Met-ocean Study for Reliability of Jacket Platform

Regression Analysis

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***Abstract*—Over 60% of PETRONAS Carigali Sdn. Bhd. (PCSB) operated fixed jacket platform installed in Malaysia water regions had already been put into service for more than 20 years, where their design life is only 20 – 25 years. In order to extend the service life of these aged platforms, their current structural integrity conditions need to be assessed. Reliability analysis is emerging as one of the popular methods to review the strength of a structure. In this study, the reliability indexes of an offshore structure at different environmental loadings are compared. Besides traditional combination of 100 year wave and 100 year current, combination of current of 10 year associated with 100 year wave are analyzed. Monte Carlo Simulation and First Order Reliability Method (FORM) are used to generate reliability index and the probability of failure of the platform. In addition, three different formulations of environmental load response function are discussed. Regression analysis is performed in MATLAB to obtain the response function.**

Keywords—Reliability index; Monte Carlo; First Order Reliability Method (FORM); Regression

I. INTRODUCTION

Oil and Gas (O&G) industry is one of the most important economic sectors in Malaysia. It has expanded rapidly since the ‘90s, after the first discovery of oil in 1909 and the first oil production in 1910. As the biggest player and also the custodian in this industry, PETRONAS Carigali Sdn. Bhd. (PCSB) is vested with the entire oil and gas resources in Malaysia and is entrusted with the responsibility of developing and adding value to these resources under the Petroleum Development Act (1975).

Among many offshore production platforms, fixed jacket platform is most widely installed for oil and gas production in shallow and intermediate water depths. Table I records the total number of jacket platforms in three Malaysia water regions that are operated by PCSB. The three Malaysia water regions include Peninsular Malaysia Operations (PMO), Sarawak Operations (SKO) and Sabah Operations (SMO). Typical offshore platform is designed for a service life of 20 – 25 years. However, due to the discoveries of new oil/gas and/or the enhanced oil recovery technology, many of PCSB’s operating platforms have been put in service beyond their initial design life. As a result, these platforms might be subjected to higher loading due to upgrading and work-over demands, which the platforms were not initially designed for. Besides, there might be some changes in the environmental loadings over the years, unexpected gas blowout, seismic activities, etc., which will increase the loads acting on the platforms.

TABLE I. PCSB PLATFORM PROFILE – AGE DISTRIBUTION

Water Region	**Age Distribution, x (Years)**				
	x<10	***10<x<20***	***20<x<25***	***25<x<30***	***x>30***
PMO	13	5	13	4	
SBO	1	3	7	10	6
SKO	1	33	17	19	33

In order to extend the service life of the aged platforms, it is necessary to conduct requalification process on them. Reliability methods are becoming increasingly popular tool for reassessment of structures in the offshore industry where the ultimate goal is to ensure the level of safety is above the minimum requirements of the relevant design code. Structural reliability is the ability of a structure to serve its purpose under operational and extreme met-ocean conditions throughout the structure’s design life. It can be expressed as probability of failure, P_f and reliability or safety index, β. A structure is reliable when its probability of failure is low or its reliability index is high.

There are several popular reliability methods, include approximate analytical methods such as first and second order reliability methods (FORM, SORM), as well as simulation methods such as the Monte Carlo simulation (MCS). The choice of method depends on the computational ability, data availability and the level of accuracy desired. MCS involves sampling at random that generates a large set of artificial data for several types of uncertain variables. A random vector is then formed from many generated random variables and is used to check the limit state equation. If the limit state function is less than zero, the structure is considered to have failed. This process is repeated many times and the probability of failure is simply the number of failed samples divided by the total number of simulations. When the probability of failure is small (i.e., 10*E-5* or 10*E-10*), this method becomes inaccurate and requires long computing time. [1]

The principle of approximate analytical method characterizes random variables by their mean (first moment), variance (second moment) and skewness and flatness of the distribution (higher moments). FORM was developed as an enhancement of the FOSM method, which the probability distributions are approximated only about the mean and variance (first and second moments, respectively). FORM approximation only gives sufficient results when the limit state surface has one minimal distance point and the function is nearly linear close to the design point. For cases where the failure surface has large or irregular curvatures (high nonlinearity), the failure probability estimated by FORM, using the safety-index, may give unreliable and inaccurate results. Due to this, SORM had been developed using the second order approximation to simplify the original surfaces.

Due to the complication and time consumption of performing a full system reliability assessment, many studies had been carried out and several simplified system reliability methods were developed. Bea, [2] [3] [4] [5] Cornell, [6] and AME [7] provide easier approaches for evaluating the reliability of a structure.

Reliability of a jacket platform is governed by the structural system and this system is the combination of series and parallel subsystems. System effects in fixed offshore platforms can be explained as the difference between the system reliability index and the failure of any one member. There are two categories of system effect: deterministic and probabilistic. Deterministic effects are related to the redundancy of a system while probabilistic effects refer to the randomness of the member capacities. Studies have shown that the most critical system effect is contributed by the deterministic aspect. However, both effects are important for to carry out reliability analysis. In order to do so, load effect is required to be represented in probabilistic manner. The formulation of the response function has been recommended by Moses [8] as

$$W = AH^{\alpha}$$

where H as wave height, α is the wave force exponent which reflects the platform type and A as a random variable reflecting the uncertainty of the wave force for a given wave height. Heideman [9] improves the function by introducing current in the equation, written as

$$W = C_1 \cdot (H + C_2 \cdot u)^{C_3}$$

where C_1, C_2, C_3 are the uncertainties coefficient , H is the wave height and u is the current value. Cossa [10] adopted a structural response model based on Moses and incorporate current component in a quadratic format. The concept is in accordance to a study by Tarp-Johansen [11] and similar to Bomel Limited [12] in the calibration study for adoption of ISO in the North Sea. The response surface expression without wind effect is as follows:

$$W = aH_{max}^2 + bH_{max} + cV_c^2 + dV_c + e$$

Often, sensitivity analysis is carried out along with reliability analysis to study the effect of design parameters. One of the most influencing parameters is the environmental loads. The effect of environmental loads acting on an offshore structure deteriorates the structure's strength throughout its entire lifetime. Wave load is the major environmental load faced by the jacket platforms while current load at a particular site can contribute significantly to the total forces exerted on the submerged parts of an offshore structure. Wind force is usually not being taken into consideration, as they are typically minor contributor to the global loads in shallow and intermediate waters.

ISO recommends three methods for defining global environment action [13]:

a) 100-year return period wave height (significant or individual) with associated wave period, wind and current velocities;
b) 100-year return period wave height and period combined with the 100-year return period wind apeed and the 100-year return period current velocity, all determined by extrapolation of the individual parameters considered independently;
c) any reasonable combination of wave height and period, wind speed and current velocity that results in the global extreme environmental action or a relevant action effect (global response) of the structure with a return period of 100-year.

In the past, traditional approach of obtaining the global environmental loads is by combining the 100-year wave and the 100-year current (extreme met-ocean condition). As a result, the predicted loading is over-conservative by up to a factor of 2.0. It was proven that extreme waves and currents do not necessarily occur simultaneously at the same time. A joint density analysis on met-ocean loads had been carried out in Malaysian waters and was concluded that the design mean return interval (MRI) for a 100-year wave associated with MRI of 10-year current. [14]

II. METHODOLOGY

The main interest of this paper is to compare the reliability index (RI) of an offshore structure (Platform A) at different met-ocean combination loadings. Formulation of several load effect response functions will be discussed as well. Met-ocean data is obtained from the design reports which hold the design values of wave height, wave period, and current speed. Platform model file is also readily available in the form of SACS file, which collapse analysis is run to obtain base shear and Reserve Strength Ratio (RSR) as some of the inputs required in reliability analysis.

A. *Structure Data*

The details of the platform are as shown:

Platform:	A
Location:	Sarawak Operations (SKO)
Water depth:	94.80m
Type:	4-Legged Symmetrical Jacket Structure

Typically, 4, 6 and 8 legged structure will be analyzed in 8 directions because of their geometric properties. Hence, Platform A is studied in 8 directions. Figure 1 is the model of Platform A:

Fig. 1. *Platform A*

B. *Met-ocean Data*

In order to perform reliability analysis, met-ocean data is one of the crucial parameters. In this exercise, omni-directional met-ocean loading is considered. Only one highest value is taken into consideration for every (8) directions.

Table II and III records the Omni-directional wave and current values at Platform A:

TABLE II. WAVE AT DIFFERENT RETURN PERIOD

Parameter	**Return Period (Year)**			
	1	***10***	***50***	***100***
Hs (m)	4.9	5.6	6.1	6.3
Tp (s)	10.2 – 10.7	10.9 – 11.3	11.1 – 11.6	11.4 – 11.7
Hmax (m)	9.1	10.4	11.3	11.7
Tass (s)	9.4 – 10.0	10.4 – 10.5	10.3 – 10.7	10.6 – 10.9

TABLE III. CURRENT VELOCITY AT DIFFERENT RETURN PERIOD

Description		**Return Period (Year)**			
Layers in Water Column	***Height above Seabed***	***1***	***10***	***50***	***100***
Surface	1.0*D	85	105	115	120
Mid Depth	0.5*D	67	83	92	95
Near Seabed	0.01*D	39	50	54	55

The different met-ocean combinations that are being studied include:

1. Comb. 1: Omni-directional 100-year wave associate with 100-year current
2. Comb. 2: Omni-directional 100-year wave associate with 10-year current

III. RESULTS

A. *Collapse Results*

Reserve strength ratio (RSR) is a measure of platform strength by dividing platform collapse base shear by its initial base shear. RSR that are obtained from performing collapse analysis are recorded in Table IV:

TABLE IV. RELIABILITY INDEX AT DIFFERENT MET-OCEAN COMBINATIONS

Direction (deg)	**100-100 RSR**	**100-10 RSR**
0	3.119635	4.120414
45	3.758364	3.848468
90	3.530418	3.669362
135	4.619131	4.78081
180	3.670857	3.699657
225	4.192097	4.341898
270	3.019671	3.129643
315	4.6501	4.853894

B. *Reliability Index*

Table V records reliability index of the structure at different met-ocean combinations while Figure 2 is the graphical illustrations of the results.

TABLE V. RELIABILITY INDEX AT DIFFERENT MET-OCEAN COMBINATIONS

Direction (deg)	**100-100 FORM**	**100-100 MCS**	**100-10 FORM**	**100-10 MCS**
0	2.865	2.847	3.305	3.333
45	3.165	3.167	3.201	3.195
90	3.067	3.079	3.128	3.125
135	3.471	3.460	3.520	3.527
180	3.128	3.109	3.141	3.142
225	3.330	3.450	3.382	3.432
270	2.810	2.791	2.871	2.893
315	3.481	3.540	3.542	3.492

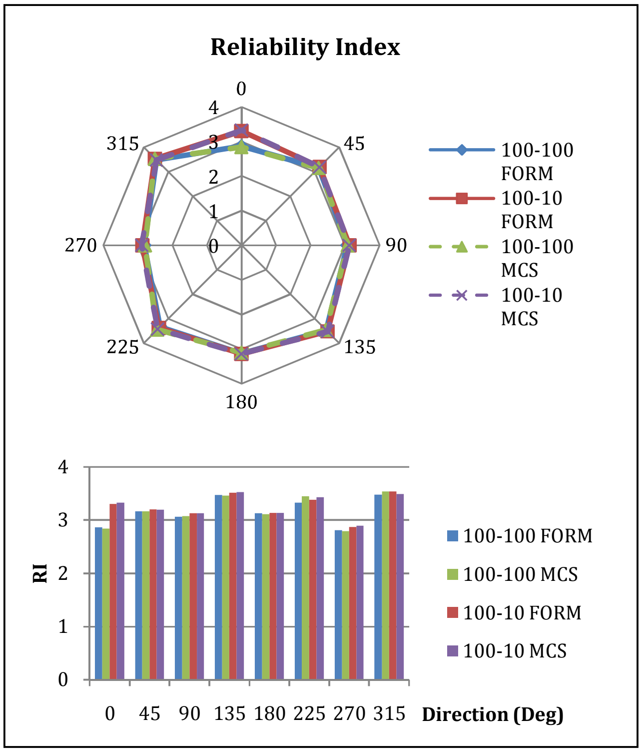

Fig. 2. *Reliability Index at Different Met-ocean Cobinations*

C. *Relationship between RSR and RI*

Figure 3 describes the relationship between reliability index and RSR at 100-100 year wave and current. Linear equations have been generated and R-squares of the equations are recorded.

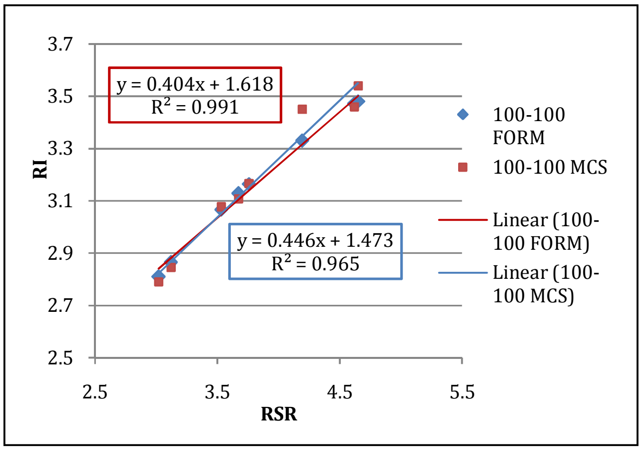

Fig. 3. *Relationship of Reliability Index and RSR at 100-100 year Wave and Current*

Figure 4 records the relationship between reliability index and RSR at 100-10 year wave and current.

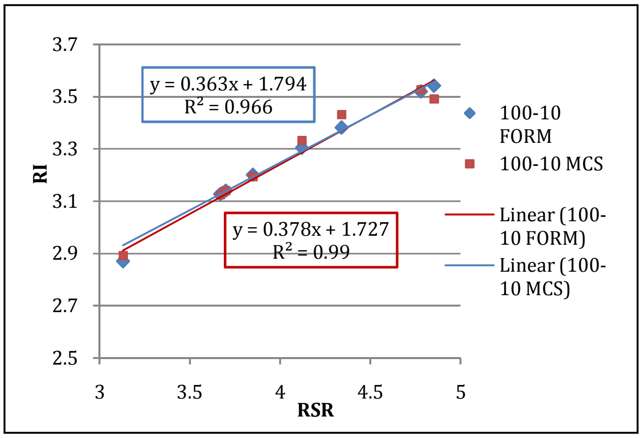

Fig. 4. *Relationship of Reliability Index and RSR at 100-10 year Wave and Current*

D. *Regression (Response Surface) Analysis*

Regression using curve and surface fitting tools in MATLAB have been carried out for different numbers of variables. Curve fit 1 and 2 has only one variable, which is the varying wave height whereas surface fit consider both wave height and current value. The results are recorded in Figure 3-5 and Table VI-VIII.

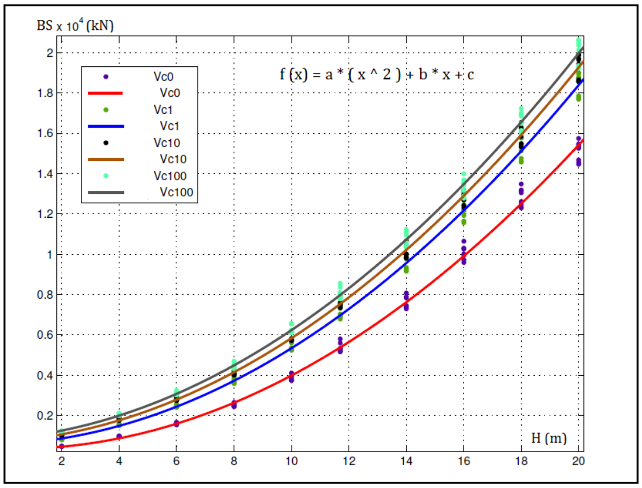

Fig. 5. *Curve Fitting 1: Polynomial Relationship between Base Shear and Wave Height*

TABLE VI. CURVE FIT 1 VALUES AND CORRESPONDING R-SQUARE RESULTS

Vc (m/s)	a	b	c	R-square
0	38.96	-25.9	353.2	0.9963
0.85	41.4	62.51	579.1	0.9976
1.05	41.4	62.51	579.1	0.9976
1.20	41.46	98.95	708.5	0.9976

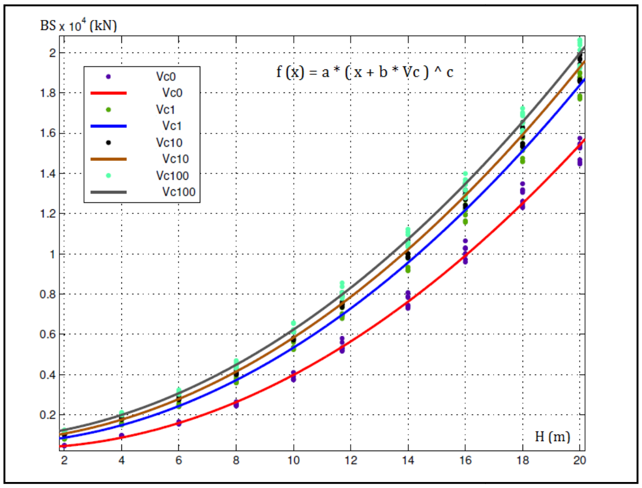

Fig. 6. *Curve Fitting 2: Relationship between Base Shear, Wave Height and Fixed Current Velocity*

TABLE VII. CURVE FIT 2 VALUES AND CORRESPONDING R-SQUARE RESULTS

Vc (m/s)	a	b	c	R-square
0	47.56	0.05428	1.928	0.9958
0.85	10.86	5.067	2.331	0.9976
1.05	10.45	4.78	2.336	0.9976
1.20	8.796	4.87	2.377	0.9975

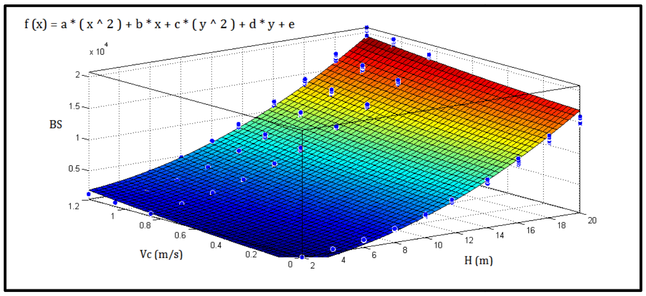

Fig. 7. *Surface Fitting: Relationship between Base Shear, Wave Height and Current Velocity*

TABLE VIII. FIT 2

a	b	c	d	e	R-square
40.88	64.52	765.6	1199	-932.9	0.991

IV. DISCUSSION

Structure under met-ocean combination of 100-100 year wave and current has lower reliability index than 100-10 year wave and current. The difference between the two can be as high as 15.32%. This indicates that applying traditional met-ocean combination of 100-100 year wave and current in designing an offshore structure can be overestimated. Reliability index generated by FORM is validated by Monte Carlo Simulation Method. The difference between the two models is low (0.82% in average). Hence, It can be concluded that FORM reliability model is accurate. Besides, Platform A has similar reliability index (2.8 - 3.5) for all direction as it is symmetrical in nature.

Overall, Platform A can be considered safe to operate as its reliability index is higher than the target reliability suggested by DNV, except for direction at 270°. Anyhow, omni-directional met-ocean condition is assumed in this study where the worst condition is used. In real life, multi-directional wave is observed at the real sea. It is possible that lower wave is hitting at 270° direction. Thus, the reliability index at that direction will be much higher. Table IX shows the target reliability given by DNV [13]:

TABLE IX. TARGET RELIABILITY

Reliability	P_f	β
System	10E-3	3.09

From the results of RI versus RSR, It is safe to conclude that RSR and Reliability Index has a linear relationship. Reliability Index found using FORM is able to capture the linearity between RI and RSR better than Monte Carlo Simulation as the R-square values for both 100-100 year, and 100-10 year wave and current conditions are higher. Monte Carlo Simulation depends very much on the generated random numbers generated. The linear equation generated by FORM has 99% of confidence level while MCS gives 95% of confidence level. It is possible to develop a regional expression to provide faster and easier method for determining the reliability of a structure. More platforms in the same region have to be studied in order to achieve that.

As for the regression analysis, three fits give considerably reliable formulations where the R-square values are as high as 0.99. Both curve fit 1 and curve fit 2 have only one variable, which is the wave height. Logically, their R-square values are and will be somewhat higher than surface fit equation, which consider both wave height and current velocity. When considering only one variable, equation from Curve Fit 1 can express the load effect slightly better than curve fit 2.

V. CONCLUSION

The following conclusions are made from the results discussed above:

1. Reliability index for structure experiencing 100-100 year wave and current effects is lower (~4%) than structure experiencing 100-10 year wave and current effects.
2. Linear relationship is observed between RSR and Reliability Index.
3. Surface fit that take into consideration more (2) variables is more flexible with promising R-square value and is advised to be used for probabilistic load effect generation.

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