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System Reliability of Existing Jacket Platform in Malaysian Water (Failure Path and System Reliability Index)

V. J. Kurian[1,a], M. M. A. Wahab[2,b], T. S. Kheang[3,c], M. S. Liew[4,d]

[1,2,3,4]Civil Engineering Department, UniversitiTeknologi PETRONAS, Tronoh, Malaysia

[a]kurian_john@petronas.com.my, [b]mubarakwahab@petronas.com.my, [c]kheang@outlook.com, [d]shahir_liew@petronas.com.my

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Abstract. The objective of this work is to determine the structural reliability of an existing jacket platform in Malaysia, by determining the system probability of failure and its corresponding reliability index. These two parameters are important indicators for assessing the integrity and reliability of the platform, and will point out whether the platform is suitable for continued operation. In this study, pushover analysis is used to determine possible failure paths of the structure, while First Order Reliability Method (FORM) and Simple Bound Formula are used to determine the failure probability and reliability index. Three failure paths of the platform are established. The reliability index of these paths is found with the highest Reliability Indexto be 18.82 from the 315-degree path, while the system reliability index is 9.23. This illustrates that the platform is robust and the chances of collapse is very small.

Introduction

In Malaysia, there are approximately over 200 oil and gas platforms to support the industry[1]. Majority of them are fixed offshore platforms which are located in the shallow waters. The design life for fixed offshore platforms, according to PETRONAS Technical Standards is 30 years. Nonetheless, some of the platforms have exceeded the design life and are still in operation. Thus, there has been lot of effort recently to assess the safety and integrity of those structures.

Among the popular methods to determine the excess strength of a platform is Reserved Strength Ratio (RSR) method. It is the ratio of platform ultimate strength over the platform design strength, which illustrates the excess load that a platform can take. However, it does not decisively show how reliable the platform is and its corresponding probability of failure.

Reliability analysis can be done either on 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. The system reliability analysis is employed to determine dominant failure paths, the failure 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.

This study aims to determine the system reliability index and its corresponding probability of failure of an existing jacket platform in Sarawak Operation region with a water depth of 94.6m. Aging parameters of the platform was assumed insignificant for the purpose of this initial study.

Methodology

System Reliability analysis is a relatively new area with extensive ongoing researches in the field. For statistically determinate structures, in some instances the reliability of individual members is sufficient since the failure of one member will lead to the whole structure failure. However, this is not the case for 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 paths. A failure path is defined as the failure sequence of members in the structure until it totally collapses. Based on the random nature of load and resistance distributions, some failure paths are more likely to occur than other. The probability of those failure paths and the method of determinations are the basis of system reliability analysis.

A structure especially for complex one can contain a large number of possible failure paths. Including all the possible failure paths in the analysis is infeasible and inefficient, since many of the failure paths have a very low probability of occurrence. A variety of methods to determine dominant failure modes are discussed in[2].The methods are divided into three approaches: "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 analysis) 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 branch-and-bound method, on the other hand, employs probabilistic search algorithm, which searches possible failures mode by considering their probabilities of occurrences. Though the branch and bound method is theoretically rigorous, the required computing power can be very high.

In this study, pushover analysis is used to determine most probable failure paths. The environmental load was applied from three critical directions namely 270^o, 315^o and 360^o relative to platform North.

Limit State Function and Probability of Failure. In this study, the limit state functionas in Eq. 1 is derived from utilization ratio for cylindrical members subjected to combined compression and bending.The adopted utilization ratio formula is according to API-RP2A WSD[3].

$$g(\cdot) = 1.0 - \left(\frac{f_a}{F_a} + \frac{f_b}{F_b} \right). \qquad \text{(Equation 1.)}$$

Where:

- f_a and f_b are axial stress and bending stress respectively, obtained from structural analysis.
- $F_a$and F_b are the resistance parameters determined from API RP 2A-WSD code equations.

The limit state function divides the surface into two different regions which are safe region, where $g(\cdot)\geq 0$ and unsafe region, where $g(\cdot)<0$. The probability of failure, P_f, can be determined from Eq. 2 with X as random variables.

$$P_f = P[g(X) < 0]. \qquad \text{(Equation 2.)}$$

When X is normally distributed and uncorrelated, the reliability index is determined from Eq. 3.

$$\beta = -\phi^{-1}(P_f). \qquad \text{(Equation 3.)}$$

Similarly, P_f can be calculated from Eq. 4.

$$P_f = 1 - \phi(\beta) = \phi(-\beta) \qquad \text{(Equation 4.)}$$

Where $\phi(\cdot)$ is the standard normal distribution.

In general, the probability of failure P_f,is given by the integral as in Eq. 5.

$$P_f = \int \dots \int_{g(\cdot)<0} f_x(x_1, x_2, \dots, x_n)\, dx_1 dx_2 \dots dx_n \qquad \text{(Equation 5.)}$$

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

Since the direct integration of Eq. 6 is extremely complicated, methods 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.

Load and Resistance Parameter

Wave: Two-parameter Weibull distribution is used to fit the significant wave height data,*Hs* for the platform. From that, shape and scale parameter for the distribution is obtained and used to generate random loads.

Current: Similarly, Weibull parameters for current speed at water surface are derived.The current velocity is independently generated from the wave height as wave height and current velocity is not always correlated due tothe random nature of the sea.

Wind: Wind is determined as static point load and applied on the topsides. Wind is assumed to be deterministic and not a random parameter for this study purpose.

Resistance Variables: The resistance parameters used in this study is based on the study in[4].The axial resistance,F_a,and bending resistance, F_b, of the tubular components are given in API RP 2A-WSD code.The random parameters (diameter, wall thickness and yield strength) are used to determine both $F_a$and $F_b$which will be the inputs of the limit state functions.

Analysis Method

Structural Idealization:A structural system usually can be modelled as a series system, parallel system or combination of both[5].A series system is a system in which failure in a structural element will lead the whole system collapse. For parallel system failure in a member does not usually lead to total system collapse. For complex structures it is assumed that the structural system is a series of parallel systems, in which each parallel system represent a failure path.In this study, the structure is regarded as a hybrid system in which each failure path is a parallel system.

Reliability Bound. In order to determine the probability of failure of the system, approximate techniques or bounding techniques were used. Simple Bounds is described below.

Simple Bound. 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 elementE_i,$i=1,\ldots,n$,a Boolean variable $e_i$is defined by:

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

For series system, the simple bound is given by:

$$\max_{i=1,\ldots,n} P\left(e_i=0\right) \le P_{fs} \le 1-\prod_{i=1,\ldots,n}\left(1-P\left(e_i=0\right)\right). \qquad \text{(Equation 6.)}$$

The lower bound in Eq. 6 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:

$$\prod_{i=i,\ldots,n} P\left(e_i=0\right) \le P_{fp} \le \min_{i=1,\ldots,n} P\left(e_i=0\right). \qquad \text{(Equation 7.)}$$

The lower bound in Eq. 7 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.

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 perfectly brittle element or perfectly ductile element. For brittle element, it will become ineffective after failure. However, if the element is ductile, it still effective and is able to carry some load.

In this study, a semi-brittle model is used as shown in Fig. 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 φ = 0.4 was used for members failing in compression and φ= 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.

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."

Global Response Surface: 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. The wind speed is not taken as one of the variable as its contribution to the load is insignificant. The G function is taken as the global response as in Eq. 8.

$$BS = aH_{max}^2 + bH_{max} + cV_c^2 + dV_c + e\ . \qquad \text{(Equation 8.)}$$

In order to determine the response of the structure, 20 sets of environmental loads (H_s and V_c) were generated based on Weibull distribution.Structural analysis is then carried out. From the analysis, 20 sets of base shears are obtained. The coefficients *a,b,c,d and e* in Eq. 8are determined using Matlab Curve Fitting Tool.

Local Response Surface: The local response surface, which are $f_a$andf_b, relate the global response of the structure to the local response of each member. Second-degree polynomial equation is used as in Eq. 9 and 10 respectively.

$$f_a = aBS^2 + bBS + c\ . \qquad \text{(Equation 9.)}$$

$$f_b = aBS^2 + bBS + c\ . \qquad \text{(Equation 10.)}$$

The local response surface was used in the Limit State Function to determine the probability of failure of the component.

Failure Tree Generation and Reliability: From non-linear collapse analysis, the structure and members are incrementally loaded beyond its yielding capacity. At the point where a member will be no longer able to sustain the load, it will buckle or fracture. The first member that fails in that way is recorded. In order to choose the second failure element, the first member needs to be removed and replaced with fictitious loads. If the first member failed in compression, a pair of load with the magnitude of $0.4\text{x}R_C$ will be applied at the joints. If it failed in tension, the load of $1.0\text{x}R_T$ will be used instead. Pushover analysis will be then carried out again with this new modified structure, and the first member that fails for this new matrix is the second failure element in the path. The same process is repeated until there are no longer members fail in either buckling or fracture, and the structure fails by collapsing or by having large deflection. In this way, for each direction a path is generated.

In the pushover analysis, before removing that failed element, the member reliability must be obtained. 20 random environmental loadsare generated to determine the global response of the platform. From that, local response is obtained. After that, it is used as the input in the limit state function along with resistance variables. First Order Reliability Method (FORM) from FERUM 4.1 Program is used to determine the P_f, and reliability index from the limit state function.

After carrying out the analysis, failure tree is produced based on the sequence of the failures 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 three paths will be determined using the Simple Bound formula for parallel system. The system reliability of the structure is then determined from those three probability of failures using Simple Bound formula for seriessystems.

Results

Failure Tree. Fig. 2 shows the failure tree of the platform. Each branch represents a possible failure path, and each node is the failed member in the corresponding damaged structure. The number in the node is the failure element, identified by two joint numbers.

Probability of Failure and Reliability Index: The probability of failure for the first path, second path and third path are shown in Table 1, Table 2and Table 3 respectively.

The reliability bound for the failure paths determined using Simple Bound for parallel system formula. The lower and upper bound of the three failure paths is shown in Table 4.

Table andTable 6 show system reliability and probability of failure based on lower bound and upper bound respectively.Simple Bound for Series System is used to determine those parameters, which are based on the upper and lower bound of those failure paths.

The third path has the highest reliability index, β=18.82, and thus lowest probability of failure. This may be due to that the load of the path is applied at the corner of the structure, which contains more members. The system reliability index based on the upper bound is found out to be $\beta = 9.23$ with corresponding probability of failure of $P_f = 1.36\mathrm{E}-20$

β=9.23 is less than the reliability index determined on a platform in Sotong Field as in [6]. The author 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 in [6].

Conclusion

In this study, three failure paths of the platform are established. The reliability index of those paths are also found with the highest β of 18.82 from 315-degree path, while the system reliability index is β=9.23. This illustrates that the platform is robust and the chances of collapse is very small.

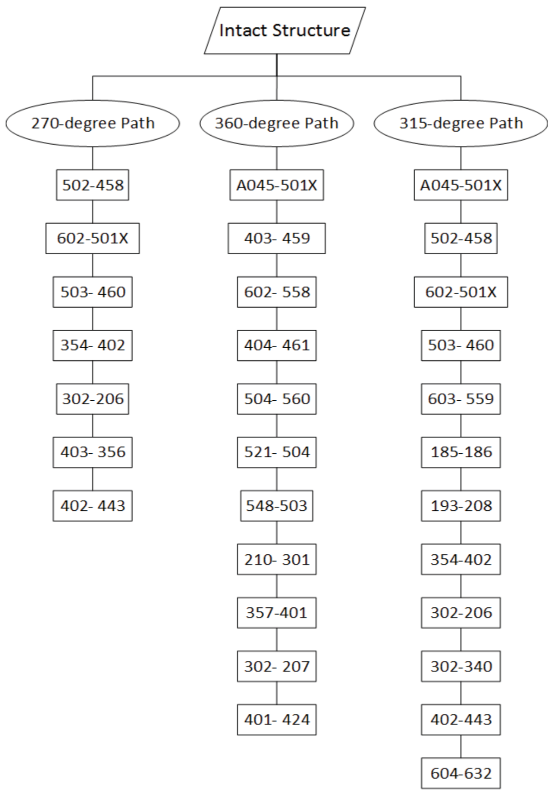

Figure 2. Failure Tree

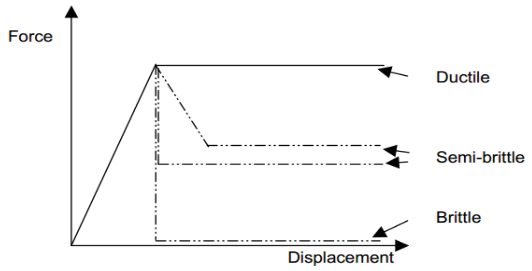

Figure 1. Element Failure Model

Table 1. First Failure Path

Sequence	Member	β	P_f
1	502-458	3.54	1.99E-04
2	602-501X	6.62	1.80E-11
3	503-460	6.70	1.03E-11
4	354-402	4.73	1.13E-06
5	302-206	4.18	1.47E-05
6	403-356	4.50	3.50E-06
7	402-443	9.23	1.36E-20

Table 2. Second Failure Path

Sequence	Member	β	P_f
1	A045-501X	6.29	1.62E-10
2	403- 459	11.98	2.29E-33
3	602- 558	13.50	8.60E-42
4	404- 461	12.21	1.39E-34
5	504- 560	11.90	6.51E-33
6	521- 504	10.06	4.03E-24
7	548-503	8.87	3.68E-19
8	210- 301	8.76	1.01E-18
9	357-401	12.66	5.18E-37
10	302- 207	6.07	6.54E-10
11	401- 424	5.36	4.07E-08

Table 3. Third Failure Path

Sequence	Member	β	P_f
1	A045-501X	7.00	1.26E-1
2	502-458	6.00	9.65E-10
3	602-501X	7.21	2.73E-13
4	503-460	10.02	6.23E-24
5	603-559	9.42	2.27E-21
6	185-186	13.02	4.83E-39
7	193-208	3.43	2.97E-04
8	354-402	18.82	2.79E-79
9	302-206	17.24	7.25E-67
10	302-340	2.20	1.38E-02
11	402-443	1.91	2.82E-02
12	604-632	8.56	5.76E-18

Table 4. Failure Probability and Reliability Index of Each Path

Path	Lower Bound		Upper Bound	
	P_f	β	P_f	β
1st Path	2.93E-62	16.6105	1.36E-20	9.23
2nd Path	5.95E-263	34.6217	8.60E-42	13.50
3rd Path	3.05E-285	36.0726	2.79E-79	18.82

Table 5. System Probability of Failure and Reliability Index Based on Lower Bound

Lower Bound		Upper Bound	
P_f	β	P_f	β
2.93E-62	16.61	0	inf

Table 6. System Probability of Failure and Reliability Index Based on Upper Bound

Lower Bound		Upper Bound	
P_f	β	P_f	β
1.36E-20	9.23	0	inf

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