Bayesian Updating for Probability of Failure of Jacket Platforms in Malaysia

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Abstract- **The Jacket platform codes such as API LRFD and ISO 19902 are based on probabilistic design of component and joint reliability. They consider overall structural integrity, redundancy and multiple failure paths only indirectly by using structural integrity assessment methods. In this paper, probability of failure is determined as per design requirement of 100 year extreme conditions using Monte Carlo simulation. To get information on maximum strength, maximum wave height was increased till the reserve strength ratio reached 1, using SACS pushover analysis. Stokes's 5th order theory and Morrison Equation were used for finding the environmental loads. Regression analysis was used for the load model using surface fit tool of Matlab. The wave which gave an RSR value of 1 is considered as the maximum wave, the jacket can withstand with the available resistance of material. This theory has already been applied on land based structures, such as proof loading used against existing structures to gauge the strength of structure. This new maximum wave height has been used to find the updated failure probability and compare it with failure probability of design wave. The study covers one platform, and recommendation is made whether the platform is suitable for the extension of life or not. This study can further lead to updating based on new information on material resistance of platforms.**

Keywords: **Jacket platform; Probability of failure; Environmental loading; reserve strength ratio; Bayesian updating**

I. INTRODUCTION

The updating of probability of failure (Pf) using additional information collected on material and on load, has been used in many engineering applications. Here it is used to update the probability of failure for jacket platforms in Malaysia. The concept is based on risk and reliability of structures. The characteristics of structural design are dependent on uncertainties arising from environmental loads and resistance of material. The reliability based structures are designed so that their probability of failure is always less than the minimum specified by the well-established standards [1] and [2]. Target reliability for manned platforms should be made by selecting probability of failure due to environmental loads and it must be small compared to other high consequences, major risks like fire, explosions and blowouts. There is an agreement among researchers that if annual probability of failure due to some cause is less than 1 in 10,000, then it is small in relation to major risks [3]. The assessment of jacket platforms is governed by the rare event which might strike the platform during its entire design life. The codes recommend that platforms should be checked against a 10,000 year return period of wave as criteria for extending the life of platforms. The information gathered after the installation of jacket is used to extrapolate the extreme environmental event for wave height, wind speed and current velocity and material resistance. These observations at site can be used to update the probability of failure of jacket. Here in this study, this new information is used in SACS push over analysis to gain knowledge about the behavior of jacket. Corresponding base shear of platform, used to find the reserve strength ratio (RSR), is obtained. Wave heights are increased in steps until a wave which produces an RSR value of 1 is reached. Then this wave height is used for updating the failure probability using total probability theorem (Bayesian updating theory). This theory can be applied for many engineering applications of jacket like fatigue, dented or corrosion damaged Jackets. Ultimate limit state design is used to find the reliability of jacket platforms.

II. BACKGROUND

Jacket Platforms are designed using the limited data available during design phase. Therefore insufficient data and information available about the loads and resistance in future, leads to uncertain belief for the mathematical modeling of the structural design. This is where the probabilistic design is used and which is checked against the notional failure probability as recommended by codes of practice for jacket platforms. Depending on the type of uncertainty, probability distribution is used to build the frame work of probabilistic evaluation of uncertain parameters. The assumption used against the uncertainty of material as well as environmental loading, based on limited amount of data available for jacket behavior during design phase, may raise concern for the design engineer. Jacket platforms are designed for 30 year structural life, but they have to withstand a 100 year return period of environmental loads. Codes used for the design are based on component and joint reliability. Once in operation, these Jackets are assessed for 10,000 year return period for environmental loads or $1x10^{-4}$ probability of failure. This is due to the importance of jacket platform from economic, health, safety and environmental view point. This extreme event may or may not arise at site during 30 years. The main problem with this assessment is that the collected data ranges between10 or 20 years which is not enough to assess jacket for 10,000 year return period. Therefore it is required, on the basis of available data, that simulation methods should be used to find the reliability. This will give us insight into the behavior of jacket, if that rare event was ever to occur.

In this study, the probability of failure for a jacket platform was determined against a design return period of 100 years using ultimate limit state design. The probability of failure was updated based on survival of structure after undergoing more than 10,000 year wave loads. Finally, the probability of failure was checked for damaged structural members during the extreme sea conditions.

III. LITERATURE REVIEW

The present work aims to show quantification and updating the uncertainties in wave loading, specific for existing jacket platforms in Malaysia. This will be used for providing a frame work for determining the updated probability of failures for existing Jackets. The given methodology is based on four Jackets from three different regions of Malaysia, by using platform specific data on environmental load. The results will be used to assess whether these platforms are fit for life extension or not as per ISO code requirements. The updating of probability of failure using Bayesian approach has been recommended by [4]. Bayes' theorem is used in cases when combined knowledge of statistical and judgmental information is available for updating probabilities based on observed outcomes [5]. This theorem calculates the probability of occurrence of event 'A', which depends on other mutually exclusive and collectively exhaustive event 'B', given that event 'B' has already occurred [6]. When additional information has become available about an existing jacket, the knowledge implicit in that information may be used to improve the prior estimate of structural probability of failure [7]. Assessment of existing structure becomes real when damages are observed, use of platform is expected to be changed, deviations from project descriptions are observed, the life time is up to extension beyond what was planned and inspection schedules were planned to be revised [8]. For jacket it was used by [9], [10], [11] [12] for Gulf of Mexico and North Sea but for South China Sea it has never been used. Bayesian updating procedure allows the updating the probability distributions for modeling uncertainty parameters and structural global response within the simulation routine [13]. Bays theorem uses rational approach for incorporating the prior information or judgment into prediction of future behavior of structures [14]. Here in this paper first probability of failure for 100 years was determined. Then it was updated and probability of failure for 10,000 years was determined. Finally it has been updated in case of damaged members.

IV. METHODOLOGY

These platforms are designed as per API RP 2A WSD and the Reserve Strength Ratio (RSR) is found using SACS push over analysis. Failure of a single component does not prove that the capacity of platform has reached and hence for the reassessment of old platforms component based approach becomes unviable. This is due to its redundancy, jacket will now acts more like a system not as individual element. When jacket has been put into use, new information on load and resistance is collected which is used for its reassessment and now updating of probability of failure becomes essential for system reliability analysis. This is also primary requirement of ISO 19902 which requires that jacket component and joint should be designed as per 100 year return period of load but checked for its integrity assessment for 10,000 year return period.

A Distribution model for wave load

Two parameter Weibull distribution was used for modeling the significant wave height, wind and current.

$$Fx;(a,b) = 1 - exp\left[-\left(\frac{x}{a}\right)^b\right] \quad (1)$$

Parameters, a= scale and b= shape

Table 1 and Figure 1 show the extrapolated values of wave heights at four different platforms along with the parameters of distributions. Coefficient of variation (COV) ranges between 0.14 and 0.41 and standard deviation (SD) between 0.57 and 1.06. These parameters were used for the reliability analysis of Jackets.

TABLE 1:
RETURN PERIOD AND PARAMETERS OF SIGNIFICANT WAVE BASED ON WEIBULL DISTRIBUTIONS

	Jacket	10	10^2	10^3	10^4	Mean	SD	COV	Linear fit for extrapolation
PMO	A	4.9	5.3	5.5	5.7	4.2	0.57	0.14	A=0.577x+4.418
SBO	B	3.8	4.3	4.6	4.8	3.0	0.62	0.21	B=0.720x+3.199
SKO	C	4	5.2	5.9	6.4	2.6	1.06	0.41	C=1.731x+2.556
SKO	D	5.6	6.3	6.7	7.0	4.5	0.89	0.20	D=1.009x+4.757

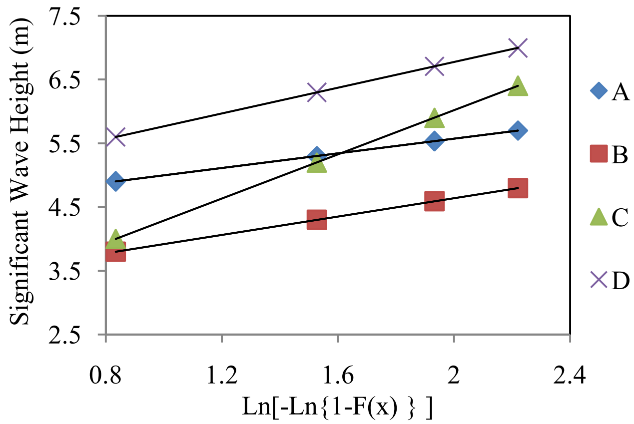

Fig: 1 Extrapolation of Hs based on Weibull Distribution

B Uncertainty Model for Load

The wave height H used in load model uncertainty is varying according to Weibull distribution, scale and shape parameters as shown in (2). These platform specific parameters from each region are used to find the probability of failure at design load

$$L = A_i * c_1 * (H + c_2 * u)^{c_3} \quad (2)$$

Where c_1 , c_2, c_3 are factors taken from curve fitting, H is variable wave height with respect to particular platform, u is the current speed and A_i is load model uncertainty factor.

C Uncertainty Model for Resistance

The actual design load i.e. design maximum wave height for each platform along with actual strength of structure gives us the Resistance model uncertainty, (3):

$$R = B_i * RSR * c_1 * (H_d + c_2 * u)^{c3} \quad (3)$$

$$Wheere \quad RSR = \frac{Q_u}{Q_d}$$

Q_u = First member failure load and Q_d=design 100 year environmental load

H_d is design wave height with respect to particular platform, B_i is resistance model uncertainty factor.

D Probability of failure

The platform will fail if the load effect exceeds the resistance of the member and structural failure is shown as,

$$P_f = P\,[g(x) \leq 0] \quad (4)$$

$$g = R - L \leq 0 \text{ or } g = \frac{R}{L} \leq 1 \quad (5)$$

Where, R = Resistance, L= load

Structural safety requires that, Required strength (Stress) > Design Strength (Loads), the failure probability is given by (6),

$$P_f = \frac{\text{Number of failures}}{\text{Total number of simulations}} \quad (6)$$

The Limit state function for finding the failure probability is shown by (7)

$$g = B_i * RSR * c_1 * (H_d + c_2 * u)^{c3} - A_i * c_1 * (H_d + c_2 * u)^{c3} \quad (7)$$

To find the probability of failure and reliability index 'Monte Carlo simulations method' is used [7]. The number of simulations used in this study is fixed at $1*10^7$. For each simulation there was new wave height and new model uncertainty factor for load and resistance.

E Bayesian Updating of Probability of failure against overloading of waves and damaged members

The jacket platform is overloaded with increase in wave height till an RSR value of 1 is reached and the corresponding wave is recorded. Now based on our experience acquired from this analysis we are confident enough that the platform will be safe against a corresponding wave height as shown in Figure 2. This new wave now will be used to find the survival probability of platform (P_s).

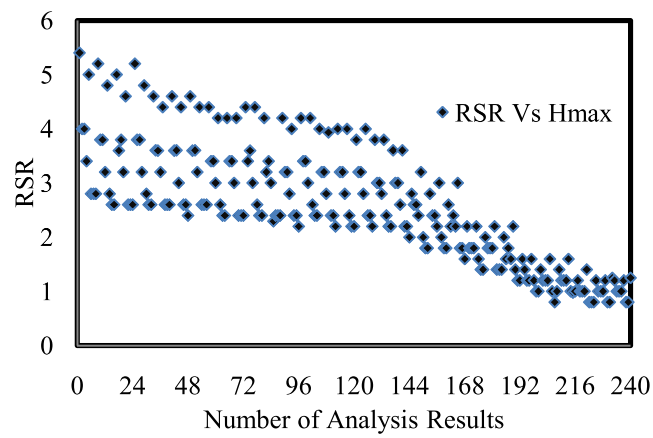

Fig: 2 Increase of wave height with different RSR values

Survival limit state function is given by (8),

$$g = B_i * RSR * c_1 * (H_d + c_2 * u)^{c3} - A_i * c_1 * (H_R + c_2 * u)^{c3} \quad (8)$$

H_R = Wave height when RSR is 1.0

$$P_s = \frac{\text{Number of survival}}{\text{Total number of simulations}} \quad (9)$$

When P_f is found given that Ps is also known then we can find the updated probability of failure based on (10-12)

$$P_{uf} = P(g < 0|S > 0) \quad (10)$$

P_{uf} = Updated Probability of failure,

$P(g < 0) =$ Probability of failure of limit state function,

$P(S > 0) =$ Probability of survival of limit state function

$$P_{uf} = \frac{P[g(x)<0 \cap S>0]}{P[S>0]} \quad (11)$$

$$P_{Uf} = P(g|S)P(S) \quad (12)$$

F Uncertainty model variability effects

Before probability of failure is found it is necessary to find the sensitivity of statistical properties of model uncertainty parameters. Load model and resistance model uncertainty parameters are given in Table 2. The resistance model uncertainty factors are taken from Efthymiou [10] i.e. mean is 1.0 and coefficient of variation (COV) is 0.1 and the values of COV used by Det Norske Veritas (DNV) are in range of 0.05-0.1. DNV gives conservative values and here Efthymiou' [10] recommended values are taken. For load model uncertainty Haver [10] has given COV of 0.15. The RSR value range considered is 1.5-2.25 which are reasonable values for in this region. The minimum RSR is recommended by ISO and API i.e. 1.6 as per API RP 2A WSD for high consequence platforms and 1.85 for ISO 19902 codes.

TABLE 2
FACTORS USED FOR LIMIT STATE EQUATION

Factor	Description	Value	Reference
A_i	Load model uncertainty	Normal distribution $\mu = 1.0$, $\sigma = 0.15$	[10]
B_i	Resistance model uncertainty	Normal distribution $\mu = 1.0$, $\sigma = 0.10$	[10]

V. RESULTS & DISCUSSION

Table 3 shows the RSR values achieved for this jacket in different directions. Our design should always be optimal therefore here our target was minimum RSR which was achieved in direction of 270 degrees. This direction was further analysed for further research for this jacket

TABLE 3
FACTORS USED FOR LIMIT STATE EQUATION

Direction	Type of Member Failure	Base Shear		RSR
		Collapse load	Design load	
0	L13	35162	8702	4.04
45	L13	42296.38	12818.31	3.30
90	LG6	39767.77	12428.01	3.20
135	LG6	39176.36	12243.33	3.20
180	L19	42919.1	8941.835	4.80
225	L19	34896.13	12463.53	2.80
270	XF1	34798.45	12428.34	2.80
315	L13	35380.36	12636.78	2.80

A. Uncertainty model load variability effects

Figure 3 shows the effect on uncertainty model for load that with resistance model uncertainty of 5% and 10% and RSR of 1.5 and 2.0. When RSR is 2 probability of failure is decreasing as compared to RSR of 1.5. The variability in load model uncertainty lies between 10% - 40%. The variability of probability of failure with RSR of 1.5 is 1×10^{-2} to 1×10^{-6} and with RSR of 2.0 this variability varies from 1×10^{-3} to 1×10^{-8}. Even with resistance model variability is kept constant at 10% the variability at RSR of 1.5 is between 1×10^{-2} to 1×10^{-4} and with RSR is 2.0 this variability reaches to 1×10^{-3} to 1×10^{-7}. Thus the effect of the parameters of reliability is big, and thus fixed target reliability is difficult to achieve for jacket platforms. This shows that reliability in offshore structures is based on personal judgment.

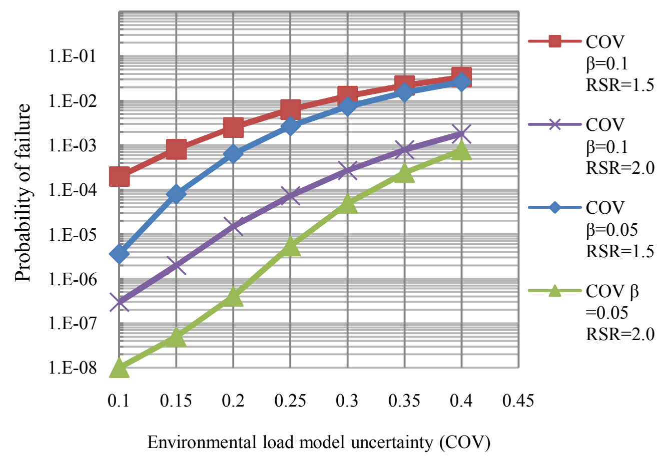

Fig.: 3 Effect of environmental load model uncertainty on resistance model uncertainty

B. Probability of failure and RSR sensitivity

Figure 4 shows the effect of RSR on probability of failure with load model uncertainty in range of 0.15-0.45. Figure shows that risk increases with reduction in RSR value i.e. probability of failure decreases sharply with increase of RSR. It shows that with RSR value of 2.5 the risk becomes extremely rare with probability of failure reaching up to 1×10^{-8} for COV of load of 0.15. In case of COV of 0.45, the probability of failure reaches up to 1×10^{-4} with RSR of 2.5. Here in this paper COV of 0.15 on load was used that is the reason an RSR value of 1.5-2.5 is considered safe for analysis. The bottom level of risk for overload on the jacket, due to wave load, has been taken as 1×10^{-5} which is considered safe for offshore structures. This results in minimum RSR in range of 2-2.5 depending on COV of load model uncertainty.

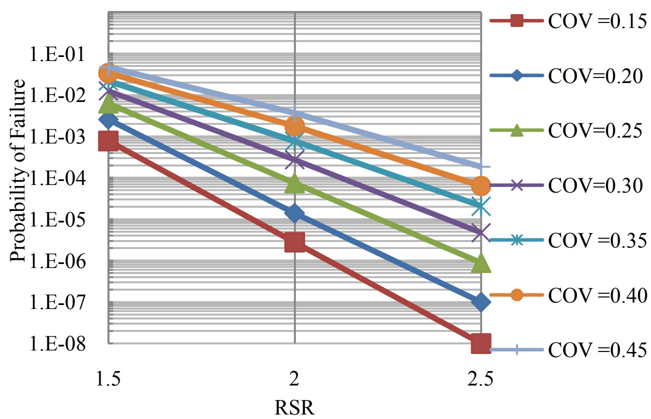

Fig.: 4 Effect of load model uncertainty on RSR of Jacket platform.

C. *Updating the probability of failure:*

The probability of failure was determined using an RSR value of 1.5 and 2. The Figure 5 shows that the probability of failure with design load of 7.7 m maximum wave height and at RSR of 1.5 was $1x10^{-3}$ but if the wave height reaches up to 10 m the probability of failure decreases, reaching up to $1x10^{-5}$. For RSR of 2.0, the design probability of failure decreases to $9x10^{-6}$ for design wave height but same reduces up to $6x10^{-6}$ if it reaches at wave height of 18m. The main advantage here is that the platform is considered safe against a wave of 10,000 year return period.

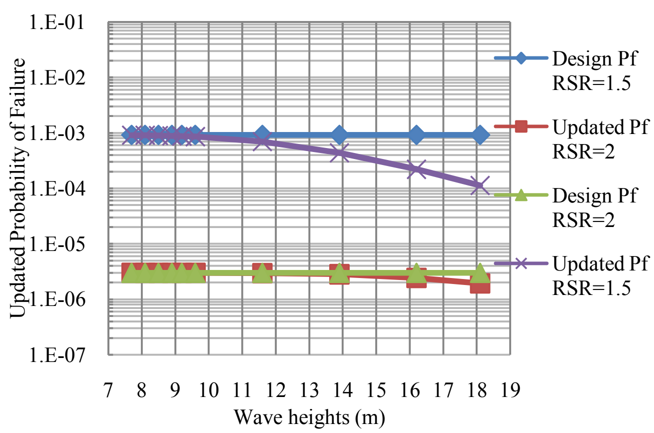

Fig. 5 Probability of failure and updated probability of failure

Figure 6 shows the effect of experienced waves on probability of failure. The Effect of variation of wave height on probability of failure is significant with variation of COV of load model uncertainty. Failure probability decreases with increase in wave height.

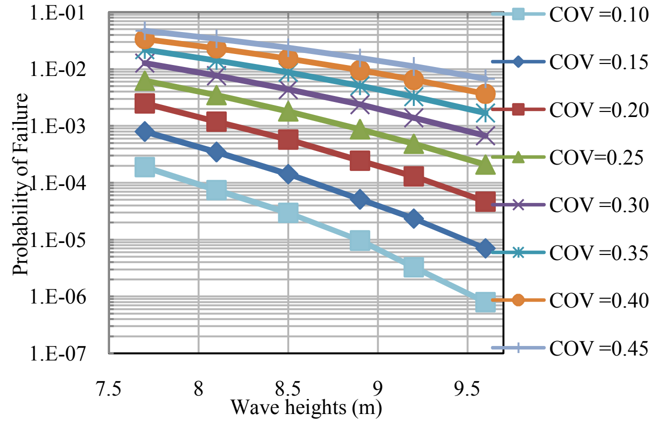

Fig.: 6 Effect of wave heights on load model uncertainty.

D. *Bayesian Updating of Probability of failure against damaged members:*

In case some jacket members fail their overall capacity of jacket was reduced as shown in Table 4. Damaged strength factor is determined from (13). The capacity was reduced about 50% in case of three member failures; therefore probability of failure was determined up to two member failures.

$$DSf = \frac{Q_f}{Q_e} \qquad (13)$$

Q_f= First member failure base shear in damaged state,
$Q_e =$ 100 year design load

TABLE 4:
CAPACITY REDUCTION OF DAMAGED MEMBERS

X-Brace	EL	CL	DSR	RCF	Capacity Reduction
intact	12637	35380	2.80	1.00	1
One member failure	12555	31387	2.50	0.89	0.89
Two member failure	12494	24987	2.00	0.80	0.71
Three member failure	12292	18439	1.50	0.75	0.54

This reduced capacity was used to find updated probability of failure as shown in Figures 7 - 8. The result shows that with experienced waves the probability of failure shows a decrease. When RSR is 1.5 the case of capacity reduction of 0.7 showed the probability of failure of $5x10^{-3}$. When RSR of 2, and capacity reduction of 0.9 shows a probability of failure of $7x10^{-4}$ and with capacity reduction of 0.7 the probability of failure reaches only up to $6x10^{-3}$ which is suitable for only 1000 year storm.

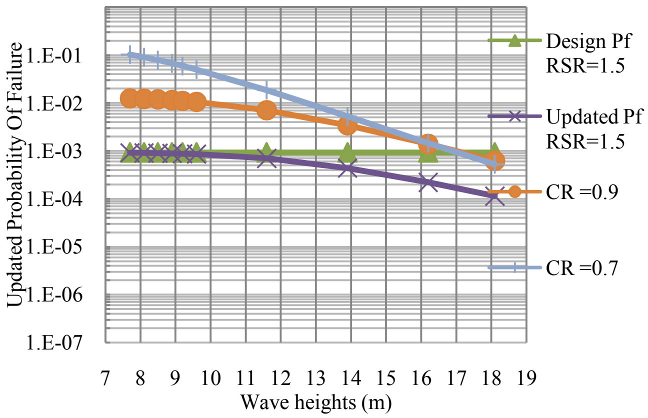

Figure: 7 Updated probability of failure with damaged members with RSR of 1.5

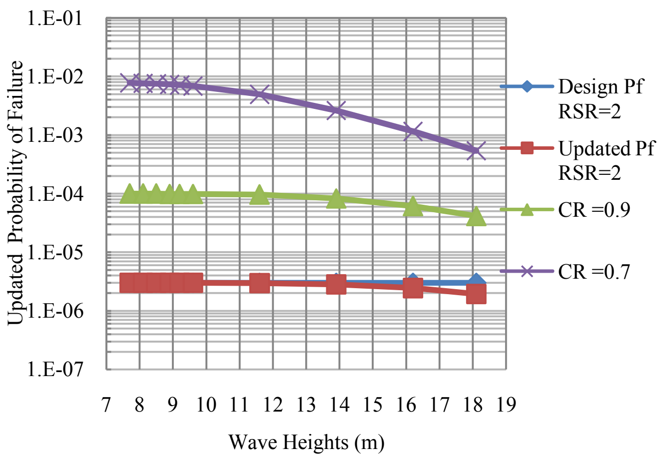

Figure: 8 Updated probability of failure with damaged members with RSR of 2.0

V. CONCLUSION

In this study maximum environmental load was found, which the jacket must endure, before significant changes occur in probability of failure of jacket. The paper uses 100 year design wave height first to find the probability of failure for jacket platforms in Malaysia. Then updated probability of failure was calculated based on the experienced wave heights. The lower bound value of RSR i.e. 1.5 and actual minimum values of RSR i.e. 2 were used to find the probability of failure.

The main conclusions are:

1. Minimum probability of failure achieved with design wave load at RSR of 1.5 was $1x10^{-3}$ which is not suitable as per ISO reassessment code requirement. The RSR value of 2, the probability of failure at design wave was less than $1x10^{-4}$.as desired by the codes.
2. When updated probability of failure was determined against RSR of 1.5, it reduced up to $9x10^{-4}$ which is required by ISO /API codes for life extension. For RSR of 2 it was it was already below 10^{-4} therefore safe for life extension. Thus platform life now can be extended even at RSR of 1.5.
3. In case of RSR of 1.5 and with damaged condition the updated probability of failure showed that member can survive only1000 year load.
4. In case of RSR is 2 and with one member failure the jacket can survive 10, 000 year load but with two member failures it can survive only a load with probability of failure of $6x10^{-3}$.

ACKNOWLEDGMENT

This work was supported by the UTP graduate assistantship scheme.

REFERENCES

[1] API-RP2A-LRFD, "*RP for Planning, Designing and Constructing Fixed Offshore Platforms – Load and Resistance Factor Design*," in American Petroleum Institute, ed, 2003.
[2] ISO19902, "*International Standard Organization 19902*," in International Standard Organization 19902, ed, 2007.
[3] Efthymiou, M and C. G. Graham, "Environmental Loading on Fixed Offshore Platforms," Society for Underwater Technology vol. 26, pp. 293-320, 1990..
[4] Ang, W. & Tang A, *Probability Concepts in Engineering* 2nd ed. vol. 1, ``````2007
[5] Nowak.A.S&Collins K. R., *Reliability of Structures*, 2000.
[6] Haldar, A. M. *Probability Reliability and Statistical Methods in Engineering Design*: John Wiley & Sons, 2000.
[7] Melchers.R.E, *Structural Reliability Analysis and Prediction*, Second ed.: John Wiley & Sons, 2002.
[8] Ditlevsen, H.O., *Structural Reliability Methods*, 2007.
[9] Bea R,, *"Developments in the assessment and requalification of offshore platforms*," presented at the OTC 7138, 1993.
[10] Ersdal J G., *"Updating of Structural Failure Probability Based on Experienced Wave Loading*," presented at the International Offshore and Polar Engineering Conference, Honolulu, Hawaii, USA, 2003.
[11] DNV2018, "*Guidelines for Offshore Structural Reliability Analysis-General, appendix B*."
[12] Faber, M. H. "*Basics of structural reliability* " 2002.
[13] Fatemeh J., Iervolino,L, Manfredi,G, "*Structural modeling uncertainties and their influence on seismic assessment of existing RC structures*," Structural Safety, vol. 32, pp. 220-228, 2010 2010.
[14] Enright, D.M "*Condition prediction of deteriorating concrete bridges using bayesian updating*," Journal of Structural Engineering, 1999.