Development of Partial Environmental Load Factor for Design of Tubular Joints of Offshore Jacket Platforms in Malaysia

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Abstract: The reliability analysis methods have been effectively applied to develop load and resistance factor design (LRFD) codes, such as the ISO 19902, that provide optimum structural safety taking into account the uncertainties of both the load and resistance parameters. Although, these methods have been developed since the early 1960's their application in the design of offshore structures is still not extensive. This paper presents the procedure for reliability analysis and evaluation of the environmental load factor for design of tubular joints of offshore platforms in Malaysia, for the proposed ISO. The uncertainties affecting the joints' resistance and loading were investigated and their statistical parameters presented. The reliability indices of a platform designed using both API RP2A – WSD and ISO 19902 were evaluated and compared. The partial environmental load factor of 1.29 was obtained, which provides a significant reference towards the adoption of ISO in Malaysia.

Keywords: Environmental Load Factor, Steel Jacket Platforms, Reliability Analysis.

INTRODUCTION

The exploration and production of oil and gas in offshore environment is conducted using offshore platforms. The most conventional type of platforms is the fixed steel jacket platforms. Jacket platform consist of tubular members welded together to form a three-dimensional frame, that supports the deck, on which the operations take place. The welded connections, also known as tubular joints, play a very importance role on the integrity of the whole structure. Typical tubular joints are classified into three types, namely K-, T/Y- and X-joints. This classification depends on both, the geometry of the connection and the loading transfer pattern. Among various modes of failure of tubular joints, the most common are yielding, buckling and fatigue.

For many years, the tubular joints have been designed based on the Working Stress Design (WSD) method [1]. However, in recent years it has been found that the WSD has some disadvantages [2, 3] and [4]. For instance, the WSD method merely depends on the safety factor (*FS*), which is determined by comparing the resistance with the predicted load, without taking into account of the uncertainties in both loads and resistances, as shown in Equation (1).

$$\frac{R_n}{FS} \leq \sum Q_i \qquad (1)$$

Where the R_n is the nominal resistance, Q_i is nominal loads, in which the subscript *i* represents the types of loads (dead, live and environmental). Note that the nominal values are deterministic and are often eventuated as a percentile of the recorded values. Consequently, there may be a case that tubular joints with greater uncertainties in resistance and/or in apply load to be judged as safe as those with smaller uncertainties, if their nominal values of resistance and load do not match each other. In order to avoid the disadvantages of WSD, the Load and Resistance Factor Design (LRFD) method has been introduced in design of offshore structures, thus is also applied in the design of the tubular joints. The LRFD method is based on the structural reliability analysis. That is the safety levels of the tubular joints are assessed taking into account the uncertainty of the resistance and load on them. This achieved using the partial safety factors of resistance (γ_R) and partial safety factor of the applied load applied (γ_i). Hence, the safety equation is given as follows:

$$\frac{R_n}{\gamma_R} \leq \sum \gamma_i Q_i \qquad (2)$$

The Internationally accepted, LRFD design method has been recommended in the API RP 2A-LRFD in published in 1993 [5] and subsequently on the ISO-19902 published in 2007 [6]. Although, the principles of the LRFD method have been made clear in the API and ISO standards, design parameters, such as the partial safety factors of resistance (γ_R) and partial safety factor of the applied load applied (γ_i), should be checked or evaluated using reliability theory when the environmental conditions. Furthermore, structural designs are different from the regions covered by the above codes.

Malaysian oil and gas industry is in the process of adopting the LRFD method. Given that the environmental conditions in the Malaysian waters are different from those in the Gulf of Mexico and in the North Sea, to which the API RP2A-LRFD and ISO 19902 design codes were developed, respectively, reliability analysis should be performed to determine the design parameters that are suitable for the local conditions. In continuation of the study presented by Cossa

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et al. [7], this paper presents and discusses the procedure of the reliability analysis undertaken on tubular joints of a fixed steel jacket platform located in one of the Malaysian Operational regions. The objectives of the study include the following aspects:

1. Assessment and quantification of the input parameters uncertainties.

2. Analyze and evaluate of the reliability index and environmental partial load factor.

PROCEDURES FOR RELIABILITY ANALYSIS

The fundamental theory of reliability analysis and its application in structural design has been explained by Melchers [8], and Nowak and Collins [9]. Studies on realibility based design in offshores structures started in the early 1970's, pioneered by researchers such as Bea, Stahl, Moses, Marshall and others [10]. The ISO 2394 provides the general principles for the reliability analysis of structures [11], and explicitly highlights the requirement of statistical analyses of the basic variables for the action loads and the structural resistance (capacity). In course of the development of the API RP2A – LRFD, extensive calibration of offshore structures in GoM were conducted, by Moses [12, 13] and [14]. Similarly, under the Joint Industry Project, calibration of the North Sea environmental load factors was conducted for subsequent recommendation in ISO 19902. The Bomel Ltd study provides an overview of the reliability theory as applied in the calibration of load and resistance factors, for existing structures [15].

RELIABILITY CONCEPT AND LIMIT STATE FUNCTION

Reliability analysis is used to estimate the probability that the design criteria are not met (fail), by taking into account the parameters variability (e.g. geometric/material properties), and by defining suitable design criteria on critical performance quantities [16].

The reliability index, β is calculated based on probability of failure (P_f) using Equation (3) [17].

$$\beta = -\phi^{-1}(P_f) \tag{3}$$

The relationship $\Phi^{-1}()$ is the inverse of the standard normal distribution function (zero mean and unit variance). Basic reliability analysis evaluate the structural failure by determining whether the limit state function, also known as performance function, is exceeded. The performance function indicates the margin of safety between resistance and the load of structures and is defined as [17].

$$g(R,Q) = R - Q \tag{4}$$

In this research, the Equation (4) is extended depending on the model used to evaluate the resistance and the load actions. On Equation (5) and Equation (6), the resistance term (R) is defined, based on the resistance model provided in the ISO 19902, here represented as Pd_i, and the partial resistance factor is replaced by the model uncertainty bias factor (X_m). The load action term (Q), is defined such that it will result in load value that will cause the structure to fail. That is possible by assuming that the load action term (Q) is equal to the predicted design resistance or capacity (Pd/FS) multiplied by the bias terms of the load ($dD+lL+wW$), which ensures that uncertainty of the load is captured. The letters d, l and w represent the proportions of dead (D), live (L) and environmental (W) load actions, respectively. The design resistance (Pd) is determined as per model provided in the code for which the reliability index is to be evaluated, that is it could be as per API RP2A – WSD or ISO 19902, as follow:

Performance function for API RP2A – WSD

$$g(R,Q) = Pd_i \cdot X_m - \left[(\mathrm{dD} + \mathrm{lL} + \mathrm{wW}) \cdot \frac{Pd}{FS}\right] \tag{5}$$

Performance function for ISO 19902

$$g(R,Q) = Pd_i \cdot X_m - \left[(\mathrm{dD} + \mathrm{lL} + \mathrm{wW}) \cdot \frac{Pd}{FoS}\right] \tag{6}$$

In Equation (6), the *FoS* is the equivalent of the factor of safety (*FS*), in the API RP2A – WSD. Since it is evaluated for the ISO 19902, its value is determined using the partial safety factors, as demonstrated in Equation (7).

$$FoS = \frac{\gamma_R(\gamma_D \mathrm{D} + \gamma_L \mathrm{L} + \gamma_W \mathrm{W})}{(\mathrm{D}+\mathrm{L}+\mathrm{W})} \tag{7}$$

Where, γ_R, γ_D γ_L and γ_W are resistance, dead load, live load and environmental load partial factors, respectively.

For Equation (5) and Equation (6), structural safety is reached when $R = Q$ and failure will occur when:

$$g(R,Q) < 0 \tag{8}$$

Then reliability index, β, can be, simply, determined as ratio of performance function mean value to standard deviation, for normally distributed variables:

$$\beta = \frac{\mu_g}{\sigma_g} \tag{9}$$

There are number of approaches used for the finding out the reliability index of structural components, however the commonly used is the First Order Reliability Method (FORM). In the FORM, the limit state function is linearized, but the probability distributions are no longer approximated only about the mean and variance (first and second moments, respectively). The most common FORM algorithms for evaluation of the reliability index are "*Hasofer-Lind Reliability Index*", in which the limit state function is evaluated about a point known as "*design point*" or "*most probable point*" instead of the mean values. The other, is the modified method, known as "*Rackwitz-Fiessler Procedure",* in which the distributions of the design variables are transformed into an equivalent standard Normal space using appropriate techniques, such as the Normal tail transformation for independent variables or the Rosenblatt transformation for dependent variables [9]. The accuracy of both FORM algorithms depends on the ability of approximating the surface to represent the true limit state.

CASE STUDY

Location and Properties of the Platform

The platform used in this study was fabricated and installed in Malaysia's South China Sea offshore operations, at a water depth of 71.5 meters. The platform has four legs and is designed for a 100-year return period maximum wave

Table 1. Geometry Properties for X – Joint

Group	Chord Diameter (mm)	Chord Thickness (mm)	Brace Diameter (mm)	Brace Thickness (mm)	Angle (Degree)
1	660	25	660	13	60
2	660	32	660	19	65
3	610	25	610	13	75

Table 2. Geometry Properties for T/Y – Joint

Group	Chord Diameter (mm)	Chord Thickness (mm)	Brace Diameter (mm)	Brace Thickness (mm)	Angle (Degree)
1	1854	51	610	16	80
2	1880	64	660	13	85
3	908	41	604	29	50

Table 3. Geometry Properties for K – Joint

Group	Chord Diameter (mm)	Chord Thickness (mm)	Brace Diameter (mm)	Brace Thickness (mm)	Angle (Degree)	Gap
1	1854	51	660	19	55	50
2	1880	64	610	13	120	50
3	660	25	406	13	55	50

height of 9.9 meters and associated period of 10.2 seconds. The selection of this platform was based on the availability of complete metocean design data and the SACS (Structural Analysis Computer System) model of the jacket [18].

The platform is manned platform hence it falls under a life-safety exposure level of 1, as indicated in ISO 19902 [6], cross checking it with the ISO 2394 [11], indicates that the annual reliability index, for the ultimate limit state design of the platform shall not be less than 3.0.

1. Joints Considered

This research considered joints that play an important role in the integrity of the structure, and those that are located at the peripheral edges of the jacket. These joints are typically connections of leg-to-bracing, and brace-to-brace. Note that the term brace refers to the member, typically with a smaller diameter and is welded, at a certain angle, on the perimeter of a second and larger member. The structural analysis results obtained using the 100-years return period action values; allow the selection of the critical joints that have the highest unity check.

2. Geometry Groups

The joints were also divided into groups based on their geometry. This exercise was conducted to find the calibration points and subsequently the weighting factors for averaging of the final reliability index and partial environmental load factor. The groups are shown in Table **1**, Table **2** and Table **3**.

RESISTANCE PARAMETERS

The resistance uncertainty, of the components is evaluated using the ISO 19902 formulations without the safety factors, because these provide the best model, and based on the recent research studies. The exclusion of the safety factors, aims to capture the actual resistance strength of the joint. The model is a function of the uncertainties of the basic variables (geometric and material parameters) and the model uncertainty (X_m) associated with the particular ISO formulation.

$$R = f(Dia, Thi, Fy, \dots, X_m) \tag{10}$$

The basic random variables, namely diameter (*Dia*), thickness (*Thi*) and steel yield strength (*Fy*), for resistance were determined and presented in a paper by Idrus *et al.* [19].

GRAVITY LOADS MODELING

The probabilistic description of gravity loads was based on North Sea data. For dead loads, *D*, a bias of 1.00 and a COV of 0.06 were used. The live loads, *L*, considered bias was 1.00 with a COV of 0.10 [15].

ENVIRONMENTAL LOAD MODELING

The uncertainties of environmental parameters were evaluated based on the metocean data provided in the design report [20]. The evaluation of the long term distribution of the environmental parameters is executed using the extreme value statistics. The most typical probability distributions used in evaluation of the offshore environmental conditions are *Gumbel*, *Weibull* and *Frechet* [21]. In practice, the observed metocean data, during a certain period is fitted to these theoretical distributions, and the best-fit curve is selected. In this research, the original hindcast data was not available, and statistical parameters were obtained by fitting the *Weibull* distribution to the existing designed values. The

Table 4. Statistical Parameters of Metocean Data

Parameter	Weibull		Statistical		Design Values 100 - year
	Scale	Shape	Mean	Std. Dev.	
Significant Wave Height (m)	2.92	2.64	2.59	1.06	5.20
Wind speed (m/s)	20.91	4.67	19.12	4.67	44.00
Current speed (m/s)	0.86	7.73	0.81	0.12	1.05

selection of the type of distribution applied was based on Cheng *et al*. [22], work in which the two-parameter *Weibull* distribution provides the optimum fit for the significant wave height. The *Weibull* distribution function is shown in Equation (11).

$$F_X(x) = 1 - \exp\left[\left(\frac{x-a}{b}\right)^c\right] \tag{11}$$

This can be manipulated to give the following linear expression:

$$ln\{-\ln[1 - F_X(x)]\} = cln(x - a) - cln(b) \tag{12}$$

It is obvious that a plot of $ln\ \{-ln\ [1 - F_X(x)]\}$ against $ln(x - a)$ is a linear function. The linear regression is performed to determine the values of parameters a, b. and c, and for two parameter *Weibull* distribution, the parameter a is reduced to zero (a = 0). Applying the least-square method, to two of the design values, in this case the extreme values with return periods of 10 and 100 years the probability of exceedence per year is 0.1 and 0.01 respectively, provided in the metocean report, the two unknown parameters (scale and shape) of the distribution can easily be calculated analytically using Equation (12).

Generally, the wave period is associated with the significant wave height by a certain joint distribution. Again, the selection of the joint distribution is only possible if the original data of the metocean parameters is available. In the absence of this, the Equation (13) was obtained through regression analysis of the significant wave height (H_s) and its corresponding peak period as per metocean report.

$$T_p = 5.001 \cdot H_s^{0.4778} \tag{13}$$

The summary of the statistical parameters of the significant wave height, current speed and wind speed is displayed in Table **4**. These values are used to evaluate the variability of the environmental load acting on the structure. Note these values were fitted to annual extreme events.

Table 5. Calibration Parameters for Reliability of Joints

Parameter	Value
Dead : Live load ratio,	1:1
Environmental Load factor,	1.35
Dead load factor,	1.10
Live load factor,	1.10
Resistance factors,	1.05
Q_f factor	1.00
Factor of Safety,	1.67(1.25)

ENVIRONMENTAL LOAD MODELING

Offshore structures are installed in fluid environment. The load effect is evaluated using hydrodynamic and aerodynamic concepts. Morison's Equations [23] are applied to evaluate the effect of hydrodynamic loads on the offshore structures [21]. SACS Software, for structural analysis of the jacket platform, was used to compute the loads on each structural element under a given metocean input data. The load acting on the tubular joints depends on the structural response to the action of the wave, current and wind loads, the size and location of the joint on the structure. To execute the reliability analysis, loads acting in the tubular joints must be represented by the statistical parameters. Since, the variability of the load depends on the variability of the primary input (wave, current and wind), the response surface method was applied to find an expression that relates the input variables and the load on each joint. According to Tarp-Johanson [24], in drag-dominated structures, the hydrodynamic response model is quadratic, given that the wave height is raised to the second power. Therefore, the expression takes the following form:

$$W = a + bH_{Max}^2 + cH_{Max} + dV_c^2 + eV_c + fV_w^2 + gV_w \tag{14}$$

$$H_{Max} = 1.90 \cdot H_s \tag{15}$$

Where the coefficients a, b, c, d, e, f and g depend on the structural element location and these values could be different for each tubular joint. The H_{Max} is the maximum wave height, which is obtained from the evaluated significant wave height (H_s), as shown in Equation (15). The V_c and V_w represent the current and wind speed, respectively.

CALIBRATION PARAMETERS

The reliability index evaluation of typical joints was based on the input that has already been defined. For each type of joints a range of calibration points, were defined and applied to investigate the effect of different load effects and partial factors parameter. The reliability indices of the API RP2A – WSD and ISO 19902 codes were evaluated for the parameters shown in Table **5**.

Table 6. Reliability Index for API RP2A WSD

	K-Joints		T-Joints		X-Joints		Total Averaged	
	β	***P_f***	***β***	***P_f***	***β***	***P_f***	***β***	***P_f***
Compression	2.589	4.81E-03	1.853	3.20E-02	2.022	2.16E-02	2.231	1.28E-02
Tension	2.589	4.81E-03	2.829	2.34E-03	2.366	9.00E-03	2.628	4.29E-03
In Plane Bending	3.678	1.17E-04	4.275	9.56E-06	4.023	2.88E-05	3.946	3.97E-05
Out Plane Bending	2.361	9.12E-03	4.182	1.44E-05	2.615	4.46E-03	3.029	1.23E-03
All	2.804	2.52E-03	3.285	5.11E-04	2.756	2.92E-03	2.959	1.55E-03

Table 7. Reliability Index for ISO 19902 (γ= 1.35)

	K-Joints		T-Joints		X-Joints		Total Averaged	
	β	***P_f***	***β***	***P_f***	***β***	***P_f***	***β***	***P_f***
Compression	2.702	3.45E-03	3.050	1.14E-03	2.595	4.73E-03	2.800	2.56E-03
Tension	2.702	3.45E-03	3.254	5.68E-04	2.837	2.27E-03	2.915	1.78E-03
In Plane Bending	3.021	1.26E-03	3.849	5.92E-05	3.943	4.03E-05	3.478	2.53E-04
Out Plane Bending	2.586	4.85E-03	4.037	2.71E-05	2.417	7.83E-03	3.047	1.15E-03
All	2.753	2.96E-03	3.548	1.94E-04	2.948	1.60E-03	3.060	1.11E-03

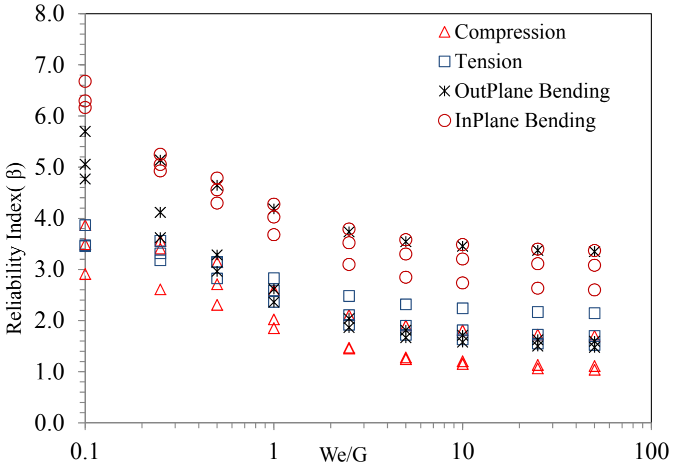

Fig (1). Reliability index at the calibration points for all joints using API RP2A – WSD.

RESULTS AND DISCUSSION

The reliability indices of the tubular joints were evaluated and plotted against the environmental-to-gravity loads (*We/G*) ratios for the calibration points shown in Table **5**. This exercise was executed for both codes of design.

Reliability Index

The reliability index of the platform designed for both codes were initially evaluated at the extreme conditions, that 100 – year return storm event, to provide means of comparison. For the WSD the safety factor was fixed at 1.25, which corresponds to the one – third increase in strength, as recommended in the code [1]. For the ISO 19902 a partial environmental load factor of 1.35 is recommended. Part of the results and graphical illustrations were reported in Cossa *et al.* [7]. The summary and calculation of the average reliability index is shown in Table **6** and Table **7**. These values were taken at the environmental – to – gravity (*We/G*) load ratio of one (1). The overall of both codes reliability index was evaluated to be approximately close to three (3), with the ISO 19902 predicting a relatively higher value, than the API RP2A – WSD.

For different loadings actions and joint types the ISO had higher and more consistent values of reliability index, as compared to the API which tends to have lower values for joints in compression, and generally high values for joint under moment, most particularly In-plane Bending. The Fig. (**1**) and Fig. (**2**) show the reliability index of all joints at the calibration point.

Partial Environmental Load Factor

The process of evaluating the partial environmental load factor consists of, first, identifying the target reliability index, in this case the averaged API RP2A safety index, evaluated at the *We/G = 1.0*. Subsequently, at the same *We/G,* the

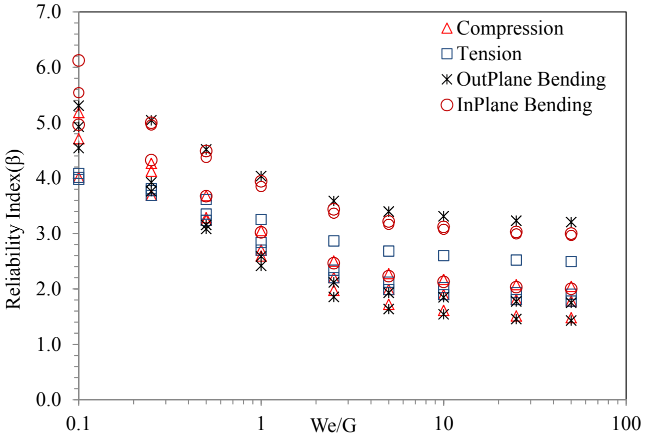

Fig (2). Reliability index at the calibration points for all joints using ISO 19902

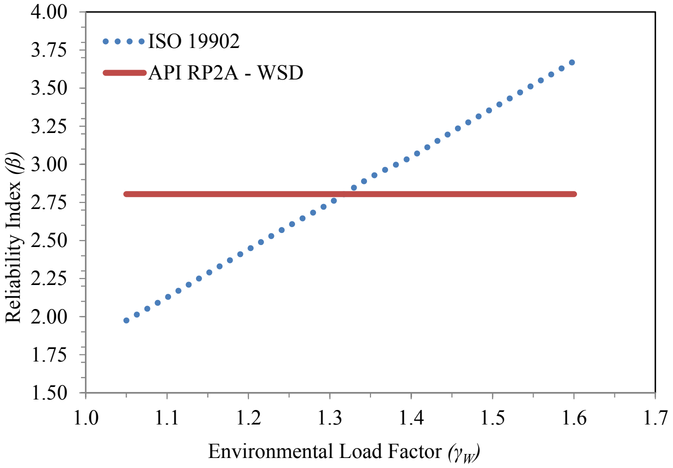

Fig (3). Environmental Load Factor K-Joints

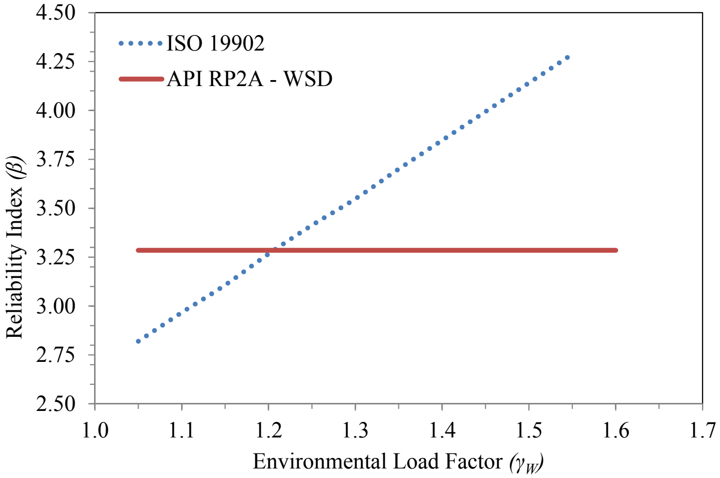

Fig (4). Environmental Load Factor T-Joints

series of reliability indices are calculated for different partial environmental load factors. These results are plotted and the factor is selected at the point of intersection of both curves.

The partial environmental factors were initially evaluated for different types of joints and then an overall partial factor was obtained, based on the weighted averaging. The values of the partial load factors are 1.32 for K-joints, 1.21 for T/Y-joints and 1.24 for X-joints as plotted in Fig. (**3**), Fig. (**4**), and Fig. (**5**), respectively. The K-joints high environmental load factor is the result of the existing difference between both codes on the evaluation of the resistance capacity, with the API tending to be over conservative.

Based on the number of tubular joint count that were considered in the analysis, the weighted overall partial envi-

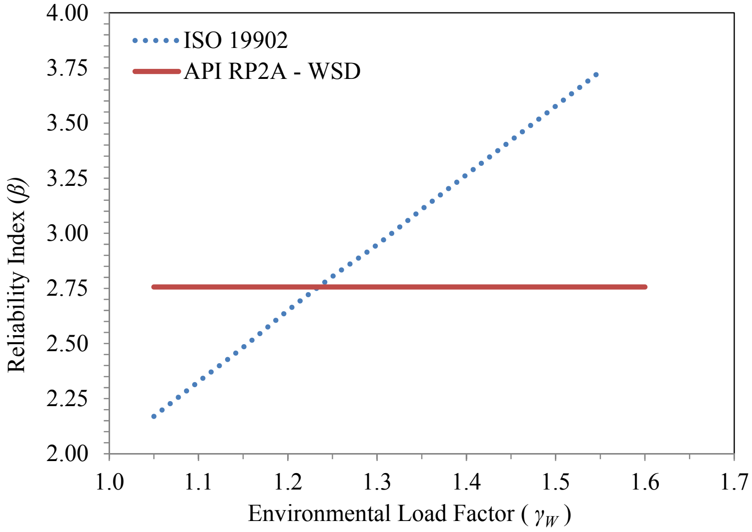

Fig (5). Environmental Load Factor X-Joints.

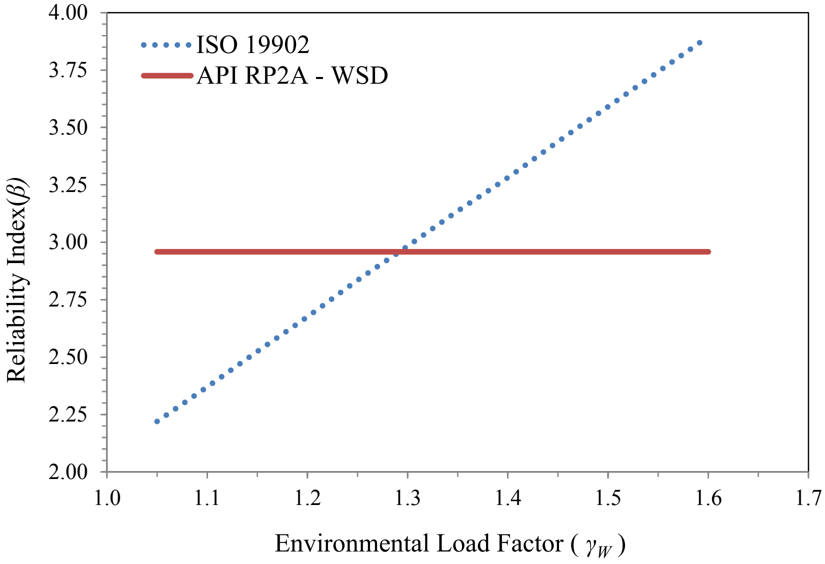

Fig (6). Environmental Load Factor All Joints.

ronmental load factor was found to be 1.29, as illustrated in Fig. (**6**). This shows that the ISO design of the jacket platform would achieve reliability levels similar to that with API RP2A WSD at the lower partial environmental load factor, than the recommended 1.35.

The environmental load factor obtained confirms that the metoceanic conditions of Malaysia are less extreme than those of the Gulf of Mexico, for which the ISO 19902 environmental load factor was calibrated. Recalling that the statistical properties applied in this study were based on the already processed metocean data, it is possible that with a detailed stochastic analysis of the hindcast data the environmental load factor could still be lesser than 1.29.

CONCLUSIONS

The paper presented and discussed the overall process of reliability analysis leading to the evaluation of the partial load factors for design of tubular joints of offshore jacket platforms in Malaysia. The study was conducted on existing platform, and designed as per API RP2A – WSD. SACS model was used to conduct the structural analysis and study the structural response due to variability of the environmental loading. The reliability analysis of tubular joints showed that the safety index evaluated for the ISO was relatively higher and reasonably more consistent for different joint types and loading than the API RP2A – WSD. The calibration of load factor for the platform showed that the if the ISO provision were to implemented, a partial environmental load factor of 1.29 would be required to produce the similar levels of structural safety as the API RP2A – WSD. The authors recommend that a reliability studies be conducted using more detailed hindcast metocean data.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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