Component Reliability Prediction Model for Malaysia Offshore Regions

Static and Regression Analysis

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***Abstract*—Majority of the fixed jacket platforms installed in Malaysia water regions had already exceeded their design life. In order to prolong the service life of these aged platforms, their current structural integrity conditions need to be reviewed. System reliability governs the reliability of a structure. However, a system is consisted of many components. Combination of individual (component) reliability in dominant failure path(s) explains the system reliability. As oppose to the system reliability assessment method, generation of component reliability is much simpler. This paper presents the methodology for computing a simplified component reliability model. Interpolation methods for obtaining the met-ocean design values at different return periods are discussed. Also, effects of different met-ocean combinations are studied.**

Keywords—component reliability; met-ocean; interpolation

I. Introduction

Oil and Gas (O&G) industry in Malaysia has expanded rapidly since the '90s. Fixed jacket platform is most widely installed for oil and gas production in shallow and intermediate water depths. PETRONAS Carigali Sdn. Bhd. (PCSB) is currently operating approximately 180 fixed jacket platforms in Malaysia offshore O&G operation regions, namely Peninsular Malaysia Operations (PMO), Sabah Operations (SBO), and Sarawak Operations (SKO). 60% of PCSB's operating platforms have already been put in service for more than 20 years whereas their initial design life is only 20-25 years. 20% of the platforms have already exceeded 30 years with several others in the very near future reaching their initial design life. Table I records the total number of jacket platforms in Malaysia water regions that are operated by PCSB.

These platforms have been extended beyond their original design life due to new oil/gas discoveries, and/or because of the introduction of enhanced oil recovery technology. Consequently, these platforms might be subjected to higher loading due to upgrading and work-over demands, which the platforms were not initially designed for. Apart from that, there might be changes in the environmental loadings over the years, unexpected gas blowout, seismic activities, etc., which the initial platform designs did not take into account for.

Summed from the above, a requalification process is indeed necessary to be implemented to extend the service life of the platforms. Over years, 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. The study of structural reliability involves calculation and prediction of the probability of limit state violations at any stage of a structure's life. The probability of such event to occur is calculated based on Probability Distribution Factor (PDF), while introducing random variables, processes, and fields to represent uncertainty.

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

II. Background

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. Windforce is not taken into consideration in this study, as it is typically minor contributor to the global loads in shallow and intermediate waters.

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 figured 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 50-year wave associated with MRI of 10-year current [2].

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 index, β. These values can be computed using any of the several available reliability methods, including 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.

Understanding system effects can be very useful in determining the reliability of a jacket platform. System effects in fixed offshore platforms can be explained as the difference between the system reliability index and the failure of any one member. It can be categorized into two groups: deterministic and probabilistic effects. Deterministic effects are related to the redundancy of a system, which allows load redistribution after first member failure, giving higher ultimate load capacity. On the other hand, probabilistic effects refer to the randomness of the member capacities. Studies have shown that the most critical system effect contributed by the deterministic aspect. It was concluded that component based approach with deterministic resistance representation (or COV = 10%) is a suitable representation for system reliability assessment [3].

III. Literature Review

Reliability assessment was first introduced in the offshore field in 1980s. Uncertainties such as fluctuations in loads, variations in material properties, and uncertainty in the structural models used can be well taken care of by reliability methods. Reliability of a jacket platform is governed by the structural system and this system is the combination of series and parallel subsystems. For instance, jacket legs illustrate series or chain reliability system. When a member fails, the entire system fail. On the other hand, structural bracings are an example for parallel (or chain) system. One bracing member fails does not cause immediate failure to the structure. Instead, the load carried by the failed member will be transferred to the other intact members in the group [4] [5].

Figure 1 shows some of the more commonly applied methods for system reliability assessments. The increase in available computational resources encourages the development of search algorithms method to determine the critical failure path and also to calculate the combined system probability of failure. Besides, pushover analysis is one of the methods that determine the most dominant failure path, and the reliability index of the failure path identified through a deterministic pushover analysis is very close to the value obtained after extensive searches or simulations [6] [7]. Simplified system reliability methods developed, by Bea, [8] [9] [10] [11] Cornell, [12] and AME [13] provide an easier approach for evaluating the reliability of a structure. As for component-based approach, the whole structure is treated as one component for assessment.

Component approach is considered to be the easy way to evaluate a structure's reliability. A structural system consists of many components. Hence system reliability can be computed as combinations of individual reliability. A time-variant formulation technique was developed for accurate estimation of corroded jacket structural system reliability in Niger Delta. It was done utilizing series and parallel reliability theory. The study determined the reliability of a jacket structure as the product of bracings and legs reliabilities and this value decreases with platform age [14]. The influence of tubular joints failure modes on jacket structures global failure modes was studied too. Comparison was made between the global failure modes of a jacket structure obtained with and without the influence of tubular joint failure modes [15].

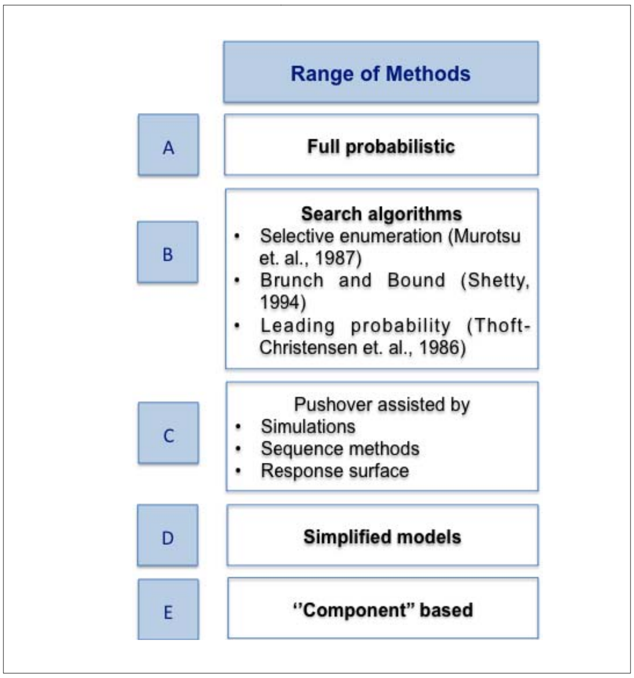

Fig. 1. Classification of methods for system reliability assessment

IV. Methodology

This paper discusses the methodology of performing component based reliability analysis of jacket platforms under different met-ocean conditions. Met-ocean data of three (3) main Malaysian water regions, namely Peninsular Malaysia Operations (PMO), Sarawak Operations (SKO) and Sabah Operations (SBO) were obtained from the design reports, and from Petronas Technical Standards (PTS), which holds the design values of wave height, wave period, and current speed, for different return periods were obtained. Platform model files were also readily available in the form of SACS files.

Critical members of the platform were selected according to the member's groups: leg members, vertical diagonal members and horizontal members. The method of selection is based on ISO 19902. After that, In-place analysis was performed using SACS software. Stresses of critical components under different met-ocean conditions were studied. Later, load and resistance models will be developed.

Reliability is how well a member's load bearing capacity (resistance) take the load effects, L acting on it without failure. To execute reliability of the members, both loads acting and member's bearing capacity (resistance) must be represented with their statistical properties that consist of mean, coefficient of variance and distribution type. Lastly, general reliability equation that is applicable to all jacket platforms in Malaysian waters will be formulated using regression analysis.

A. Load

Loads acting on a fixed jacket platform are recorded as:

1. Dead load
2. Live load
3. Environmental load

ISO describes the statistical distribution for dead and live loads to be normally distributed. The gravity (dead & live) loads statistical parameters are given in Table II.

TABLE II. GRAVITY LOADS STATISTICAL PARAMETERS [16]

Load Type	Bias	COV
Dead load of structure G1	1.0	0.06
Dead load of fixed facilities G2	1.0	0.06
Long-term live load Q1	1.0	0.10
Short-term live load Q2	1.0	0.10

Environmental load is however, varied significantly due to the uncertainty of wave, current and wind load. The combination of wave, current and wind load makes up most of the load effect on the structure. Among them, waves are found to induce the largest force on most offshore structures.

For efficient structural design, it is important to choose the most appropriate methods to transform environmental loads into forces acting on the structure. Various wave theories have been developed to predict the wave and current characteristics. Some of the popular ones include Linear Airy's Wave Theory and Stokes Wave Theory. Stokes 5th order wave theory is adopted in this study for better illustration of the environmental loads. In highly irregular sea states, any of these regular wave theories cannot describe the wave characteristics accurately. In such case, energy spectra such as the Pierson and Moskowitz (P-M) and JONSWAP wave spectrum have to be used to describe the irregular sea states. Finally, the environmental load (forces) acting on the structure is calculated using the Morison's equation.

For this study, different met-ocean data were obtained from the design reports (specific location) and PTS (regional). In order to generate a general equation that can be applied for different platforms in Malaysian waters, regional design values need to be taken into consideration. Data interpolation is performed for obtaining PTS intermediate design values of 10-year and 50-year. Weibull's and Gumbel's cumulative distribution equation were compared for the accuracy of the results. The interpolated values were justified by applying similar interpolation method to the design values given in the design reports, and compared them with the recorded data. Cumulative distribution functions for Weibull and Gumbel are show in Eq 1 and Eq 2:

Weibull: $$\ln[-\ln(p)] = -\lambda\ln(\sigma) + \lambda\ln(x) \quad (1)$$

Gumbel: $$-\ln[-\ln(1-p)] = -\frac{\mu}{\sigma} + \frac{1}{\sigma}x \quad (2)$$

Parameters such as shape, λ, scale, σ, and location, μ can be easily solved from the linearized graphs in Figure 2 and 3.

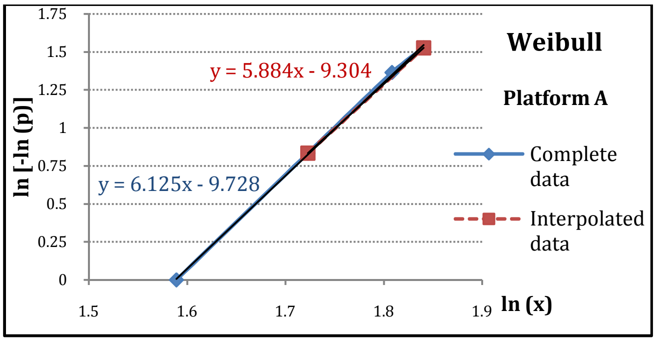

Fig. 2. Data interpolation via Weibull's cumulative distribution function

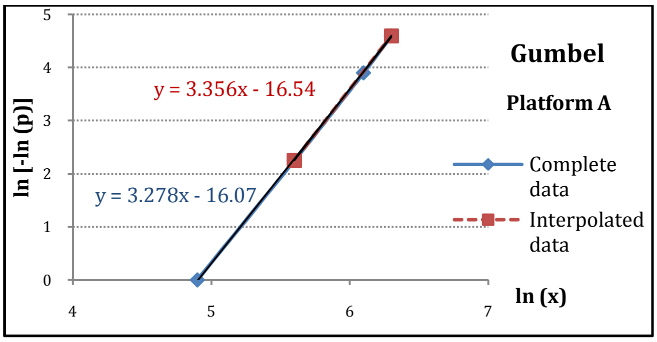

Fig. 3. Data interpolation via Gumbel's cumulative distribution function

Table III is the summary of the comparisons of Weibull and Gumbel interpolated data with the recorded design values.

TABLE III. COMPARISONS OF INTERPOLATED SIGNIFICANT WAVE HEIGHT VALUES

Tr	Hs				
	Design Report	*Gumbel*	*% Difference*	*Weibull*	*% Difference*
1	4.9	4.902	-0.031	4.896	0.082
5	-	5.376	-	5.269	-
10	5.6	5.600	0	5.600	0
50	6.1	6.092	0.132	6.128	-0.459
100	6.3	6.300	0	6.301	-0.016

Besides, recent findings from joint density analysis on met-ocean loads in Malaysia water regions (50-year wave associate with 10-year current) [2] will be referred to in this study. Stresses developed in the components were compared with the traditional method of taking the resultant of 100-year wave and 100-year current. Component stresses are checked with the allowable values and are recorded as unity check ratio (UC). In the study, critical horizontal members are determined by UC > 0.5. Figure 4 shows comparison of UC for critical horizontal members at the combination of 100-year wave associates with 100-year current, and 10-year current.

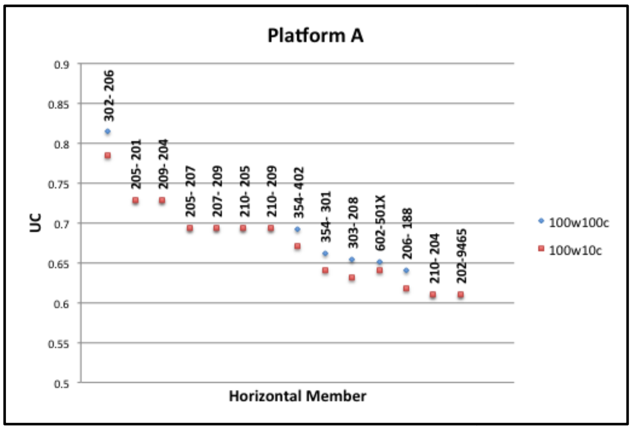

Fig. 4. Comparison of UC for critical horizontal members at different met-ocean combinations

B. Resistance

The resistance part is derived from several limit state functions, which define the performance of each member under specific load conditions. For this study, static analysis will be conducted to obtain the structure's ultimate strength. Hence, static strength will be the main interest here.

The geometry/fabrication, material, and loading that a structure is subjected during its service life will determine the strength of the structure. The major sources of resistance uncertainty can be divided into three groups, namely Geometry/Fabrication, Material and Model Uncertainties.

ISO [16] suggested statistical properties for the resistanceare given in Table 4. In Malaysia, study had been carried out and the statistical data for resistance was based on material test report and field measurements at one of the leading fabrication yards in Malaysia. Details of the statistical analysis of resistance parameters are recorded in Table IV. The values do not differ much as the fabrication of steel is standardized everywhere.

TABLE IV. STATISTICAL PROPERTIES OF THE RESISTANCE [16]

Parameter	MC	COV	Distribution
Diameter	1.000	0.0025	Normal
Thickness	1.000	0.015-0.050	Normal
Yield strength	1.1193	0.050	Normal
Tensile strength	NA	NA	NA
Young's modulus	1.000	0.050	Normal

TABLE V. STATISTICAL PROPERTIES OF THE RESISTANCE MEASURED IN MALAYSIA [17]

Parameter	MC	COV	Distribution
Diameter	1.001	0.002	Normal
Thickness	1.024	0.016	Normal
Yield strength	1.193	0.035	Lognormal
Tensile strength	1.183	0.033	Normal
Young's modulus	NA	NA	NA

Before selecting members for calibration, members will be first grouped into respective primary members such as leg members, vertical diagonal members and horizontal members at the periphery as labeled in Figure 5. Members from each group will be selected based on the slenderness (k*L/r) and diameter to thickness ratio (D/T) for finding the target reliability index. The k value is recommended in [16] while r is the radius of gyration.

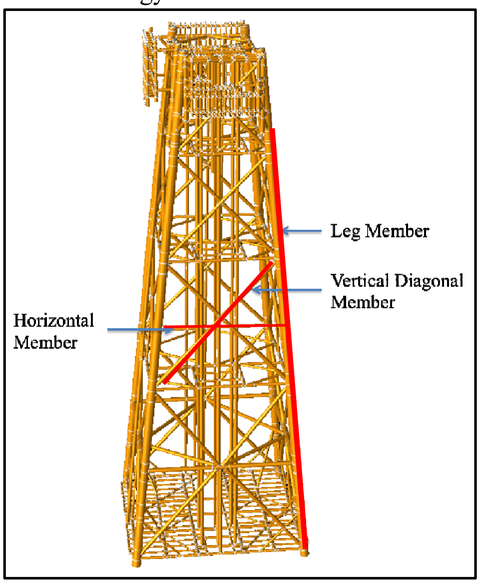

Fig. 5. Primary members of the structure

C. *Reliability*

The behavior of a structure can be determined by the values of loads (actions) or load effects, S acting on it and its load bearing capacity (resistance), R. The acceptance criterion of the structure for limit state failure mode is as shown in Eq. 3:

$$R - S > 0. \quad (3)$$

A structure is considered reliable when the resistance is larger than the loadings exerted on the structure. The safety margin, Z is expressed as in Eq. 4:

$$Z = R - S. \quad (4)$$

In critical condition where the resistance is equal to the load values, the limit state equation can be written as in Eq. 5:

$$Z(X) = 0 \quad (5)$$

From the limit state function, one can easily determine the status of a structure. If Z(X) is equal or larger than zero, the structure is safe; if it is smaller than zero, the structure is considered to be in the failure region. The probability of failure for each limit state can be formed as in Eq. 6:

$$P_f = P[Z(X) < 0]. \quad (6)$$

Considering probabilistic models for the variables assessment and simplifying that they are described by time independent joint probability density function, the probability of failure can be written in the form of integral as in Eq. 7:

$$P_f = \int_{Z(X)<0} \varphi_x(x)\, dx. \quad (7)$$

Reliability index is an equivalent term for probability of failure, which is usually used in the design standards and relevant documentation. Reliability index can be expressed as in Eq. 8:

$$\beta = -\varphi^{-1}(P_f). \quad (8)$$

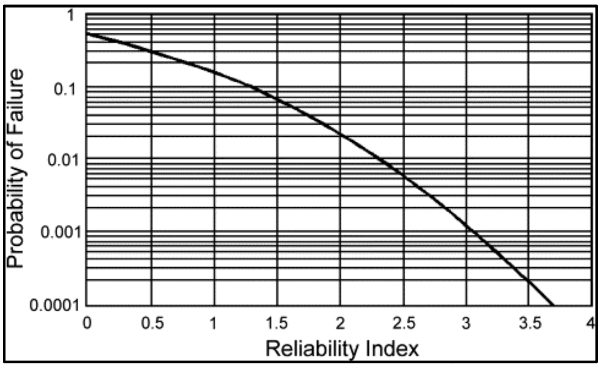

Fig. 6. Relationship between reliability index and probability of failure

Figure 6 explains the relationship between reliability index and the probability of failure. The probability of failure decreases asreliability index increases. Thus, structure with higher reliability index is less likely to fail.

As time passes, load acting on a platform gradually increases while the strength of the platform deteriorates. At the point where the increasing loads meet with the decreasing strength, reliability index can be determined. Reliability index is actually the area below the intersection of load and resistance (structure strength) curves as shown in Figure 7.

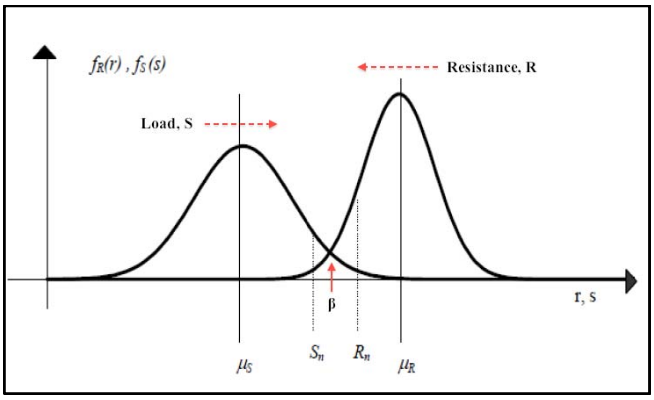

Fig. 7. Definition of reliability index

Table 6 shows the target reliability given in ISO [16]:

TABLE VI. ISO TARGET RELIABILITY [16]

Load Effect	P_f	β
Compression & Bending	5.8E-5	3.84
Tension & Bending	5.8E-5	3.85
All	5.9E-5	3.85

There are several methods available in literature for the assessment of structural reliability .In this study, Monte Carlo Simulation (MCS) and First Order Reliability Method (FORM) will be utilized to determine the component's reliability index. MCS is also used to determine the statistical description of the random variables (for both resistance and load) while FORM is applied only to compute reliability using the complete distributions.

D. *Regression Analysis*

After execution of a finite series of simulations, the response of each member can be identified and response equation can be formulated through data regression analysis.

Regression analysis is the investigation of the functional relationship between two or more variables. There are two types of regression analysis: linear and nonlinear. Linear regression refers to approaching the dependent variable as a linear function of some parameters (independent variables). Otherwise, it is referred as nonlinear. Anyhow, linear regression is always the fundamental concept followed to develop a function that relates two (or more) variables.

Using regression analysis, component reliability and its affecting variables can be related and formulated.

V. DISCUSSION

Weibull and Gumbel distribution function both give rather accurate values in predicting the design met-ocean values at different return period. Determining which distribution function to be applied is important as ISO recommends probability of failure to be checked for 10,000 year environmental load for reassessment for extension of jacket life. The same interpolation method will be used to determine the met-ocean values for 10,000-year of return period.

Apart from that, ISO suggests 100-year load return period for environmental loads to be considered for the calibrations of jacket platforms. Studies shown that a 100-year current is not likely to be observed at the same time as the 100-year wave. Joint densities study on met-ocean loads that had been carried out for Malaysian waters found that a 50-year wave is most likely to be associated with a 10-year current. [2] Static analysis had been carried out by the author and found that member stresses produced by 50-year and 100-year load are identical. Hence the comparison of different combination of wave and associate current loadings was performed with 100-year wave associate with 10-year current, and 100-year wave associate with 100-year current. 100-year wave that is associated with 10-year current generates lower stress in critical horizontal members as compared to the traditional method of considering 100-year wave and 100-year current. The variation is not big (1-3%) but it will influence the calibrations for jacket platforms.

VI. CONCLUSION

The following conclusions are made from the results discussed above:

1. Both Weibull and Gumbel cumulative distribution function are suitable to be used for interpolation of met-ocean values at different return period.
2. Combination of 100-year wave and 10-year current loadings can be considered in calibrations for jacket platforms in order to obtain a more realistic assessment.

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