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Reliability Based Assessment of Existing Fixed Offshore Platforms Located in the Persian Gulf

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ABSTRACT

This paper presents a detailed structural reliability procedure in order to achieve an acceptable safety margin for template type offshore platforms located in the Persian Gulf. Probability of failure in this study is calculated by considering the cumulative effects of all levels of wave loading during the lifetime of the structure and uncertainties associated with soil, material properties, connection strength and environmental conditions in the reliability analysis. For this purpose, the conditional probability of failures is computed for different levels of wave loading and then converted to the rate of failure by applying the total probability theorem. Annual explicit probability of failure is then computed by using probability distribution of wave heights in the Persian Gulf region. The calculated probability of failure is also compared with Reserve Strength Ratio of the platform considering different failure modes. The results show that RSR may not indicate a unique safety margin for assessing the existing platform in the Persian Gulf and carrying out a reliability analysis may help to overcome this deficiency.

1. Introduction

Occurrence of various expected and/or unexpected loading conditions, after completion of the fabrication/installation of an offshore platform may lead to assessment of existing structure. Modification and degradation of an existing platform or expiry of defined life time may change platform loading condition with respect to the design basis and therefore may reduce the strength of the platform against environmental loading acting on the structure. In order to evaluate the integrity of a platform under normal and extreme loading conditions, engineering analysis may be utilized similar to other types of existing structures. However, in the case of marine structures the assessment will be very challenging considering the number and variety of uncertain natural conditions, the high costs of removal of an existing platform and construction/installation of a new structure as well as consequences of interference in operation.

There are some guidelines for assessment of the existing platforms in different regulations and standards such as API RP 2A [1] and ISO 19902 [2]. Based on API RP 2A if one of the platform assessment initiators exists and also if the structure does not pass the requirements, two sequential analysis scenarios including Design level and Ultimate Strength level should be performed. The first scenario is a linear analysis and the second scenario is a non-linear analysis including component checks as integrated parts of the system. The acceptance criteria for the ultimate strength level are specified based on the ratio of the platform ultimate capacity to the design loading (usually 100 year wave loading), which is called Reserve Strength Ratio (RSR). Furthermore, some guidelines have been proposed in the API RP 2A for the assessment of the platforms through the use of explicit probabilities of failure when measured RSR of the platform does not meet the regulation values (procedural requirement). In ISO 19902 [2] there is a more detailed procedure including 5 analysis levels and 2 empirical methods which are similar to the API RP 2A recommendations except that a level has been proposed based on Structural Reliability Analysis.

It is important to note that although the structural reliability theory has made huge advances and considerable developments in recent years, however, its application for the assessment of offshore structures is still very limited.

2. Literature Review

Structural reliability analysis may be used to estimate the integrity of an existing structure based on a pushover analysis. This analysis is based on the assumption that there are several hidden potentials in

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a structural system like redundancy of structure and load redistribution following a component failure, which makes the structural strength capacity be enough to withstand the current loading condition. This topic has been the subject of comprehensive research during recent years. Lloyd & Clawson [3], Moan, Amdahl & Hellan [4], Stewart [5], Stewart, Moan, Amdahl & Eide [6], Stewart & Tromans [7], Hellan et al. [8], Amdahl et al. [9], Stear & Bea [10], Skallerud & Amdahl [11] are among those who investigated this subject. Also .DNV, SINTEF and BOMEL published the reports of the Ultiguide project [12, 13] in this respect.

In line with the progress of scientific knowledge during recent decades, some procedures and methods have been proposed by authors to assess structural safety and to perform reliability analysis of offshore platforms, which are presented hereafter.

Bea et al. [14, 15] proposed and verified a simplified analytical procedure for evaluation of probability of failure of fixed offshore platforms subjected to extreme storm conditions. In this procedure a platform can be considered as a combination of series of components and parallel elements. The series components are the superstructure (deck), the substructure (jacket), and the foundation (piles). Simplified formulations were developed to estimate the ultimate lateral shear capacity of the three primary structural components of a platform. The capacity of the platform is assumed to be reached when the capacity of any one of these components is reached. Within each component there are parallel elements. In order for a component to fail, all of its parallel elements must fail. The maximum static force acting on and also the capacities of platform elements and components are treated as functions of random variables.

Another method of reliability analysis of offshore structures has been established by Benjamin & Cornell [16]. They presented a procedure for calculation of structural probability of failure against seismic loading. Later considerable research was done in the area of application of this procedure to on-shore structures such as Cornell & Krawinkler [17], Cornell & Jalayer [18] and Moehle & Deierlein [19]. Inspired by what was presented in Ref 16, Manuel, Schmucker, Cornell & Cardallo [20] employed a procedure for probabilistic assessment of platforms under extreme wave loading. In this approach the probability of failure is estimated in terms of the structural capacity considering its uncertainty as determined from nonlinear static pushover analyses; and a probabilistic description of the external wave loads.

Another method, which is used in recent years, is the one proposed by Ersdal [21]. Ersdal proposed a simple probabilistic model including a relation between the RSR indicator and the annual failure rate for existing structures installed in the North Sea in shallow or intermediate water depth. In this study, wave load was calculated in terms of the annual maximum wave height with probability of exceedance equal to 10-2. The annual maximum wave height was also assumed to follow a Gumbel distribution. The ultimate capacity was assumed to be equal to the calculated wave loading multiplied by the RSR using the equation $UC = RSR \times \left(C_1 \times H_{100}{}^{C_3}\right)$ in which RSR is the Reseve Strength Ratio, $C_1 \times H_{100}{}^{C_3}$ is assumed to be the design loading. C1 and C3 are the load coefficients that have to be extracted from a curve fitted to the results of load calculation. Probability of failure is then estimated using Monte Carlo approach based on the total number of simulations and the number of samples falling into the failure domain. The relationship between the RSR versus annual probability of failure has also been established as $P_f = 10^{-0.0886-1.9976\times RSR}$. It is also important to note that there is some limitation in this study and some possible hazards like corrosion and pile related failure mode have not been included.

In recent years research has focused on the calculation of the probability of failure such as studies on seasonal storms in the Gulf of Mexico [22 & 23]. In these studies performance of fixed steel jacket platforms in Katrina and Rita has been assessed.

We will now focus on some research published during the past few years with respect to platforms in the Persian Gulf. Although Monte Carlo simulation technique provides a perfect and straightforward tool for performing the reliability analysis of systems, nevertheless this approach is time consuming and computationally expensive. Due to this fact, new methods have been proposed such as LHS [24] and SA [25], which are useful for reducing the required simulations in reliability analysis. Golafshani & Ebrahimian employed SA technique for analysis of fixed offshore platforms in the Persian Gulf considering seven variables in resistance and loading model [26 & 27]. This research proposed and compared two types of dynamic and static incremental wave analysis for calculation of ultimate strength of offshore structures.

Based on the above review of different reliability analysis methods for offshore platforms, in this paper it is tried to include all uncertainties which are important and effective in order to obtain a full probabilistic description of environmental loading and collapse behavior of the offshore platforms located in the Persian Gulf. The goal of probabilistic performance assessment of offshore jacket platforms in this research is quantifying the variability of structural collapse. This probabilistic description of response is required in order to estimate probabilities of failure.

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3. Proposed Evaluation procedure

The probability of failure is defined as the combination of all possible loading patterns. Using the total probability theorem the following expression can be employed for P_f as the probability of failure:

$$P_f = \sum_{all\ h} P[L-R>0 \mid H_{max}=h] \,.\, P[H_{max}=h] \qquad (1)$$

where the term $P[H_{max}=h]$ is the likelihood of a loading pattern which is a function of wave height, h. $P[L-R>0 \mid H_{max}=h]$ is also the probability of the loading effect being greater than structural resistance given $H_{max}=h$. The above mentioned equation can be re-written as follows:

$$P_f = P[L-R>0] = \int_{all\ h} P[L-R>0|H_{max}].f[H_{max}]\,.\,d_{H_{max}} \qquad (2)$$

In the above equation, $f[H_{max}]$ is the probability density function of maximum wave height, H_{max} as the indicator of selected wave loading pattern. The pattern of lateral forces is derived using applicable wave theory so that it simulates the pattern of shears that are expected during an extreme event. The load profile used is the one that results in the largest base shear in the most critical direction. Equation (2) can be re-written in the following format:

$$\begin{aligned}\lambda_f &= \nu.P[L-R>0] \\ &= \int_{all\ h} P[L-R>0|H_{max}].\nu.f[H_{max}].d_{H_{max}} \\ &= \int_{all\ h} P[L-R>0|H_{max}].\nu.\left|\frac{dF[H_{max}]}{d_{H_{max}}}\right|.d_{H_{max}} \\ &= \int_{all\ h} P[L-R>0|H_{max}].d\lambda_{H_{max}}\end{aligned} \qquad (3)$$

In the above expression, λ_f is the annual rate of failure, $F[H_{max}]$ is the cumulative probability density function (*CDF*) of maximum wave height. $\lambda_{H_{max}}$ denotes the wave hazard in terms of the mean annual frequency of exceedance of specific maximum wave heights and ν is the number of sea states in one year. $d\lambda_{H_{max}}$ is the differential of the mean annual frequency of exceeding a specific maximum wave height.

4. Geometric data and Environmental Condition

In this paper, the proposed procedure is applied to a four legged jacket platform located in the Persian Gulf where the mean water depth is 69.7 m. A 3D view of the platform model is shown in Figure 1. Jacket dimensions are 15.240m x 15.240m at working point

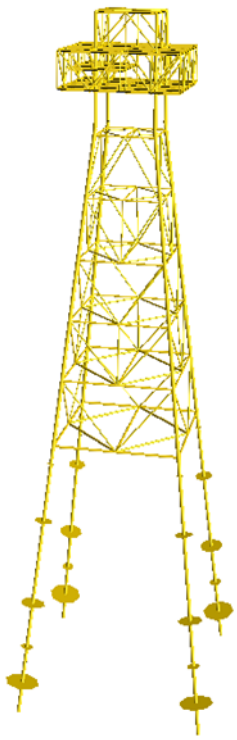

Figure 1. General 3D view of the selected platform model

elevation (El. +4.572) and 33.452m x 33.452m at mud line elevation. The main deck is 21.5 m above the mean water level. The legs diameter is 1.016 m and through the leg pile diameter is 0.9144 m and pile penetration is 64 m. Main framing members of the topside are included in the model. The appurtenances such as conductors and boat landings have not been included in the model. A Pile-Soil-Structure interaction using nonlinear simulation of soil elements is considered in the model.

The natural period of the selected platform is equal to 2.1 and therefore according to API RP 2A regulations, since the natural period of the structure is less than three seconds, a non-linear static pushover analysis has been utilized.

The environmental loads such as wave, current and wind loads are assumed to be acting simultaneously in a particular direction. The wave loading is modelled using the Stoke 5th order wave theory. Static Pushover analysis in this study has been performed using USFOS software.

USFOS 3D model has been generated using existing as-is drawings of the selected platform. Structural geometry data and dimensions have been incorporated in the 3D model based on the drawings and inspection results. Therefore the structural model is the same as designed platform but some changes such as thickness of members located in the splash zone and increasing the water depth in the location of installed jacket, have been considered in the model. Nevertheless the final model of the platform may obviously be different to as-is condition to same extent.

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4.1. The Software for Analysis of Ultimate Strength for Framed Offshore Structures (USFOS)

USFOS is a numerical tool for ultimate strength and progressive collapse analysis of space frame structures. The formulation includes nonlinear geometry and nonlinear material properties. The basic idea of the program is to use only one finite element per physical element of the structure, i.e. to use the same finite element discretization as in linear, elastic analysis.

This software uses an arc length iteration procedure with a special algorithm for passing load limit points or bifurcation points in nonlinear analysis.

Consequently, large structural systems can be modelled by means of a relatively small number of elements. The basic principle for implementation of buckling in USFOS is to represent each individual member in the structure by one finite element and providing an exact solution for the equation. Therefore USFOS can simulate column buckling including the influence of initial imperfections as well as material nonlinearities. Local buckling may also be accounted for in USFOS considering included strength formulation in USFOS.

Local flexibility of tubular joint is included in USFOS through a simplified, but very efficient formulation which provides very good results compared with shell analysis of the joint, but requires no special modelling of the joint geometry. The joint capacity check included in USFOS takes into the account simple tubular joint and is based on capacity formulas and description of the joint behaviour developed during the MSL Joint Industry Projects and also coves code variants from Norsok, ISO and API RP 2A.

Plasticity in USFOS is modelled using lumped plasticity and the nonlinear member behavior is simulated by incorporating plastic hinges at the ends and the mid-point of the member.

5. Distribution of Maximum Wave Height

Due to irregular nature of random sea waves and its effects on shape, height, period and kinematics of wave, the calculation of maximum wave height and corresponding wave period in each region is associated with numerous uncertainties. The long-term variation of wave climate can be described in terms of generic distributions or scatter diagrams for governing parameters of sea states, which are considered as Significant Wave Height, HS, and Mean Zero Up-crossing Period, Tz, for each direction. In this study the mean annual occurrence of significant wave height is extracted directly from meteocean data of the location of platform [28].

As recommended by DNV RP – C205 [29], the following equation can be used for evaluation of maximum wave height in a region.

$$\lambda_{H_{max}}(h) = \int_{h_s}\int_{t_z} \upsilon\, P[\{H_{max} > h | T_z = t_z, H_s = h_s\}] \times f_{T_z,H_s}(t_z,h_s).d_{t_z}d_{h_s} \quad (4)$$

where, $\lambda_{H_{max}}$ is the mean annual frequency of exceedance of the wave height, Hmax, and $f_{T_z,H_s}(t_z,h_s)$ is the joint probability density function of Tz and Hs , and υ is the number of sea state in one year. In this study the mean annual occurrence of significant wave height is extracted directly from meteocean data of the location of platform [28]. Based on the above equation and this data in Ref [30] the results for the location of platform in the Persian Gulf were presented. Figure 2 shows the in terms of log $\lambda_{H_{max}}$ and Hmax. According to Figure 2 from a probabilistic point of view, very high wave heights may occur in this area, however, with a very low probability of occurrence.

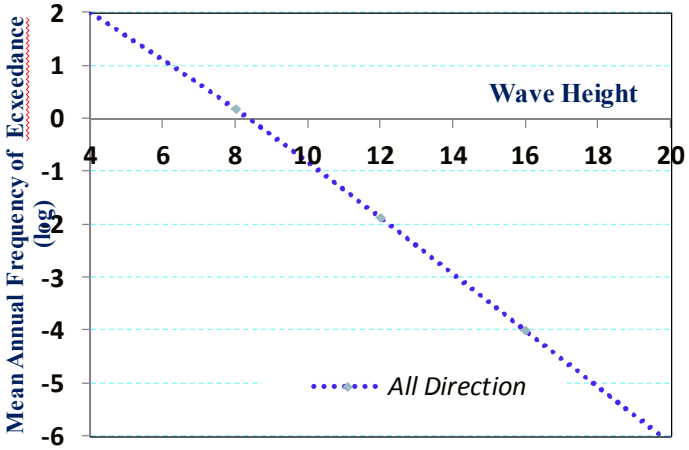

Figure 2. Wave hazard curve in the Persian Gulf

6. Uncertainty Consideration

Natural phenomena such as environmental loads, geometric model, and material properties have random nature and their values should be considered as random variables.

In the past, much effort has been spent in order to identify and assess the main random variables in the calculation of the probability of failure of a fixed offshore platform. In the present procedure of reliability-based evaluation, the effect of 23 random variables has been incorporated in the analysis. All expected random variables of the loading condition and resistance function are shown in Tables 1 & 2. Further description is presented hereafter about the selected variables.

- *Uncertainty in wave load coefficients*: Hydrodynamic coefficients, C_M and C_D, are sources of uncertainty in calculation of wave forces using Morrison equation.
- *Water depth uncertainty*: The results of instrumental bathymetry in the Persian Gulf

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Table 1. Selected random variables of loading condition

Random Variable		Mean	C.O.V	PDF	Ref
Drag Coefficient, C_D		1.05	0.2	LN	[1 & 32]
Inertia Coefficient, C_M		1.2	0.1	LN	[1 & 32]
Water Depth	(m)	69.7	.0072	LN	[33]
Current Speed	(m/s)	1	0.68	W	[34]
Marine Growth	(m)	0.0075	0.3	LN	[32]
Deck Weight	(t)	1730	0.1	N	[36]
Wave-in-Deck	(N)	*	0.35	LN	[35]
Wave Period corresponding to maximum wave height		**	**	LN	**

* : Refer to section 6.3.2
** : Refer to section 6.1

Table 2. Selected random variables of resistance of platform

Random Variable		Mean	C.O.V	PDF	Ref
Yield stress in legs	(kg/cm^2)	3400	0.1	LN	[37]
Yield stress in piles	(kg/cm^2)	3400	0.1	LN	[37]
Yield stress in braces	(kg/cm^2)	3400	0.1	LN	[37]
Corrosion allowance	(m/year)	0.0003	0.5	LN	[38 & 39]
Joint Connection No.1, 2, 3, 4, 5, 6		***	0.29	LN	[1]
Soil Capacity Factor in Layer No.1, 2, 3, 4, 5		****	0.25	N	****

*** : Refer to section 6.2
**** : Refer to section 6.3

show that in average 0.5m variation in sea depth measurements may be expected.

- *Current velocity* uncertainty: Probability distribution function of the surface current velocity generally follows a 2-parameter Weibull distribution. In the Persian Gulf area, it includes a scale factor $\lambda = 1.0$ and a shape parameter $\gamma = 1.5$ [33].
- *Marine growth uncertainty*: Marine growth is generally found in splash zone down to seabed. It increases the wave and current forces due to the increase of diameter of the structural members and their roughness.
- *Deck weight uncertainty*: The uncertainty in dead and live loads arises from different loading on the structure including rolling tolerances, fabrication aids, paint and fire protection, approximations in weight take-off, variation in fluid volumes and densities, drill pipe volumes, drill rig position, etc.
- *Wave in deck*: Small exceedance of the water level from the actual air gap can generate significant loads with considerable uncertainty on the platform deck and thereby has a major influence on risk and reliability. API approach has been used for calculation of Wave-In-Deck force in the current study. More details are presented in section 6.3.2.
- *Material strength uncertainty*: The physical properties which are considered in this research as the random variables are yield strength of jacket legs, jacket braces, and piles.
- *Corrosion uncertainty*: *The* corrosion allowance is deducted from the wall thickness of tubular member for calculation of stiffness and strength in the analyses. Mean corrosion allowance for members in the splash zone is equal to 0.3 mm/year in the Persian Gulf [37].

In order to use each of the random variables tabulated in Tables 1&2 in the paper and consider the combined effects of their uncertainties, we need to quantify the correlations between the variables. Generally the correlations are of two basic types:
(a) Correlations between parameters of a given element; and (b) Correlations between parameters of different elements. In the current research there is no correlation within an element; whereas the parameters influencing the wave force on the jacket platform as well as structural model random variables are perfectly correlated for different components. It is also assumed that parameters influencing modeling uncertainty are fully correlated for different elements. [31,39]. This assumption was done to reduce the number of random variables, and thus the computational time. On the other hand, the simplifying assumption of full correlation of modeling random variables between elements of different levels does not allow for the fact that partial correlation may cause one level to be weaker or less ductile than adjacent levels, thus causing the damage to concentrate unequally in that level. [39,40]

6.1. Wave period associated with maximum wave height

Wave periods associated with maximum wave heights are considered to lie in the range of 1.05 Tz – 1.4Tz of the associated sea states [41]. The results of research works have shown that for larger waves, the push-over capacity is almost independent of the applied wave height but it depends on wave period [42].

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According to the available statistical data of the Persian Gulf, a simple linear equation between $T_{H_{max}}$ and T_z may be assumed as follows:

$$T_{H_{max}} = 1.11 \times T_z \quad (5)$$

Based on this equation it may be concluded that $\mu_{T_{H_{max}}} = 1.11 \times \mu_{T_z}$ and $\sigma_{T_{H_{max}}} = 1.11 \times \sigma_{T_z}$. Therefore based on Ref 29 a lognormal conditional distribution could be found for $T_{H_{max}}$conditioned on H_s as:

$$f_{T_{H_{max}}|H_s}(t_z|h_s) = \frac{1}{\sqrt{2\pi}.\sigma_{\ln T_{H_{max}}}.t_{H_{max}}} \times \exp\left\{-\frac{1}{2}\left(\left(\ln t_{H_{max}} - \mu_{\ln T_{H_{max}}}\right)/\sigma_{\ln T_{H_{max}}}\right)^2\right\} \quad (6)$$

where, $\sigma_{\ln T_{H_{max}}}$ and $\mu_{\ln T_{H_{max}}}$ are standard deviation and mean of $T_{H_{max}}$, respectively.

6.2. Evaluation of Uncertainty in Connections

API RP 2A [1] is currently the most updated code with respect to joint capacity. The joint capacity formulae are as follows:

$$N_{Rd} = (f_y.T^2)/(FS.\sin\theta)Q_uQ_f$$
$$M_{Rd} = (f_y.T^2.d)/(FS.\sin\theta)Q_uQ_f \quad (7)$$

where N_{Rd} is the joint axial resistance, M_{Rd} is the joint bending moment resistance, f_y is the yield strength of the chord member at the joint, Q_u is the strength factor, Q_f is the chord action factor, T is the thickness of chord member, d is the diameter of brace and FS is the safety factor [43] used for design of connection which is equal to 1.0 in order to calculate the ultimate resistance of the tubular connections.

From Equation 7, it is obvious that there is a direct relation between joint capacity and fy. It means that if fy is changed, capacity of the joint will be changed accordingly. Therefore in order to take into account the uncertainty in joint capacity one may define fy as a random variable and assign the intended distribution to it.

In the commentary of API RP 2A [1], a complete collection of the joint data (K, Y and X) has been presented considering some comparisons of screened test data with the API and FE data, for the four brace load cases. The statistical properties of the data including the mean bias, COV, and number of cases (tests or FE) N are given in this reference. According to this reference, the COV for different load cases and joint classification vary between 0.06 and 0.29. Therefore in this work a COV equal to 0.29 has conservatively been assumed for fy of the chord in selected critical joints.

It must be mentioned that, COV equal to 0.1 in Table 2 for the uncertainty of fy as the yielding stress in the members (legs, braces and piles) are conceptually different from fy uncertainty equal to 0.29 in joints which are used for calculation of tubular joint capacity. It is also important to note that although selection of one value for all joint classifications is conservative but considering the limitation of existing software, it is the only practical way for consideration of the uncertainty of joint capacity in the reliability calculation.

6.2.1. Selection of critical joints

As illustrated in Figure 3, there are 48 joints in the platform selected for this study. It is obviously time consuming to consider all the joints as critical ones and to consider the uncertainty in their capacity. Therefore in order to avoid increasing the computational time, only critical connections have been selected. Critical connections are defined as tubular joints which have reached their ultimate capacity in a pushover analysis of the platform. This type of analysis has been carried out considering different cases of wave loadings and 6 joints have been selected as critical ones, which are shown in Figure 3.

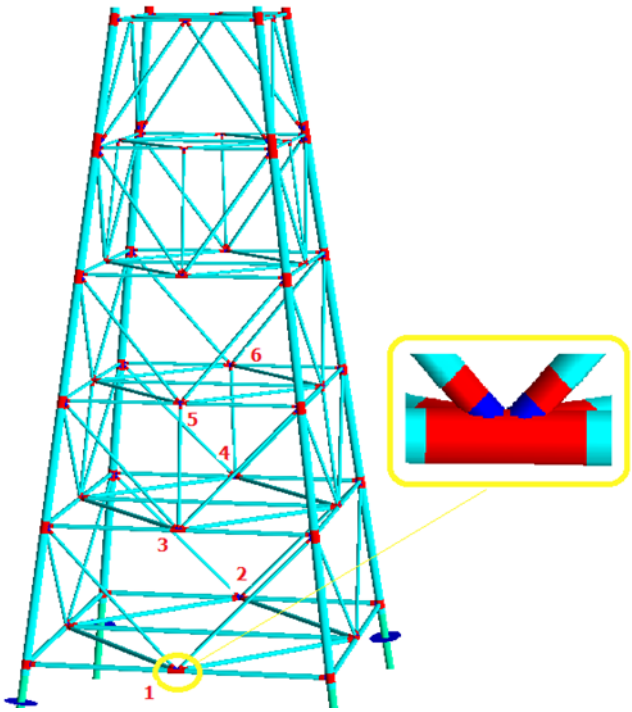

Figure 3. Joints selected as random variable for reliability analysis

6.3. Modeling of Soil Uncertainty

The statistical properties of the soil to be used in the reliability analysis are difficult to assess. In the current model the quantification of the model uncertainty, are based on Guideline for Offshore Structural Reliability Analysis, Survey of Expert Opinions and Case Studies [44].

In general, soils which surround the piles, exhibit non-linear behavior for both axial and transverse loads. Therefore, soils can be modeled using nonlinear

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curves, which represent the P-Y, T-Z and Q-Z data. They define the relationship between lateral load and deflection, soil axial resistance or end load bearing and axial deflection of pile respectively. These curves are developed using the geotechnical investigation report of the site, which included the basic parameters of soils such as different types of clay and sand in each layers, layer depths, submerged unit weight, undrained shear stress, end bearing factor and soil-pile friction angle.

Available geotechnical data in the site consists of a few bore holes in a distance of couple of hundred meters. These data have been used to identify the soil layers found to be five layers of clay and sand.

For clay characteristics, the random variables considered are the skin friction factor along the pile, the undrained shear strength and at times correction factors to account for specific effects, for example pile length or cyclic effects. In addition, the end bearing factor, which is used to calculate end bearing, is considered as a random variable.

For sands, the random variables considered include coefficient of lateral soil stress, soil-pile friction angle, skin friction, bearing capacity factor and end bearing. Parameters such as limit unit skin friction, limit unit end bearing and limit unit lateral pressure are assumed fixed.

The statistical properties of each basic parameters of soil in different layers have been established using the data of bore holes in geotechnical report. They are presented in Table 3.

In this research P-Y curves have been conservatively considered in cyclic case.

6.3.1. Uncertainty in axial, lateral and bearing resistance of soil

Using the mean of basic parameters of soil the mean of P-Y, T-Z and Q-Z curves in each soil layer is established. The uncertainty in these values is also estimated using a Monte Carlo Simulation Technique. Since the correlation between basic soils parameters are not known, simulations have been carried out under two cases of assumptions i.e. full correlation and no correlation between the parameters. Table 4 presents the results for both cases. As shown, COV of 0.17 to 0.25 have been obtained. But due to great uncertainty in soil parameters finally the maximum value equal to 0.25 has been selected as the uncertainty of soil resistance for both sand and clay in the probabilistic analysis.

6.3.2. Uncertainty in wave-in-deck force

As specified in Table 1, Wave-in-deck force has been calculated and applied based on API RP 2A section 17. In API approach the wave/current force on the deck, F_{dk} , is computed based on the projected area of the deck with calibration factors to account for the density of structure and equipment as :

Table 3. Statistical properties of basic parameter of soil

Soil Basic Parameters	Statistical Properties	layer 1	layer 2	layer 3	layer 4	layer 5
Soil Type of Layer		**Clay**	**Sand**	**Clay**	**Sand**	**Clay**
Thickness of Layer (m)	**Mean**	6.25	21.38	19.38	2.50	21.88
	C.O.V	0.046	0.012	0.013	0.05	0.011
Submerged Unit weight (KN/m^3)	**Mean**	6	8.50	8.50	9	9
	C.O.V	0.05	0.05	0.05	0.05	0.05
soil modulus of subgrade reaction (KN/m^3)	**Mean**	-	5500	-	16600	-
	C.O.V	-	0.05	-	0.05	-
Undrained Shear Stress [kPa]	**Mean**	4.25	-	53.75	-	212.5
	C.O.V	0.068	-	0.290	-	0.07
End Bearing Factor	**Mean**	-	11	-	12	-
	C.O.V	-	0.18	-	0.05	-
Soil-Pile Friction Angle [deg]	**Mean**	-	18.75	-	20	-
	C.O.V	-	0.13	-	0.05	-

Table 4. Calculation of COV for different types of soil

SAND	Total number of simulations	**C.O.V**
With Correlation:	1000000	**0.19**
Without correlation:	1000000	**0.17**

CLAY	Total number of simulations	**C.O.V**
With Correlation:	1000000	**0.25**
Without correlation:	1000000	**0.22**

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$$F_{dk} = {}^{1}/_{2} \cdot \rho \cdot C_d \cdot (\alpha_{wkf} \cdot U + \alpha_{cbf} \cdot U_c)^2 \cdot A \quad (8)$$

Where U is the maximum wave induced horizontal fluid velocity, U_c is the current velocity in-line with the wave, α_{wkf} is the wave kinematics factor (equal to 1.0), α_{cbf} is the current blockage factor (equal to 0.95) and ρ is the density of sea water (equal to 1025 kg/m3). The drag coefficient C_d depends on the amount of equipment on the deck as well as the wave direction, which is selected equal to 2.5 in this research. Parameter A is the part of the deck that is exposed to the wave hit .

In this work, RT software has been utilized for the simulations cases of reliability analysis. For modeling the probabilistic function of Wave-in-deck force, a mathematical formula has been considered for calculation of equation (8) including all the random variables in their mean value multiplied by a log-normally distributed function with a mean value of 1.0 and a COV of 0.35. For different cases of pushover analysis, C_d and U_c are in their mean value and U and A, have been calculated based on the wave height situation in the simulation case. Wave-in-deck calculation has been taken into the account for cases of H=13 to H=16 meters .

7. Calculation of Structural Probability of Failure

For calculation of failure probability of the selected platform in this research a numerical solution should be found for equation 3. Therefore the effects of three different ranges of wave heights including large, intermediate and small ones need to be considered. However it should be noted that in the case of large waves, probability of occurrence will be decreased and also in the case of small waves, conditional probability of structural failure will be reduced. Therefore in Equation 3 the effects of waves with intermediate heights are important. Hence, in this study, wave heights of 6 to 16 meters with 1 meter increment, have been selected for calculation of $P[L - R > 0 | H_{max}]$.

7.1. Results of the analysis

The primary objective of a reliability analysis with a limit-state function (g) is to determine the probability that the limit-state function will take negative outcomes. As described by Ditlevsen and Madsen [45] and Der Kiureghian [46], FORM algorithm includes a search for the "design point," which is the most likely realization of random variables associated with $g = 0$ in the space of standard normal variables. The FORM analysis is an appealing gradient-based reliability method because it requires only a handful of evaluations of g and $\partial g/\partial x$ to produce an accurate estimate.

For employing FORM algorithm in reliability analysis of the selected offshore platform, the RT software developed by Mahsuli & Haakus [47] is used. In order to verify the results of this method, initially the Importance Sampling Method is used to calculate the probability of failure for the 13 m wave height. The results as presented in Table.5, which show that FORM algorithm can provide reasonable results and also reduce computational time considerably.

Having calculated the conditional probability of failure for waves of different height, structural rate of failure is calculated by a summation of products of conditional probability of failure and rate of occurrence of the wave heights. Table 6 presents the results of this analysis for the selected platform, which shows that the annual probability of failure is 0.0304.

8. Reserve Strength Ratio of the platform

In API RP 2A [1], the acceptance criteria for the ultimate strength level are specified based on the ratio of the platform ultimate capacity to the design loading (usually 100 year wave loading), which is called Reserve Strength Ratio (RSR). So after carrying out the reliability analysis, the ultimate strength of the platform is also determined using the conventional static push over analysis based on the lateral loading pattern obtained from application of the design wave to the platform. It should also be noted that for this platform a 100 year design wave, which is equal to 12.2m, had been considered.

Figure 4 shows the deformed shape of the platform at final stages of the push over. It is observed that reaching the ultimate capacity of joints 1 & 2 at mudmat level and yielding of piles at the location of connection to the end of legs, dominate the global capacity of the structure. Figure 5 also shows the base shear versus deck displacement. Thus the base shear capacity is estimated to be 5.2 MN. Based on this figure, the RSR, which is the ratio of ultimate strength to design wave loading is found to be 1.77. Based on the assessment criteria, mentioned in API RP 2A, the selected platform for the current study is classified as the level L-1 platforms and therefore the acceptable RSR is equal to or greater than 1.6. It means that the platform passes the assessment requirement of API RP 2A.

Table 5. Verification of the calculations of conditional probability of failure

Case	Technique	Conditional Probability of Failure	Number of simulation	Time (hours)
H_{max} = 13 m	FORM	0.126985	376	22
	SAMPLING	0.130364	5000	384

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Table 6. Calculation of the annual probability of failure

i	h_{max}	$P(failure\|h_{max})$	Annual $\Delta\lambda_i$	$\lambda_{(failure)} = \sum P(failure \mid h_{max}) \times \Delta\lambda_i$
1	6	*0.00021074*	15.175504	0.003198
2	7	*0.00119039*	5.347666	0.006366
3	8	*0.002833*	1.814519	0.005141
4	9	*0.0121264*	0.593063	0.007192
5	10	*0.019866*	0.187217	0.003719
6	11	*0.0454222*	0.057572	0.0026151
7	**12**	***0.058022***	**0.017353**	**0.0010069**
8	13	*0.126985*	0.005154	0.0006544
9	14	*0.20469*	0.001515	0.0003101
10	15	*0.379546*	0.000443	0.0001680
11	16	*0.393998*	0.000129	0.0000508
				0.0304

However, as presented in Table.6, the annual probability of failure of this platform is equal to 0.0304. This is equivalent to a reliability index ß=1.87., which cannot be considered acceptable [48].
Considering the above results, it seems that the criteria of API RP 2A regulations need to be modified for application to the sites such as the Persian Gulf. In fact it is much preferred to use a concept such as safety index instead of RSR for assessing fixed offshore platforms.
However there are a few influential factors about calculation of probability of failure in the current research, which need to be mentioned:

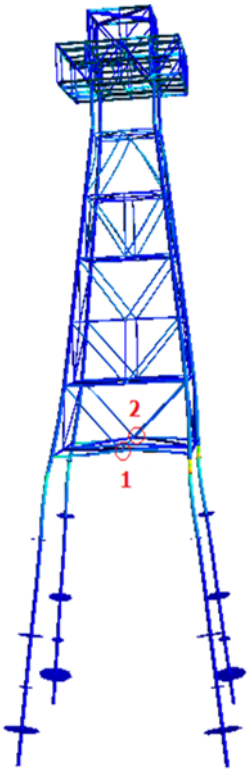

Figure 4. 3D view of the deformed shape of platform

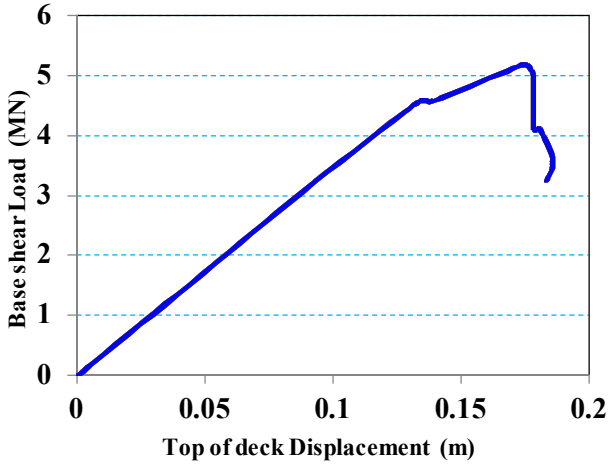

Figure 5. Pushover curve

- As presented in the paper, the structural rate of failure is calculated by a summation of products of conditional probability of failure and rate of occurrence of the wave heights (wave hazard in terms of the mean annual frequency of exceedance of specific maximum wave heights). Calculation of wave hazard (presented in Figure 2 of the paper) is highly dependent on the available statistical data. Since the available data has been produced many years ago and has not been changed/modified through recent 20 years, they may be incomplete or inaccurate to some extent. Therefore some believe/indicate that these data are highly overestimate the real condition of the Persian Gulf. Therefore it can be said that the relatively high values of wave height considered in these calculations might have had a strong impact on the resulted high probability of failure.
- As it would be discussed in section 9.4, the first three important variables affecting the reliability analysis are Wave-in-deck, Current velocity and Drag coefficient, respectively. In all simulation

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cases including wave-in-deck force, as seen in third column of Table 6, failure of the platform is inevitable. In other cases, current velocity has the most important role in the probability of failure and as seen in Table 2, its coefficient of variation is equal to 0.68. It is clear that dispersion and also the effect of this variable is very much. Certainly this needs further research.

- It must be emphasized that, in the current research, an increase equal to 2 meters has been considered in the water depth with respect to design condition of original platform. This has obviously increased the probability of wave in deck forces and consequently failure quite significantly.

9. Probability of Failure versus RSR Ratio

RSR can conceptually consider as a criteria in order to create an adequate safety margin for offshore structure if it is possible to provide a meaningful relationship between RSR and the structural probability of failure. Therefore a part of this research effort has been devoted to establish such a relationship for the sample platform located in the Persian Gulf.

9.1. Overall failure modes in the selected platform

As briefly stated in section 2, Bea et al. [14,15] using actual field experience and numerical results from three-dimensional nonlinear analyses, which were performed on a large number of jacket type offshore platforms, indicated that in most cases, overall failure modes governing the ultimate capacity of these structures can be classified as follows:

- *Deck leg failure: Plastic hinge formation in the deck legs and subsequent collapse of the deck portal.*
- *Jacket members failure: Consecutive buckling, yielding or overloading of jacket members and connections.*
- *Pile yielding: Lateral failure of the foundation piles at mudline elevation due to plastic hinge formation in the piles.*
- *Pile length: Pile pullout or pile plunging due to exceedance of axial pile and soil capacities.*

Considering the above mentioned classification, a comprehensive reliability analysis has been carried out to estimate the structural failure probability of each overall failure mode for the platform under study.

9.2. Calculation of Reserve Strength Ratio for each overall failure mode

According to what presented in first section about the calculation of RSR, in this section it is tried to create structures, which possess different values of RSRs for all introduced overall failure modes of the selected platform. For this purpose, some several increase and decrease have been considered in the yielding strength and thickness of some structural members in deck legs, jacket members, piles thickness/length and overall soil resistance. Therefore, by applying these changes in the original structural model and performing pushover analysis, RSR values for the modified platform have been calculated as presented in Table 7.

As shown in Table 7, different RSR cases have been reported for each overall failure mode, except in the first row, which is concerned with deck leg failure mode and only one case has been considered. The reason is that this mode may occur due to wave in deck forces and this condition rarely happens for such platforms located in the Persian Gulf.

9.3. Estimation of failure probability of each overall failure mode

In order to calculate the probability of failure for all different cases of overall failure modes presented in Table 7, detailed calculation similar to what presented in - Table 6, have been performed for each case. The results of the reliability analyses in terms of potential failure modes have been presented in Table 8.

Table 7. Calculation of Reserve Strength Ratio for different overall failure modes

Overall Failure	RSR_1	RSR_2	RSR_3	RSR_4	RSR_5
Deck leg failure	-	-	1.5	-	-
Jacket members failure	2.074	*1.81*	1.6	1.4	1.2
Pile yielding	2.22	*1.8*	1.6	1.5	1.2
Pile length	2.035	-	-	*1.45*	1.1

Table 8. Calculation of the annual probability of failure for different overall failure modes

Overall Failure Mode	P_{f1}	P_{f2}	P_{f3}	P_{f4}	P_{f5}
Deck leg failure mode	-	-	0.0486	-	-
Jacket members failure mode	0.0047	0.0141	0.2263	0.3047	0.3791
Pile yielding failure mode	0.0058	0.0188	0.1974	0.2929	0.4863
Pile length failure mode	0.0057	-	-	0.0672	0.4091

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Table 9. Proposed fitted curves for different overall failure modes

Overall Failure Mode	Proposed Equation	A	B	C
Jacket members failure mode	$P_f = A \times e^{-(\frac{RSR-B}{C})^2}$	0.3772	1.250	0.4092
Pile yielding failure mode	$P_f = A \times e^{-(\frac{RSR-B}{C})^2}$	0.5025	1.262	0.3340
Pile length failure mode	$P_f = A \times e^{-B \times RSR}$	117.7	5.147	-

Table 10. Calculation of RSR considering proposed value for probability of failure

Overall Failure Mode	P_f	RSR
Jacket members failure mode	0.00135	2.22
Pile yielding failure mode		2.07
Pile length failure mode		2.21

Now, by considering calculated values of annual probability of failure from Table 8 for the relevant RSR presented in Table 7, the relationship depicted in Figure 6 can be established.

Table 9 show the mathematical relationship between RSR and probability of failure for three possible overall failure modes of selected template-type offshore platforms installed in the Persian Gulf condition.

As seen in Figure 6, all the shown curves have the same trend of decreasing for Pf value near RSR ≈ 2. However according to consideration of an acceptable value for safety index, it is easily understood that by considering the desired amount of annual probability of failure, the required RSR may be obtained from the equation. As an example, if an annual probability of Pf = 0.00135 (ß=3) is regarded as a reasonable assessment criterion, the RSR should be as presented in Table 10.

Therefore it may be said that the mentioned procedure can provide a much more realistic and accurate RSR for the Persian Gulf area instead of the current criteria of RSR>1.6 mentioned in the API RP 2A, which has been calibrated for other areas.

9.4. Sensitivity analysis

A sensitivity investigation has been done for the 23 random variables involved in the limit state function. According to sensitivity studies, the influencing random variables are in the following order:

- Wave-in-deck
- Current velocity
- Drag coefficient
- Yield stress in jacket members

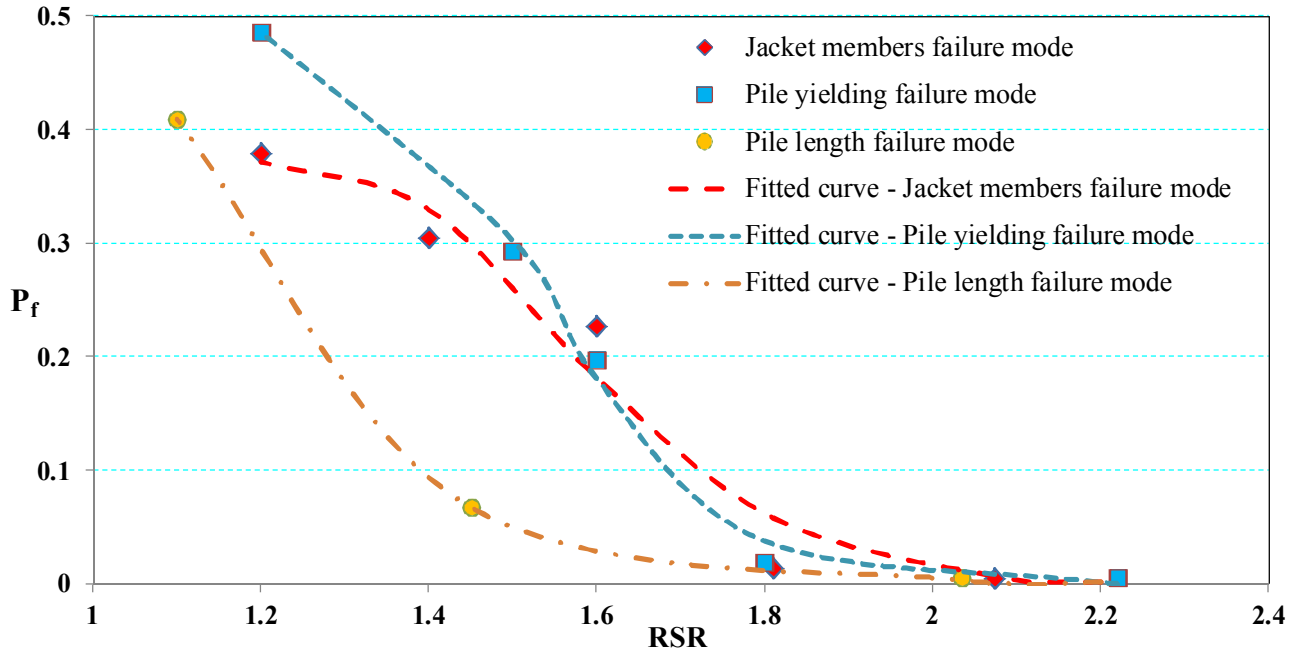

Figure 6. Presentation of the annual probability of failures for different values of RSRs

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- Wave period associated with maximum wave height
- Soil uncertainty in the first layer
- Marine growth
- Uncertainty in water depth
- Yield stress in jacket legs
- Corrosion uncertainty in splash zone
- Inertia coefficient
- Uncertainty in the weight of deck
- Uncertainty in the capacity of joints
- Yield Stress in jacket piles
- Uncertainty in the second, third, fourth & fifth layers of soil

The sensitivity studies show that the safety margin of the platform is strongly dependent on the drag components of the flow induced forces. Also the safety index is least sensitive to soil uncertainties in layers 2 to 5.

10. Conclusion

In this paper, a new algorithm for determining the probability of failure of jacket type offshore platforms is presented. The presented procedure is capable of calculating the probability of failure during the lifetime of platform considering all extreme wave loading patterns. Furthermore, it is possible to take into account the uncertainty of all affecting parameters such as connections, soil capacity, wave-in-deck, corrosion, wave period associated to maximum wave height, material yield strength. Besides, wave hazard curve for the Persian Gulf has been used to estimate the probability of failure for a sample four legged platform, which is found to be higher than what can be expected if the Reserve Strength Ratio, RSR, criteria were to be considered.

By changing the mechanical properties of the sample platform, different modes of failure have been simulated in the structure. RSR as well as probability of failure has been for all cases using the procedure presented this paper. The results show that the probability of failure for a given value of RSR depends on failure mode. Also for the RSR values recommended in API RP 2A as being acceptable, the probability of failure is higher than what is normally accepted in Reliability based codes of practice. Therefore assessment of existing platforms based on RSR may not lead to the desired level of safety and a more sophisticated analysis may be required for this purpose.

Nevertheless the probability of failure calculated in this research for a sample platform seems to be too high. As discussed in section 8 the following parameters might have had contributed to this high value.

- The wave hazard curve obtained from the existing data might have been too conservative.
- In this work, an increase equal to 2 meters has been considered in the water depth with respect to design condition of original platform. This might have caused large wave-in-deck forces for large waves, which have significant effects on failure of the platform.

So in conclusion, although the absolute figure of probability of failure calculated in this paper is obviously dependent on the assumptions made, the methodology and trends of results are quite indicative and further research are required to find more accurate figure for random variables so that more accurate probability failure may be calculated.

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References

1. American Petroleum Institute, (2010), *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms-Working Stress Design, API-RP-2A.*, Washington D.C. 21st Edition.
2. International Organization for Standardization, (2010), *ISO/DIS 13822 Bases for design of structures – Assessment of existing structures,*
3. Lloyd J R and Clawson W C., (1984), *Reserve and Residual Strength of Pile Founded Offshore Platforms. The Role Design, Inspection and Redundancy in Marine Structural Reliability*, Natural Research Council, National Academy Press. Washington DC.
4. Moan T, Amdahl J, Granli T & Hellan, (1991), *Collapse Behaviour of Offshore Structural Systems.*, 2nd Int. Conf. on Advances in Marine Structures. Dunfermline. Scotland. 21-24 May,
5. Stewart G., (1992), *Non-Linear Structural Dynamics by the Pseudo-force influence method, Part II: Application to Offshore Platform Collapse.*, Proc. Second Internal Offshore and polar Engineering Conference (ISOPE). San Francisco. USA.
6. Stewart G, Moan T, Amdahl J, and Eide O I., (1993), *Nonlinear re-assessment of jacket structures under extreme storm cyclic loading: Part I - philosophy and acceptance criteria.*, In Proceedings of the 12th International Conference on Offshore Mechanics and Arctic Engineering (OMAE). Glasgow. Scotland.
7. Stewart G, and Tromans P S., (1993), *Nonlinear re-assessment of jacket structures under extreme storm cyclic loading: Part II - representative environmental load histories.*, In Proceedings of the 12th International Conference on Offshore

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Mechanics and Arctic Engineering (OMAE). Glasgow. Scotland.
8. Hellan O, Moan T and Drange S O., (1994), *Use of nonlinear pushover analyses in ultimate limit state design and integrity assessment of jacket structures*., In Proceedings of the 7th International Conference on the Behavior of Offshore Structures (BOSS). Cambridge. Massachusetts. USA.
9. Amdahl J, Skallerud B H, Eide O I, and Johansen A., (1995), *Recent developments in reassessment of jacket structures under extreme storm cyclic loading, part II: Cyclic capacity of tubular members*., In Proceedings of the 14th International Conference on Offshore Mechanics and Arctic Engineering (OMAE). Copenhagen. Denmark.
10. Stear J D, and Bea R G., (1996), *Using Static Pushover Analysis To Determine The Ultimate Limit States of Gulf Of Mexico Steel Template Type Platforms Subjected to Hurricane Wind and Wave Loads*., University of California at Berkeley. Report to U.S.Minerals Management Service and Industry Project Sponsors.
11. Skallerud B, and Amdahl J., (2002), *Nonlinear analysis of offshore structures*, Research studies Press Ltd. Bldock. Hertfordshire. England.
12. DNV and SINTEF, (1998), *ULTIGUIDE Phase 2: Evaluation Report on Dynamic Effects*. Det Norske Veritas. Norway. Sep.
13. DNV, (1999), *ULTIGUIDE–Best practice guideline for use of non-linear analysis methods in documentation of ultimate limit states for jacket type offshore structures*. Det Norske Veritas, Hovik, Norway.
14. Bea R G, and Mortazavi M., (1992), *Experimental Validation of the ULSLEA with Results from Frame Tests*. 7th International Offshore and polar Engineering Conference. Honolulu. Hawaii. May
15. Mortazavi M., (1996), *A Probabilistic Screening Methodology for Use in Assessment and Requalification of Steel, Template-Type Offshore Platforms*, Ph.D. Thesis. Department of Civil Engineering. University of California at Berkeley. CA. January
16. Benjamin J R & Cornell C A. (1970), *Probability, Statistics and Decision for Civil Engineers*. McGraw-Hill.
17. Cornell C A, & Krawinkler H., (2000), *Progress and challenges in seismic performance assessment*. PEER Center News, 3(2).
18. Jalayer F, (2003), *Direct Probabilistic Analysis: Implementing non-linear dynamic assessments*, Stanford University, PhD Thesis, CA, 244
19. Moehle J P and Deierlein G G., (2004), *A framework methodology for performance based earthquake engineering*, Proceedings of the 13th World Conference on Earthquake Engineering. Vancouver. Canada.
20. Manuel L, Schmucker D G, Cornell C A and Carballo J C. (1998), *A reliability-based design format for jacket platforms under wave loads*. Marine Structures Vol. 11; 413-428.
21. Ersdal E, (2005), *Assessment of existing offshore structures for life extension*, PhD Thesis, University of Stavenger. Department of Mechanical and Structural Engineering and Material Science. Stavanger
22. Energo Engineering Inc., (2006), *Assessment of Fixed Offshore Platform Performance in Hurricanes Andrew*, *Lili and Ivan*. Prepared for: U.S. Department of the Interior Mineral Management Service. Engineering and Research Branch January
23. Energo Engineering Inc., (2007), *Assessment of Fixed Offshore Platform Performance in Hurricanes Andrew, Katrina and Rita*. Prepared for: U.S. Department of the Interior Mineral Management Service. Engineering and Research Branch. May
24. Helton J C and Davis F J., (2002), *Illustration of sampling-based methods for uncertainty and sensitivity analysis*. Risk Anal 22, p 591-622;
25. Vorechovsky M and Novak D., (2009), *Correlation control in small-sample Monte Carlo type simulations I: A Simulated Annealing Approach*. Probabilistic Engineering Mechanics. 24(3), p 452-462;
26. Golafshani A A, Bagheri, and Ebrahimian., (2010), *South Pars Phase 1 - SPD2 Platform Probabilistic and Reliability Assessment for Extreme Wave Loading*, Sharif University of Technology. Tehran. Scientific Research Prepared for NIOC.
27. Golafshani A A, Bagheri and Ebrahimian. (2010), *Assessment of Existing Offshore Platforms in Persian Gulf for Service Life Extension or Operative Conditions*, Sharif University of Technology. Tehran. Scientific Research Prepared for NIOC,
28. Glenn Report. (1997), *Report on Meteo-Oceanographic conditions affecting design and operation*. South-Pars phase 1 offshore complex.
29. Recommended Practice DNV-RP-C205, (2010), *Environmental Conditions and Environmental Loads*. October
30. Aghakouchak A. A, & Fayazi A. R, (2014), *Calculation of probable extreme wave height during life time of offshore platforms in the Persian Gulf*, Journal of Marine Engineering, V. 18, P.83-91, (In Persian)
31. JCSS, (2006), *Probabilistic Model Code — Part 1: Basis of Design* (12th draft), Joint Committee on Structural Safety. Available from: http://www.jcss.ethz.ch/.

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32. South Pars Project Document. (2005), *Structural Design Basis & Design Brief*.
33. Meng W. and Joses Y., (2012), *Localization of Surface or Near-Surface Drifting Mines for Unmanned Systems in the Persian Gulf*. Naval Postgraduate School Monterey, California, June
34. Health & Safety Executive., (1998), *Review of wave in deck load assessment procedure,* BOMEL Report No. C681\04\040R Revision C. Offshore Technology Report - OTO 97 073. February
35. Health & Safety Executive, (2003), *System-based calibration of North West European annex environmental load factors for the ISO fixed steel offshore structure,s code 19902*. BOMEL Research Report 087.
36. JCSS., (2001), *Probabilistic Model Code — Part II: Resistance Models*, Joint Committee on Structural Safety. Available from: http://www.jcss.ethz.ch/.
37. Iranian Ports & Maritime Organization. (2013), *Iranian Offshore Structural Design Procedure*. Available from: http://coastseng.pmo.ir. (In Persian)
38. Houyoux C, Alberts D and Heeling A., (2007), *Design method for steel structures in marine environment including the corrosion behavior,* Final report, European Commission, Technical Steel Research.
39. Golafshani A A, Ebrahimian H., Holmas T. and Bagheri V. (2011), *Incremental wave analysis and its application to performance-based assessment of jacket platforms*, Journal of Constructional Steel Research. ,vol 67, 1649-1657
40. Golafshani A A, Ebrahimian H. and Holmas T. (2013), *Assessment of offshore platforms under extreme waves by probabilistic incremental wave analysis*, Journal of Constructional Steel Research , vol 67, P 759-769.
41. Jeom Kee Paik, Anil Kumar Thayamballi,(2011), *Ship-Shaped Offshore Installations: Design, Building, and Operation*, Pusan National University. Korea. isbn: 9780521187886. Published: July
42. Singurdsson G and Cramer E., (1995), *Guideline for Offshore Structural Reliability Analysis – Examples for Jacket Platforms*, DNV Report 95-3204.
43. USFOS Version 8-6, (2011), *USFOS Joint Capacity*. Documentation
44. DNV, (1995), *Guideline for Offshore Structural Reliability Analysis – General*, Report No.2018-95, January.
45. Ditlevsen O and Madsen H O, (2007), *Reliability-based Structural Design,* Coastal, Maritime and Structural Engineering Department OF Mechanical Engineering Technical University of Denmark.
46. Der Kiureghian A, (2005), *First- and second-order reliability methods, Chapter 14 in Engineering design reliability handbook*, Nikolaidis E, Ghiocel D M, Singhal S. CRC Press. Boca Raton. FL.
47. Mahsuli M, (2012), *Probabilistic Models, Methods, and Software for Evaluating Risk to Civil Infrastructure*. PhD Thesis. University of British Colombia.
48. Health & Safety Executive., (2002), *Target levels for reliability-based assessment of offshore structures during design and operation,* Prepared by Aker Offshore Partner AS. Offshore Technology Report No. 1999/060. Norway.

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