3.2. If the first member failed in compression, a pair of load with the magnitude of $0.4*R_C$ will be applied at the joints. If it failed in tension, the load of $1.0*R_T$ will be used instead. Pushover analysis will be then carried out again with this new modified structure, and the first member that fails will be recorded. In this way, the second failure element is determined.

The same process is repeated until there are no longer members fail in either buckling or fracture, and the structure fails in collapsing or large deflection. In this way, for each direction a path can be generated.

It is should also be noted that once the failure element has been spotted from the pushover analysis, the structure before removing that failed element is used to determine the member reliability. 20 random environmental load sample will be used determine the global response of the platform. From that, local response can be obtained. After that, it can be used as the input in the limit state function along with resistance variable. FERUM 4.1 Program will be used to determine the probability of failure and reliability index from the limit state function by using FORM.

Below is the step by step guide to determine the failure tree and reliability for each direction:

1. Conduct the non-linear collapse analysis until a structural element fails. The load factor and the failed element will be recorded.
2. Determine the reliability of that failed element
3. The failed member will be replaced with a pair of fictitious loads applied at the nodes.
4. With this new structural matrix, the pushover analysis is carried out again. The first member that fails is recorded.
5. Determine the reliability of that failed element
6. Repeat step 1 to step 6 until there are no longer members failing, and the structure fails in either collapsing or large displacement. In this way, member failure sequence is developed along with its corresponding probability of failure and reliability index.

After carrying out the analysis, failure event or failure tree can be produced based on the sequence of the failure for each direction. The failure tree will consist of 3 paths. One failure path will be obtained from each direction, and the probability of failure of those four paths will be determined using the Simple Bound formula for parallel system. The system reliability of the structure are then determined from those three probability of failures using Simple Bound formula for series systems.

3.5 FERUM 4.1 Program Description

3.5.1 Introduction

FERUM (Finite Element Reliability Using Matlab) is a general purpose structural reliability code whose first developments started in 1999 at the University of Cafifornia at Berkeley (UCB) (Bourinet, 2010). This code consists of an open-source Matlab toolbox, featuring various structural reliability methods. Nonetheless, the main tool used in this study is only FORM analysis.

3.5.2 FORM Analysis Method Used in the Program

FERUM takes the probability of failure in the form of:

$$P_f = \int_{g(x,\theta_g \leq 0)} f_x\big(x,\theta_f\big)dx \tag{27}$$

Where:

- $f_x(x,\theta_f)$ is the joint density function
- θ_f is the vector distribution parameters
- $g\big(x,\theta_g\big)$ is the limit state function with random vector X
- θ_g is a vector of deterministic limit-state function parameters

Nonetheless, the joint density function, $f_x(x,\theta_f)$ is usually unknown, and thus it is replaced by Nataf counterpart specifying marginal distributions and the Gaussian correlation structure between random variables. This allows FERUM to have a rich library of probability distribution models, including extreme value distributions and a truncated normal distribution, which are very useful in this study. These distributions can be specified through either their statistical moments or parameters.

First-Order Reliability Method (FORM) aims at using a first-order approximation of the limit-state function in the standard space at the so-called Most Probable Point (MPP) of failure P^* (or design point), which is the limit-state surface closest point to the origin. In the program, in order to determine the coordinates, u^*, of the MPP, optimization problem needs to be solved, subjected to:

$$u^* = argmin\{\|u\| \mid g\big(x(u),\theta_g\big) = G\big(u,\theta_g\big) = 0\} \tag{28}$$

After MPP, P^* is obtained, the Hasofer and Lind reliability index, β, is computed.

The probability of failure, P_f and reliability index, β, are given by Equation (6) and Equation (7). The algorithm employed in the program is based on iHLRF algorithm (Lemaire, 2009).

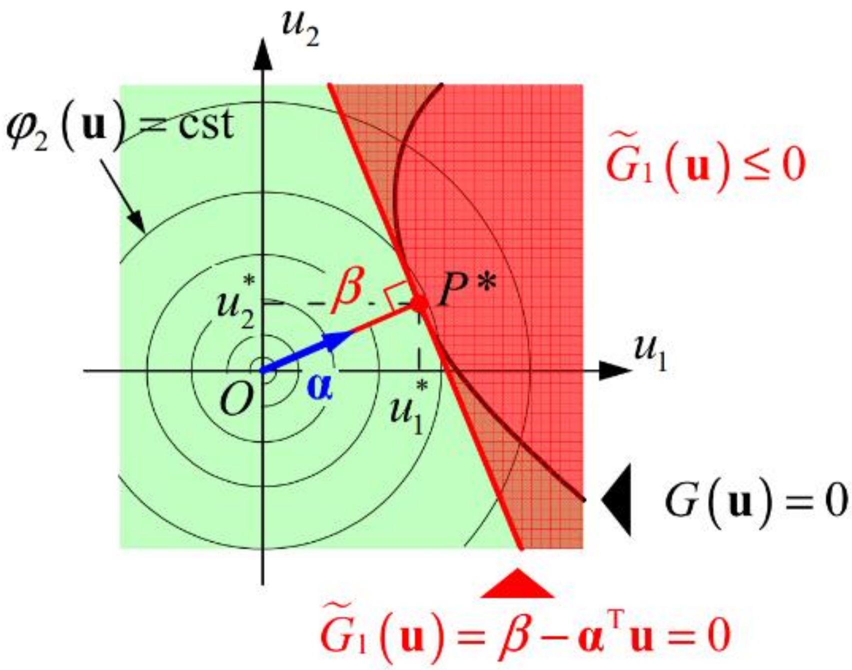


Figure 3-4 First-Order Reliability Method (FORM)

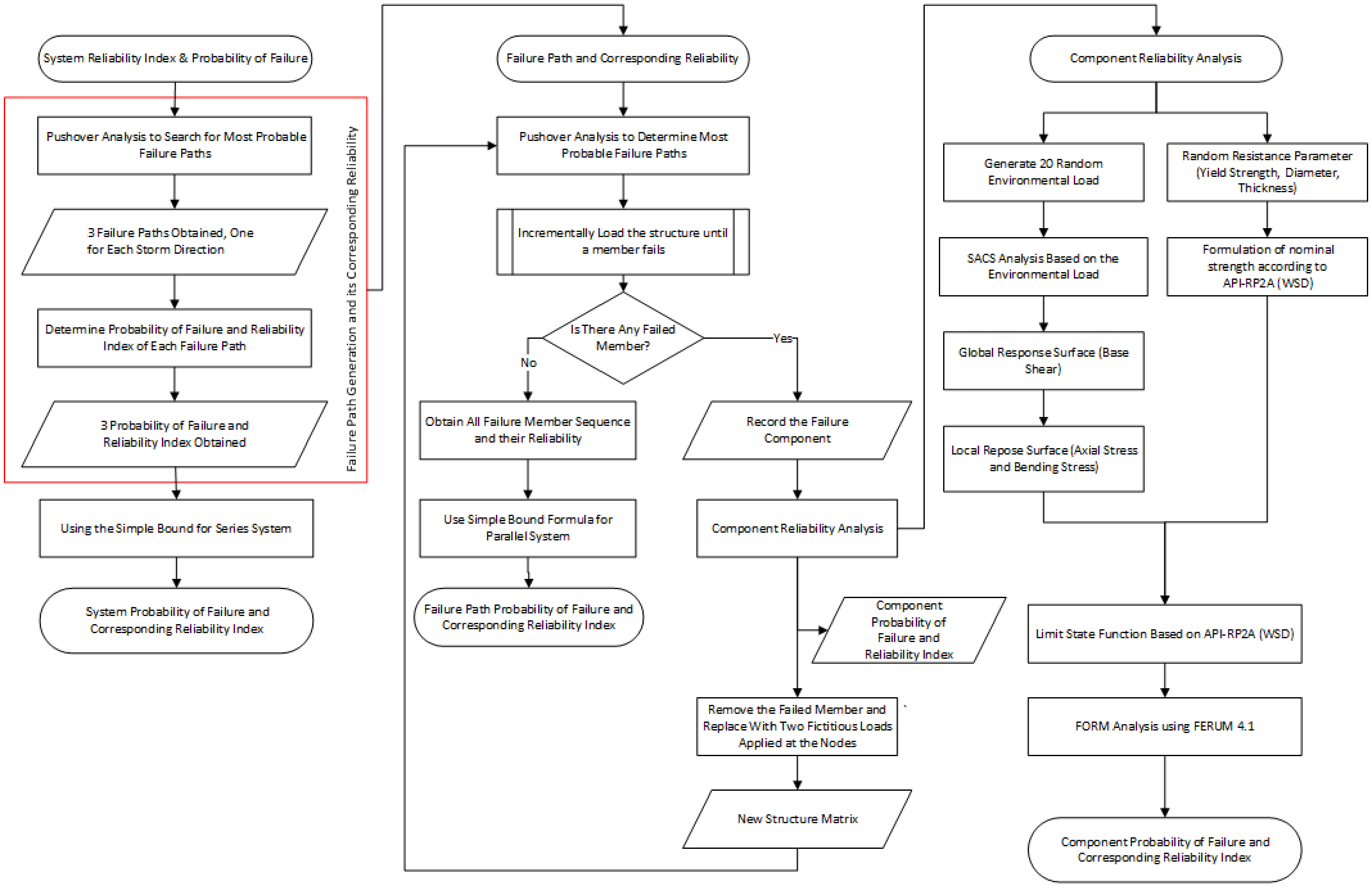
The input file and g-function file for FORM analysis is given in the Appendices.

3.6 Project Activities, Gantt Chart and Key Milestones

No	Details/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Data Preparation														
	Prepare and Search Metocean Data and Ressistance Data For Analysis	■	■												
2	Analysis Preparation														
	Create Excel VBA Code to Process Data			■	■										
	Create Matlab Functions and Input Files for FORM Analysis			■	■										
	Determine 3 Critical Storm Direction from SACS Analysis			■	■										
3	First Failure Path Determination and its Reliability														
	Generate Metocean Data					■	■	■							
	Pushover Analysis to Determine the Path					■	■	■							
	SACS and FORM Analysis					■	■	■							
4	Second Failure Path Determination and its Reliability														
	Generate Metocean Data								■	■	■				
	Pushover Analysis to Determine the Path								■	■	■				
	SACS and FORM Analysis								■	■	■				
5	Third Failure Path Determination and its Reliability														
	Generate Metocean Data											■	■	■	
	Pushover Analysis to Determine the Path											■	■	■	
	SACS and FORM Analysis											■	■	■	
6	Failure Tree and System Reliablity														
	Generate Failure Tree from the 3 Paths														■
	Determine the Reliability Index and Probability of Failure of the System														■

No	University Requirements/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Submission of Extended Proposal								■							
2	Pre-SEDEX Presentation											■				
3	Submission of Draft Report												■			
4	Submission of Dissertation (Soft Bound)													■		
5	Submission of Technical Report													■		
6	Oral Presentation														■	
7	Submission of Project Dissertation (Hard Bound)															■

3.7 Flow Chart



3.8 Development Tools

3.8.1 Hardware

Computer, ACER Aspire 4736G

- Intel® Core™ 2 Duo processor T6600
- 4GB RAM
- 500 GB Hard Disk

3.8.2 Software

- **SACS (Structural Analysis Computer System) 5.3 SP1**: Main tool to conduct structural analysis
- **FERUM 4.1:** Matlab Toolbox for FORM Analysis
- **Matlab R2011a**: Programming tool to automate mathematical analysis
- **Microsoft Excel 2013**: Spreadsheet software for data processing, data presentation and graphing.
- **Microsoft Word 2013**: Word-processing software for writing reports.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter will present progress result such as the failure trees, the probability of failure and reliability index of each component as well as that of the path. Then, those results will also be discussed.

4.2 Failure Tree

Figure 4-1 shows the failure tree of the platform. It is a representation of all possible failure paths in the structure. Each branch represent a possible failure path, and each node is member failures in the corresponding damaged structure. The number in the node is the failure element, identified by two joint numbers.

As presented earlier, a redundant system can have several failure paths. In such case, each of the failure paths can be modeled as a parallel system and all the paths, in turn, can be modeled as a series system to find the reliability of the complete system.

In this tree, three failure paths are presented which are 270 degrees storm path, 0 degree storm path and 315 degrees storm path. In the first path (270 degree storm), the first member that fails is member 502-458, which is followed by member 602-501X and so on. In this path, only 7 members fail before the whole structure collapse, while there are 11 members in 0 degree storm path. It is also interesting to note that there are 12 failed elements for 315 degrees path. It is due to that, unlike other two paths, for this path the load is applied on the side of the platform, which will provide more robustness to the structure as whole.

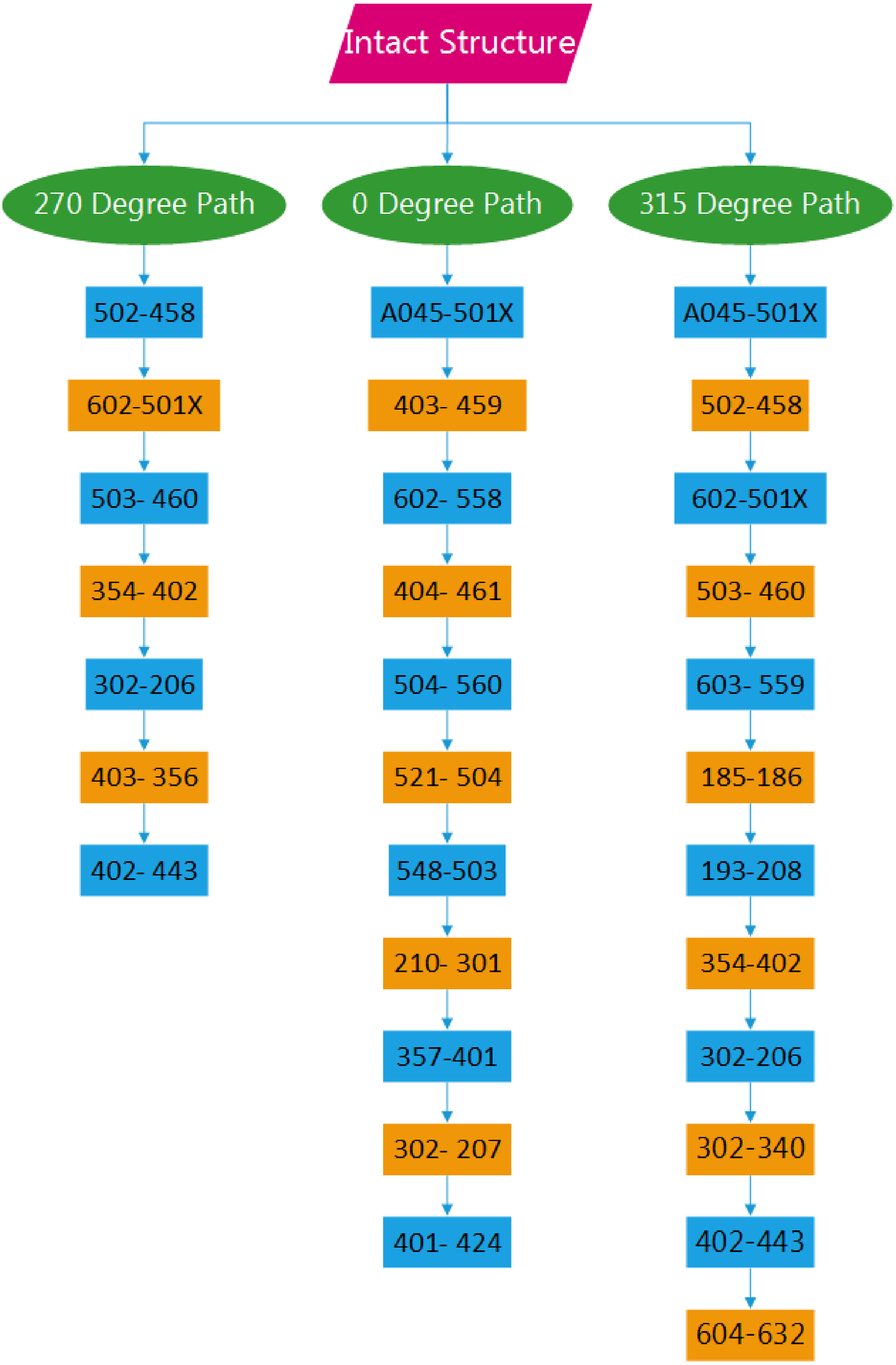


Figure 4-1 Failure Tree

4.3 Probability of Failure and Reliability Index

The probability of failure for the first path (270 Degree Storm), second failure path (0 Degree Storm) and Third Failure Path (315 Degree Storm) are shown in Table 4-1, Table 4-2 and Table 4-3 respectively.

Table 4-1 First Failure Path

Sequence	Member	Reliability Index, β	Probability of Failure, P_f
1	502-458	3.5409	1.99E-04
2	602-501X	6.6193	1.80E-11
3	503-460	6.701	1.03E-11
4	354-402	4.7291	1.13E-06
5	302-206	4.1782	1.47E-05
6	403-356	4.4936	3.50E-06
7	402-443	9.2298	1.36E-20

Table 4-2 Second Failure Path

Sequence	Member	Reliability Index, β	Probability of Failure, P_f
1	A045-501X	6.2873	1.62E-10
2	403- 459	11.979	2.29E-33
3	602- 558	13.493	8.60E-42
4	404- 461	12.209	1.39E-34
5	504- 560	11.892	6.51E-33
6	521- 504	10.063	4.03E-24
7	548-503	8.8692	3.68E-19
8	210- 301	8.7561	1.01E-18
9	357-401	12.656	5.18E-37
10	302- 207	6.0665	6.54E-10
11	401- 424	5.3639	4.07E-08

Table 4-3 Third Failure Path

Sequence	Member	Reliability Index, β	Probability of Failure, P_f
1	A045-501X	7.002	1.26E-1
2	502-458	6.0036	9.65E-10
3	602-501X	7.2135	2.73E-13
4	503-460	10.0200	6.23E-24
5	603-559	9.4292	2.27E-21
6	185-186	13.0180	4.83E-39
7	193-208	3.4348	2.97E-04
8	354-402	18.8160	2.79E-79
9	302-206	17.2350	7.25E-67
10	302-340	2.2028	1.38E-02
11	402-443	1.9080	2.82E-02
12	604-632	8.5577	5.76E-18

From Table 4-1, the reliability bound for the failure paths can be determined by using Simple Bound for parallel system formula as in Equation (11). The lower bound and upper bound of the three failure paths is shown in Table 4-4.

Table 4-4 Probability of Failure and Reliability Index of the Failure Paths

Path	Lower Bound		Upper Bound	
	P_f	β	P_f	β
1st Path	2.93E-62	16.6105	1.36E-20	9.2298
2nd Path	5.95E-263	34.6217	8.60E-42	13.493
3rd Path	3.05E-285	36.0726	2.7922E-79	18.816

The system reliability index and probability of failure can be then calculated from Table 4-4. Simple Bound for Series System, Equation (10), is used to determine those parameters, which are based on the upper and lower bound of those failure paths.

Table 4-5 and Table 4-6 shows system reliability and probability of failure based on lower bound and upper bound respectively.

Table 4-5 System Reliability and Failure Probability Based on Lower Bound

Lower Bound		Upper Bound	
P_f	β	P_f	β
2.93E-62	16.6105	0	inf

Table 4-6 System Reliability and Failure Probability Based on Upper Bound

Lower Bound		Upper Bound	
P_f	β	P_f	β
1.36E-20	9.2298	0	inf

4.4 Discussion

As can be seen from Table 4-4, the third path has the highest reliability index, $\beta = 18.82$, and thus lowest probability of failure. This may be due to that the load of the path is applied from the side of the structure, which contains more robustness.

The system probability of failure, P_{fS} can be then shown as:

$$2.93\text{E} - 62 \leq P_{fS} \leq 1.36\text{E} - 20$$

With corresponding system reliability index, β_S:

$$9.2298 \leq \beta_S \leq 16.6105$$

$\beta = 9.23$ is less than the reliability index determined on a platform in Sotong Field by Chin, 2005. She found that the β for the platform is 10.91. Nonetheless, it should be noted that in this study safety factor is employed in the limit state equation, while it was not accounted for in Chin’s project. The location of the platform also plays a major role, since the metocean criteria for each platform varies from location to location. However, from this study, it can be concluded that the platform is robust and its probability of failure is very small.

It is also interesting to note that the method to determine the system reliability was a simplified method. In order to quantify the index accurately, a more accurate method such as Branch and Bound method can be employed. Besides, the analysis is based on the design of the new platform. As for the platform which is in service, the deterioration of the platform has to be taken into consideration, such as corrosion, and marine growth. In order to include these deteriorations in the reliability analysis, the platform has to be remodeled to reflect the deteriorated condition of the platform. The analysis also does not take into account the failure of the foundation, which also plays a major part in the integrity of the platform.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

The study aims to determine the system reliability index and corresponding failure probability of an existing fixed offshore platform based in SKO Region. This can be completed by searching for possible failure paths, and from that reliability index and probability of failure can be calculated.

The literature of the system reliability of the platform has been studied, and the methodology to determine the failure path and reliability index is developed. "Pushover Analysis" is used to determine the most probable failure paths. Hundreds of simulations were also carried to generate enough data for the analysis. FORM is used to determine the reliability index and probability of failure of each component. Simple Bound formulae for both parallel and series system are used to determine the reliability index and probability of failure of the failure path and the system respectively.

In this study, three failure paths of the platform based on storm direction (0 degree, 270 degrees and 315 degree) are established. The reliability index of those paths are also found with the highest $\beta\ of$ 18.82 from 315 degree storm. The system reliability index is found out to be $\beta = 9.23$ with the system probability of failure $P_f = 1.36\text{E} - 20$. This illustrates that the platform is robust and the chances of collapse is very small.

5.2 Future Work and Expansion

The methodology adopted in this study is a simplified method, and the result may not be very accurate. Nonetheless, it can also point out the robustness of the platform generally. Many aspects for further studies can be then suggested as:

- Consider the loading from other five directions since in this study only three storm directions are considered.
- More detailed metocean data should be studied and obtained.

- The deterioration of the platform such as corrosion and marine growth should be taken into account. In this study, the analysis is based on the designed condition.
- The failure condition of the foundation of the platform should also be taken into account.
- A narrower bound formulae such as Ditlesven Bound should be used to determine the probability of both parallel and series system.
- A more detailed method to search for failure paths such as Branch and Bound method should be used. In this way, many more failure paths can be found out instead of only one path.

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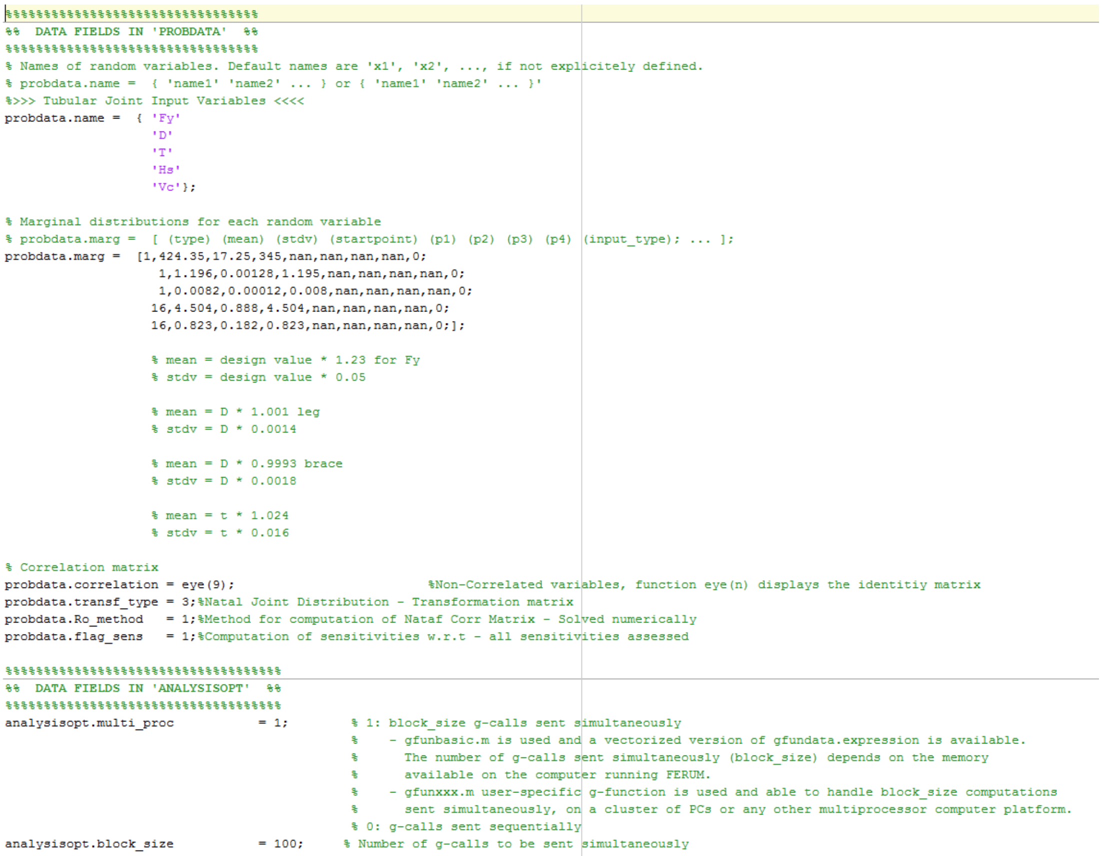
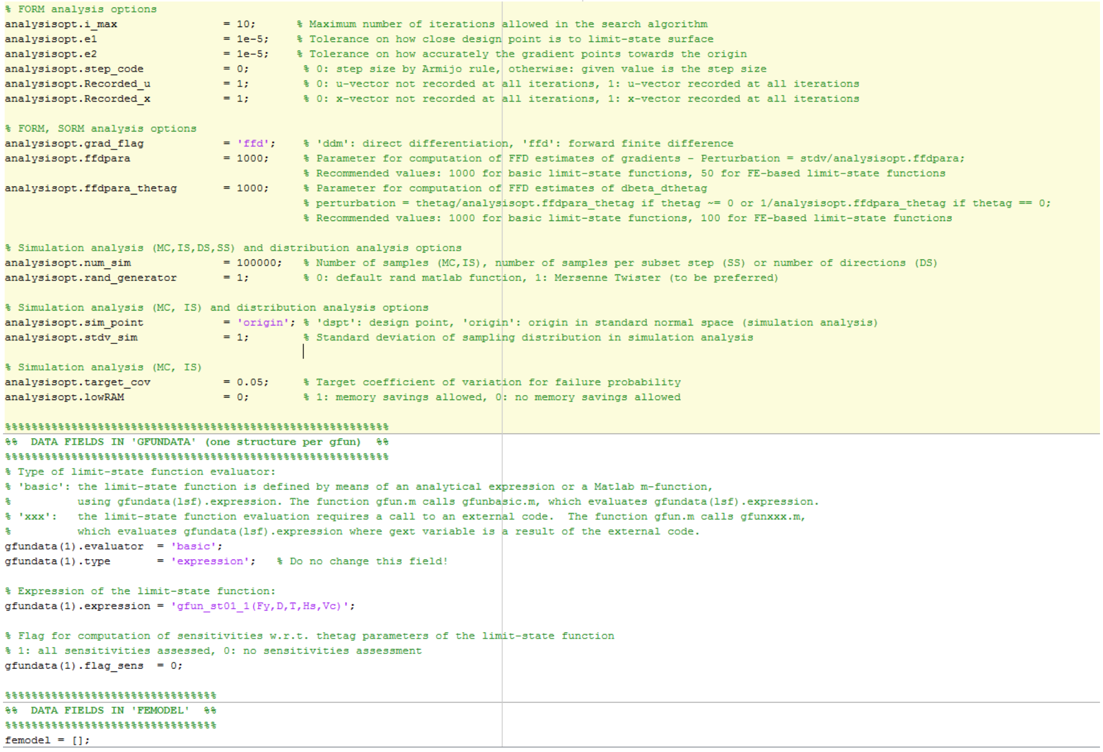
APPENDICES

FORM Input File

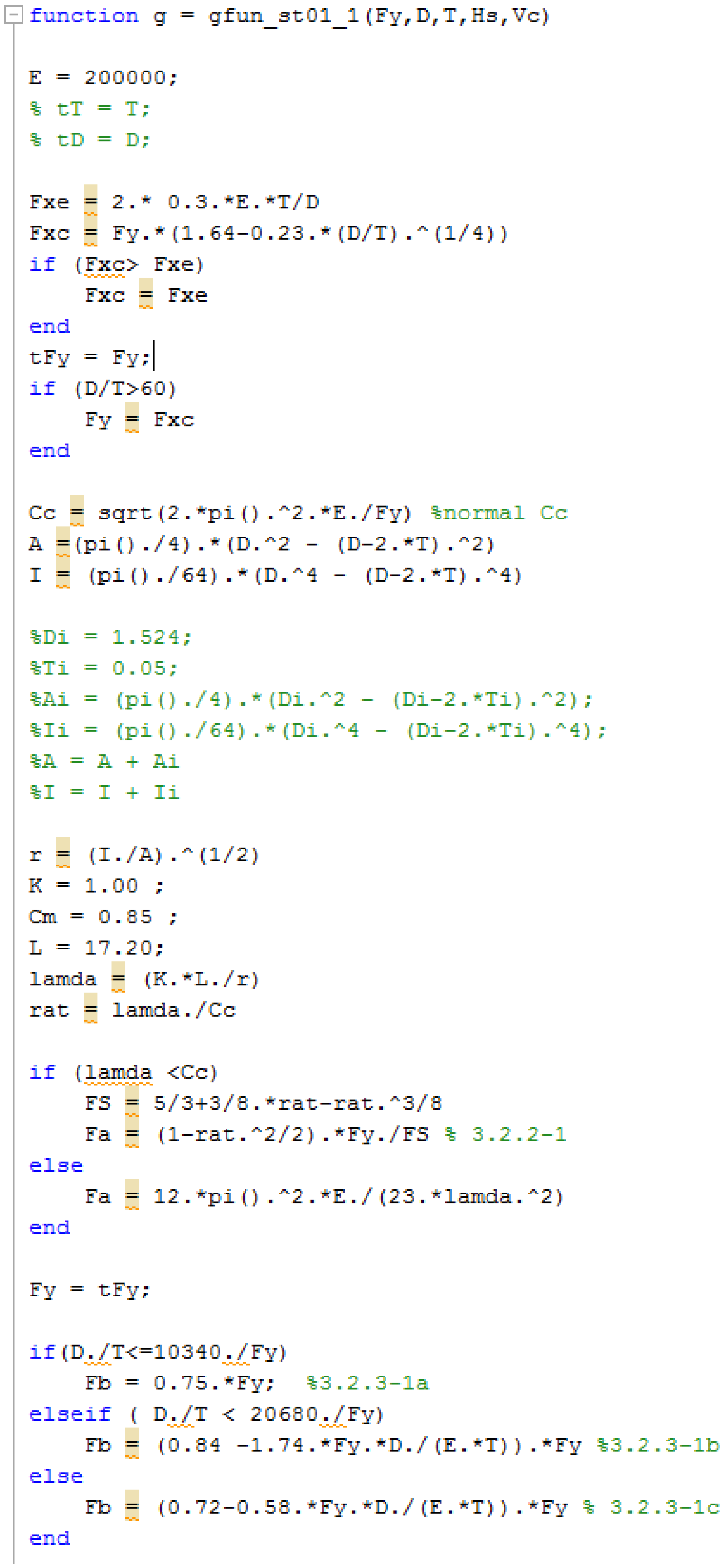


```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%  DATA FIELDS IN 'PROBDATA'  %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Names of random variables. Default names are 'x1', 'x2', ..., if not explicitely defined.
% probdata.name =  { 'name1' 'name2' ... } or { 'name1' 'name2' ... }'
%>>> Tubular Joint Input Variables <<<<
probdata.name =  { 'Fy'
                   'D'
                   'T'
                   'Hs'
                   'Vc'};

% Marginal distributions for each random variable
% probdata.marg =  [ (type) (mean) (stdv) (startpoint) (p1) (p2) (p3) (p4) (input_type); ... ];
probdata.marg =  [1,424.35,17.25,345,nan,nan,nan,nan,0;
                    1,1.196,0.00128,1.195,nan,nan,nan,nan,0;
                    1,0.0082,0.00012,0.008,nan,nan,nan,nan,0;
                   16,4.504,0.888,4.504,nan,nan,nan,nan,0;
                   16,0.823,0.182,0.823,nan,nan,nan,nan,0;];

                   % mean = design value * 1.23 for Fy
                   % stdv = design value * 0.05

                   % mean = D * 1.001 leg
                   % stdv = D * 0.0014

                   % mean = D * 0.9993 brace
                   % stdv = D * 0.0018

                   % mean = t * 1.024
                   % stdv = t * 0.016

% Correlation matrix
probdata.correlation = eye(9);                          %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
```

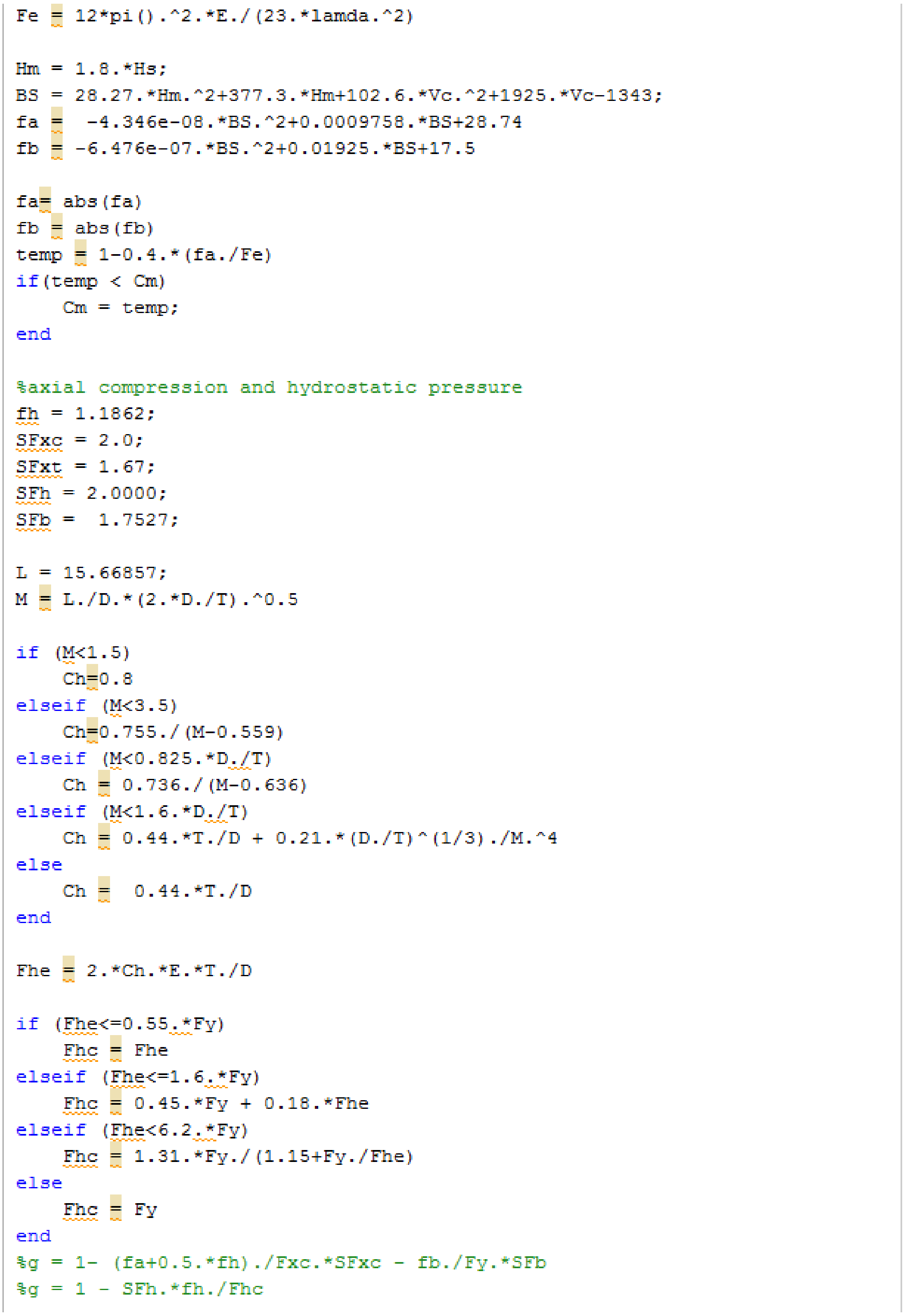


```
% FORM analysis options
analysisopt.i_max                = 10;      % Maximum number of iterations allowed in the search algorithm
analysisopt.e1                   = 1e-5;    % Tolerance on how close design point is to limit-state surface
analysisopt.e2                   = 1e-5;    % Tolerance on 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              = 100000;   % 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_st01_1(Fy,D,T,Hs,Vc)';

% 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 = [];
```

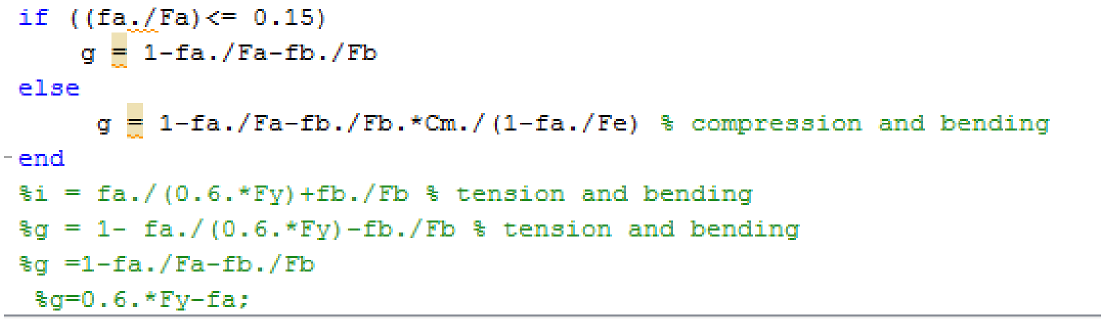
g-Function File



```
function g = gfun_st01_1(Fy,D,T,Hs,Vc)

E = 200000;
% tT = T;
% tD = D;

Fxe = 2.* 0.3.*E.*T/D
Fxc = Fy.*(1.64-0.23.*(D/T).^(1/4))
if (Fxc> Fxe)
    Fxc = Fxe
end
tFy = Fy;
if (D/T>60)
    Fy = Fxc
end

Cc = sqrt(2.*pi().^2.*E./Fy) %normal Cc
A =(pi()./4).*(D.^2 - (D-2.*T).^2)
I = (pi()./64).*(D.^4 - (D-2.*T).^4)

%Di = 1.524;
%Ti = 0.05;
%Ai = (pi()./4).*(Di.^2 - (Di-2.*Ti).^2);
%Ii = (pi()./64).*(Di.^4 - (Di-2.*Ti).^4);
%A = A + Ai
%I = I + Ii

r = (I./A).^(1/2)
K = 1.00 ;
Cm = 0.85 ;
L = 17.20;
lamda = (K.*L./r)
rat = lamda./Cc

if (lamda <Cc)
    FS = 5/3+3/8.*rat-rat.^3/8
    Fa = (1-rat.^2/2).*Fy./FS % 3.2.2-1
else
    Fa = 12.*pi().^2.*E./(23.*lamda.^2)
end

Fy = tFy;

if(D./T<=10340./Fy)
    Fb = 0.75.*Fy;  %3.2.3-1a
elseif ( D./T < 20680./Fy)
    Fb = (0.84 -1.74.*Fy.*D./(E.*T)).*Fy %3.2.3-1b
else
    Fb = (0.72-0.58.*Fy.*D./(E.*T)).*Fy % 3.2.3-1c
end
```



```
Fe = 12*pi().^2.*E./(23.*lamda.^2)

Hm = 1.8.*Hs;
BS = 28.27.*Hm.^2+377.3.*Hm+102.6.*Vc.^2+1925.*Vc-1343;
fa =  -4.346e-08.*BS.^2+0.0009758.*BS+28.74
fb = -6.476e-07.*BS.^2+0.01925.*BS+17.5

fa= abs(fa)
fb = abs(fb)
temp = 1-0.4.*(fa./Fe)
if(temp < Cm)
    Cm = temp;
end

%axial compression and hydrostatic pressure
fh = 1.1862;
SFxc = 2.0;
SFxt = 1.67;
SFh = 2.0000;
SFb =  1.7527;

L = 15.66857;
M = L./D.*(2.*D./T).^0.5

if (M<1.5)
    Ch=0.8
elseif (M<3.5)
    Ch=0.755./(M-0.559)
elseif (M<0.825.*D./T)
    Ch = 0.736./(M-0.636)
elseif (M<1.6.*D./T)
    Ch = 0.44.*T./D + 0.21.*(D./T)^(1/3)./M.^4
else
    Ch =  0.44.*T./D
end

Fhe = 2.*Ch.*E.*T./D

if (Fhe<=0.55.*Fy)
    Fhc = Fhe
elseif (Fhe<=1.6.*Fy)
    Fhc = 0.45.*Fy + 0.18.*Fhe
elseif (Fhe<6.2.*Fy)
    Fhc = 1.31.*Fy./(1.15+Fy./Fhe)
else
    Fhc = Fy
end
%g = 1- (fa+0.5.*fh)./Fxc.*SFxc - fb./Fy.*SFb
%g = 1 - SFh.*fh./Fhc
```



```
if ((fa./Fa)<= 0.15)
    g = 1-fa./Fa-fb./Fb
else
     g = 1-fa./Fa-fb./Fb.*Cm./(1-fa./Fe) % compression and bending
end
%i = fa./(0.6.*Fy)+fb./Fb % tension and bending
%g = 1- fa./(0.6.*Fy)-fb./Fb % tension and bending
%g =1-fa./Fa-fb./Fb
 %g=0.6.*Fy-fa;
```