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Probability of Failure for Fixed Offshore Structures Determination: An Analysis of a Braced Monopod and 4-Legged Platforms with Respect to Industry Standards

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Abstract

The structural integrity is susceptible to a combination of statistical and engineering design uncertainties that may remain flexible as long as the structure can successfully manage the encountered load. There are many methods for determining the probability of failure (POF) in the oil and gas sector, but they all have particular constraints. Therefore, this study is a quantitative risk assessment to establish a more reliable method for calculating the POF value. This study chose and evaluated a sample of a braced monopod and 4 legged offshore structures for global non-linear analysis. The most reliable form of distribution was predetermined, and the appropriate integral equation was applied and computed based on the load and strength model conditions. The result of the testing of stress-strength interference for 12 directions and for 8 directions of wave impact in POF indicated that the platform remained intact and reliable compared to the L2 exposure level for the reliability target of POF recommended by ISO 19902, ISO 19901, and PETRONAS. Furthermore, this established that the applied integral equation provided a high degree of confidence in calculating the new POF. This newly created approach will enable the structural engineer to outline action items as part of the organisation's risk management process.

Keywords: Probability of failure; Structural integrity; Nonlinear; Stress-strength interference method

1. Introduction

The oil and gas industry players are always looking for the opportunity to optimise brownfield's economics, making juggling between cost, safe operation, and demand to increase production from existing facilities more challenging (Animah et al., 2018; Palkar & Markeset, 2011; Wehunt et al., 2003). Therefore, there is a need to continuously ascertain the ongoing reliability of these ageing platforms. The reliability of a system is an analytical problem that involves both statistical and engineering aspects (Gnedenko et al., 1999; Negra et al., 2007; Trivedi & Bobbio, 2017). Critical attention must be given throughout the life of a system, including its development, design, production, quality control, shipping, installation, operation, and maintenance (Mat Soom et al., 2015; Rao, 1992). Reliability engineering has become a common practice in the Malaysian oil and gas industry to assess structural integrity and requalification for the life extension of an offshore platform (Chandrasekaran, 2017; Faber & Stewart, 2003).

In general, an existing structure's appropriate safety may be assured by demanding adherence to the most recent rules and regulations (Shittu et al., 2020). However, it is not clear how to comply with ageing structures in terms of extended life. Specifically, detailing further fatigue for structures surpassing its initial fatigue design life (Veritas & Lloyd, 2010), while no cracks have been discovered as an example, which is not achievable utilising the design standards (Ribeiro et al., 2020; Tofik, 2019). As a result, it is essential to devise a plan that requires minimum effort to ensure that a structure's continuous safety is assured well beyond its original design life. Today's offshore structures are reasonably safe once the structural reliability analysis is implemented to assess the probability of failure (POF) of aged platforms (Mirzadeh et al., 2015; Paulo Mendes et al., 2021; Zakikhani et al., 2020).

According to Mat Soom et al. (2015, 2016), the most commonly used procedures to evaluate the integrity level of offshore platforms are Global Ultimate Strength Assessment (GUSA) and Risk-Based Design and Assessment (RBDA). PETRONAS developed GUSA in 2014 to evaluate and assess more than 100 platforms under PETRONAS Carigali Sdn Bhd (PCSB) in the region of Malaysian offshores, while Shell developed an RBDA in 1997 (Ayob et al., 2014; Azman et al., 2017; Efthymiou & Van de Graaf, 2011; Mat Soom, 2018). Several oil and gas companies apply non-linear analysis using modern software to obtain the reserve strength ratio (Mat Soom, 2018). The reserve strength ratio is based on the ultimate base shear over the design of the return period. In practice, the reserve strength ratio is verified by a static pushover analysis or a non-linear collapse analysis (Stewart & Manzocchi, 2018). In some cases, reliability software is also used to calculate the reliability analysis of fixed-structure-platforms (Bjerager, 1990; Elsayed et al., 2016; Stewart & Manzocchi, 2018).

Kurian et al. (2014) determined the structural reliability of jacket platforms by assessing the system probability of failure (failure path) and its corresponding reliability index using the first-order reliability method (FORM) and simple bound formula. A year later, three (3) platforms, Kurian et al. (2015) indicated that the reliability index for component reliability was inversely correlated to the probability of failure. Component reliability was not affected by the variation in the met-ocean parameters. The study concluded that system-level reliability analysis (SLRA) is complicated and time-consuming based on the comparison between high-reliability indices (HRI) (Coccon et al., 2017; Mat Soom et al., 2020; Shittu et al., 2021).

According to Verma et al., (2016) and Mat Soom et al., (2020), the concept of conditional probability and multifaction rules of probabilities are the most important of all the probability theories. It is often interesting to calculate probabilities when some partial information concerning the result of the experiment is available or recalculate them in light of additional information. The probability of the intersection of two events is often needed: Let there be two events, namely A and B; the probability of A given that B has occurred is conditional probability.

The interference load and strength formulations were shown and explained in conjunction with the conditional probability notion (Low, 2017; Starokon, 2019). As an outcome, a case study of a braced monopod and 4 legged platforms was assessed. The results were compared to ISO 19901, ISO 19902, and PETRONAS recommended standards for the POF exposure level category (Chang et al., 2005; ISO 19901-2, 2004; ISO 19902, 2007; Khan et al., 2020).

1.1. Principles of Structural Reliability Analysis

Structural reliability analysis (SRA) is a superior approach to reliability assessment (RA) due to its extensive application (Bea, 1992; Cremona, 2012; Hørte & Sigurdsson, 2017). In reliability engineering, a simplified analytical procedure to evaluate the probability of failure (POF) for fixed offshore platforms subjected to extreme storm conditions was established to assess the structural safety and perform reliability analysis (Bea & Mortazavi, 1992; Kajuputra et al., 2016; Onoufriou & Forbes, 2001). The method is similar to the demand-supply or load-strength principles. Therefore, it is beneficial for general demand and supply (Bea, 1992; Mat

Soom et al., 2019; Onoufriou & Forbes, 2001). Demand is the load model, while supply is referred to as the resistance model or strength model. The structural reliability analysis is used to estimate the integrity of an existing structure based on the pushover analysis (Fayazi & Aghakouchak, 2015). The component failure occurs due to several hidden potentials, such as the redundancy integrity of the structure and load distribution.

The simultaneous probabilistic method of all three load-generating sources, such as wind, waves, and currents, is required to design load-carrying members of the offshore structures. The reason is that the designed platforms have to withstand the effects of environmental forces, as discussed in Haritos (2007), Wang and Xia (2012), Mohd Zaki et al. (2016), Mukhlas et al. (2016), Abu Husain et al. (2017); Syed Ahmad et al., (2019). Moreover, the structural reliability approach should also be considered for the other uncertainties inherent in loads and resistances (Chakrabarti, 2005; Chakrabarti, 1987).

Probability is known as a degree of belief regarding the occurrence of an event rather than the actual frequency (Ang & Tang, 1984; Ayyub & McCuen, 2016; Ebrahimian et al., 2014). In contrast, reliability is defined as the complement of the probability of failure. It is precisely known as the probability of safety of the structure over a given period (Melchers & Beck, 2018). The procedure to calculate the structural probability of failure against seismic loading was introduced (Benjamin & Cornell, 1970; Papoulis & Pillai, 2002). In addition, the probability of failure for structural capacity can also be calculated by considering its uncertainty as determined from the non-linear static pushover analysis that was established for probabilistic assessment of platforms under extreme wave loading (Jalayer, 2003; Krawinkler et al., 2006; Krawinkler & Deierlein, 2014; Manuel et al., 1998; Moehle & Deierlein, 2004).

1.2. Integral and Interference Theory

In general, probability is a tool to quantify the uncertainty of events and reason in a principled manner (Barltrop & Adams, 2013; Brebbia & Walker, 2013; Leimeister & Kolios, 2018). It is essential to know that this integral equation is applicable only if the load and strength models are statically independent for a continuous variable (Mat Soom et al., 2023; Sundararajan, 2012; Zentuti et al., 2018). The process of finding an integral is called integration. In basic reliability engineering, the meaning of reliability is the performance at or above a given standard (rated from 0 to 1, where 0 is the least reliable) (Abu Husain et al., 2013; Alati et al., 2013; Mat Soom, 2018; Mohd Zaki et al., 2016; Mourão et al., 2020; Rathod et al., 2011). On the other hand, the probability of failure is the performance below a given standard (rated from 0 to 1, where 1 is an absolute failure). Since these events (success and failure) are complements, the following is true where reliability is equivalent to 1 – the probability of failure (POF). Failures occur where loads and strength models overlap each other (Chandrasekaran & Nagavinothini, 2020; Rao, 1992; Salgado & Kim, 2014; Shen et al., 2019).

The probability of failure (*POF*) can be expressed as shown in Equation (1) to Equation (3);

$$POF = P(S \leq L) = 1 - P(L \leq S) = 1 - R \tag{1}$$

$$POF = 1 - \int_{-\infty}^{\infty} f_S(s) \left[\int_{-\infty}^{s} f_L(l) dl \right] ds \tag{2}$$

$$POF = \int_{-\infty}^{\infty} \left[1 - F_L(s) \right] f_S(s) ds \tag{3}$$

where $f_S(s)$ and $f_L(l)$ are the probability density function (*PDF*) of the strength and load, respectively. While $F_L(s)$ is the probability distribution function (*PDF**) of L in a unit of strength.

An alternate for the probability of failure (*POF*) can also be expressed as presented in Equation (4) to Equation (6);

$$POF = 1 - R = 1 - (S \geq L) \tag{4}$$

$$POF = 1 - \int_{-\infty}^{\infty} f_L(l) \left[\int_{l}^{\infty} f_S(s) d_s \right] dl \tag{5}$$

$$POF = \int_{-\infty}^{\infty} f_L(l) F_S(l) dl \tag{6}$$

where $F_S(l)$ is the probability distribution function (*PDF**) of *S* in the unit of load.

Following the present knowledge of the non-linear analysis, the RSR values considered in estimating the potential collapse of offshore fixed structures ranged between 0.80 and 1.39 (Mat Soom et al., 2019, 2020). In this study, the selected offshore structure was analysed using a reliable approach, namely the stress-strength interference method. This new method was described in the subsequent section.

2. Research Methodology

2.1 Factor of Safety

The parameter used to maintain a certain degree of safety in structural and mechanical design is called a factor of safety (Khan et al., 2020; Stacey & Sharp, 2007). The safety factor definition varies from user to user, depending on the sophistication and complexity of the problem (Low, 2017). The variables could be force, power, torque, material, surface finish, fillet radius, etc. (Rao et al., 2012; Rao & Annamdas, 2013; Vonta & Ram, 2018).

In this study, the factor of safety was the ratio of the expected strength to the expected load (Verma et al., 2016). Therefore, each load (time) step for incremental or iterative methods was correlated with the factor of safety. The factor of safety of the selected test structure element was determined based on Equation (7) for braced monopod platforms respectively:

$$Reserve\ Strength\ Ratio\ (RSR) = \frac{Ultimate\ Base\ Shear}{Base\ Shear} \tag{7}$$

2.2 Stress-Strength Interference Probability of Failure Determination Procedure

In this study, the load (time) step process was based on the ultimate limit state condition either by the incremental or iterative method (Azman et al., 2017; Mat Soom et al., 2019). The test structure element's load experience exceeded the strength capacity at a specific return period (*RP*). In other words, any load experienced by the structure element until its ultimate limit state condition or failure (Mat Soom, 2018). Figure 1 is a flowchart procedure explaining the process flow, showing the detailed steps developed to determine the test structure's POF. Further explanations of this procedure are provided in Mat Soom et al. (2020, 2023) and Yak et al. (2021)

The reserve strength ratio (RSR) and base shear (BS) are calculated from the ultimate limit state (pushover analysis) (Azman et al., 2017; Dyanati & Huang, 2014; Karimi et al., 2017; Mat Soom, 2018). The safety factor was used in accordance with Equation (7) to get the value of the other variable (Nizamani, 2015; Srikanth, 2016). It enables the determination of distribution types that are neither PDF nor PDF*. Both distributions had probability models with four (4) tails of bell-shaped curves. The strength model was produced by multiplying

BS with RSR as studied by Mat Soom (2018) and Mat Soom et al., (2023), which served as the ultimate strength model, while BS served as the load model.

Equation (3) and Equation (6) were used to estimate the values of collapse based on the RSR range of 0.8 to 1.39. This range was the total up to which POF was calculated. A region of overlap between the two probability distributions indicated the condition status when the BS was higher than the strength (Kolios & Brennan, 2009; Mat Soom et al., 2019). It can be translated as the determination of RSR < 3.5 where the load exceeds strength, and vice versa for RSR ≥ 3.5.

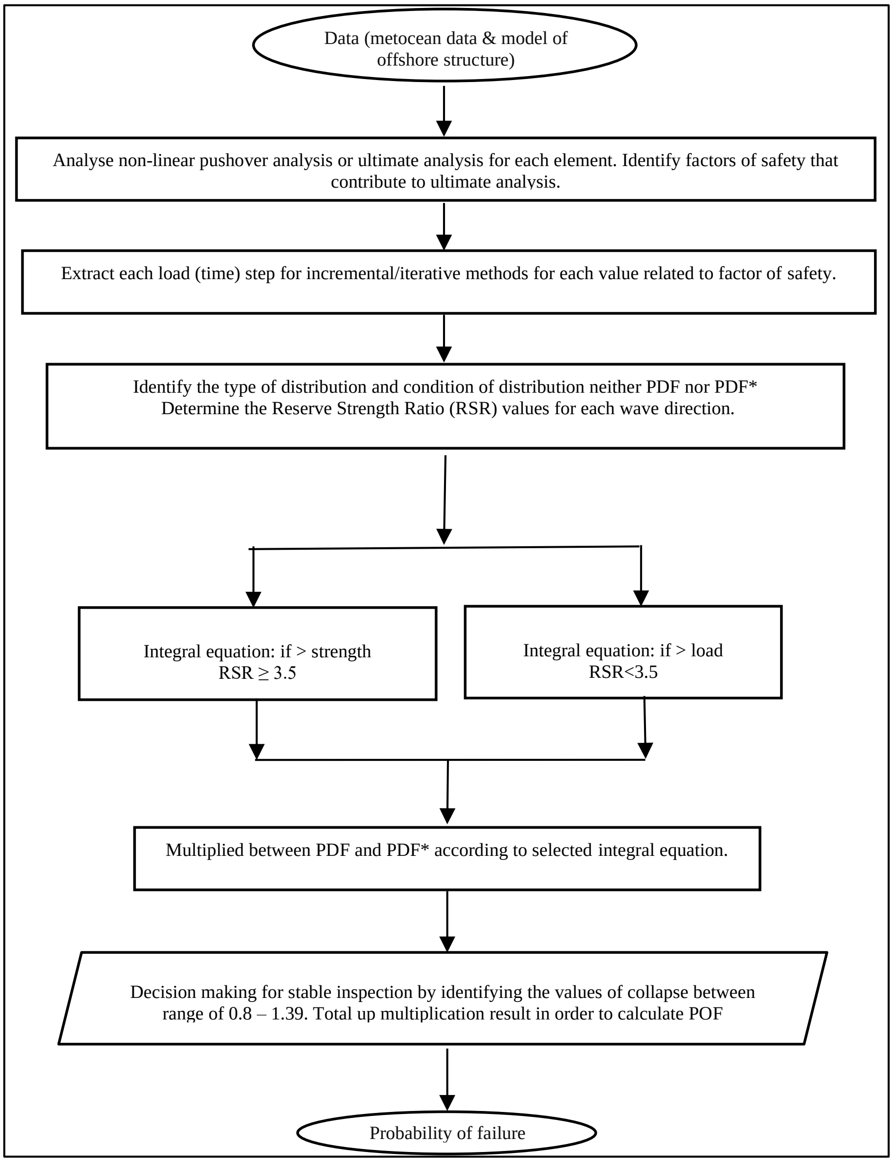

Figure 1. Methodology of a Stress-Strength Interference Probability of Failure Determination Procedure

3. Data Evaluation and Test Structure Element Analysis

3.1 Structures Element Specification

In general, the purpose of this study was to demonstrate structural reliability assessment by developing a rational and reliable engineering method (stress-strength interference method) based on an understanding of the uncertainties associated with the selected existing test structure elements, particularly those that contribute to the probability of failure (POF).

A braced monopod and 4 legged fixed structure platform were selected as the test structure elements. Both were installed offshore at 54 metres of water depth. A brace monopod has one (1) piled (pile-driven through jacket leg), and two skirt piles support the structure, while 4 legged has four (4) piled (pile-driven through jacket leg). The design was intended to last twenty years, which was twice the initially expected production life. The metocean data was based on deep water hydrodynamics and was generated using existing SEAFINE data. Twelve (12) directions were analysed, representing 4, 34, 64, 94, 124, 154, 184, 214, 244, 274, 304, and 334 degrees for a braced monopod, while for 4 legged total eight (8) directions were analysed, representing 0, 45, 90, 135, 180, 225. 270 and 315 degrees.

3.2 Global Analysis for Structural Element of Fixed Structure Platform

The long-term load distribution is an expression that allows us to predict the load level over a usually 100-year return period (RP) (Abu Husain et al., 2013; Mohd Zaki et al., 2017). The data for this study was obtained from the met-ocean data analysis performed on the fixed structure platform. To conduct this high-end study, twelve (12) and eight (8) wave load directions corresponding to degrees were selected.

The full results of the non-linear pushover study were summarised in Table 1 for a braced monopod platform and Table 2 for 4-legged platform. The reserve strength ratio (RSR) for all directions remained more than the unmanned platform RSR limit of 1.32 as determined by industry and API RP 2SIM. Before calculating the POF, the condition for each direction must be established by generating and plotting the four (4) tail bell curve distributions. The result of the four (4) tail bell curve distributions can be analysed to evaluate if the BS bell curve distribution is greater than the strength bell curve distribution or not, based on RSR values less than 3.5 or equivalent and more than 3.5, leading the correct equation to be selected. Following that, using Equation (3) and Equation (6), POF was calculated after identifying the load and strength conditions.

Based on the result presented in Table 1, the direction with the worst significant impact is 124 degrees, as indicated by a low RSR value of 1.496 and the condition is a more significant load impact with a POF of 2.66E-05. Similarly, Table 2 reveals that the direction with the worst significant impact is 270 degrees, which is analysed by an RSR of 2.260 and a POF of 3.99E-07, indicating a greater susceptibility to load impacts.

Table 1. Overall results of 12 directions of wave impact for a braced monopod platform

Directions	RSR	Condition: > load or > strength	POF Calculated based on Equations (3) and (6)
4	4.664	> Strength	2.33E-16
34	6.149	> Strength	1.12E-15
64	2.141	> Load	1.38E-06
94	1.542	> Load	1.91E-05
124	1.496	> Load	2.66E-05
154	1.649	> Load	6.22E-06
184	2.047	> Load	1.11E-06
214	2.664	> Load	6.84E-10
244	2.262	> Load	5.62E-07
274	4.379	> Strength	7.55E-17
304	4.261	> Strength	6.24E-16
334	5.626	> Strength	3.90E-17

Table 2. Overall results of 8 directions of wave impact for 4-legged platform

Directions	RSR	Condition: > load or > strength	POF Calculated based on Equations (3) and (6)
0	2.526	> Load	4.55E-07
45	2.832	> Load	2.21E-07
90	6.370	> Strength	1.24E-15
135	9.160	> Strength	2.83E-15
180	6.375	> Strength	2.07E-14
225	2.592	> Load	3.62E-08
270	2.260	> Load	3.90E-07
315	2.996	> Load	1.23E-07

3.3 Assessment for the Purpose of Calculating Probability of Failure

Two (2) samples were analyzed to determine the main effects of failure at 124 and 270 degrees of wave/load direction. For each sample, the highest load model was identified, and probability distribution models were used to determine the area of the failure region.

At 124 degrees of wave/load direction, one (1) sample showed that the highest base shear and lower RSR of 1.496 were determined as the main effects of failure. The probability distribution modelling for the load model (3-parameter log-logistic – PDF) and the strength model (3-parameter log-logistic – PDF*) was plotted, resulting in the load model overlapping with the strength model when PDF is more significant than PDF*. The development of (4) tail bell curve distribution is illustrated in Figure 2.

Following that, the integral of Equation (3) was used to multiply both PDF and PDF*. The overlap zone on the distributions indicated the area of the failure region, where the probability of failure (POF) was most likely to occur. The total of the integral area was calculated as 2.66×10^{-5} due to POF.

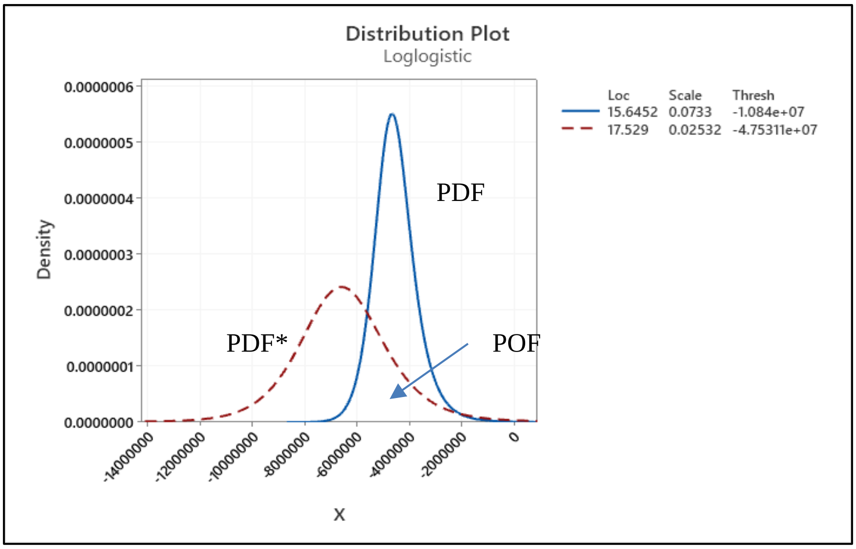

Figure 2. Sample of 124° direction of 4 tail bell curve distributions using equation (2) for a braced monopod platform

3.4 Comparison between ISOs and PETRONAS in accordance with Industry Requirements

Similarly, at 270 degrees of wave/load direction, one sample showed that the highest base shear and lower RSR of 2.260 were determined as the main effects of failure. The probability distribution modelling for the load model (3-parameter log-logistic – PDF) and the strength model (3-parameter log-logistic – PDF*) was plotted, resulting in the load model overlapping with the strength model when PDF is more significant than PDF*. The development of (4) tail bell curve distribution is illustrated in Figure 3.

Following that, the integral of Equation (3) was used to multiply both PDF and PDF*. The overlap zone on the distributions indicated the area of the failure region, where the probability of failure (POF) was most likely to occur. The total of the integral area was calculated as 3.99×10^{-7} due to POF.

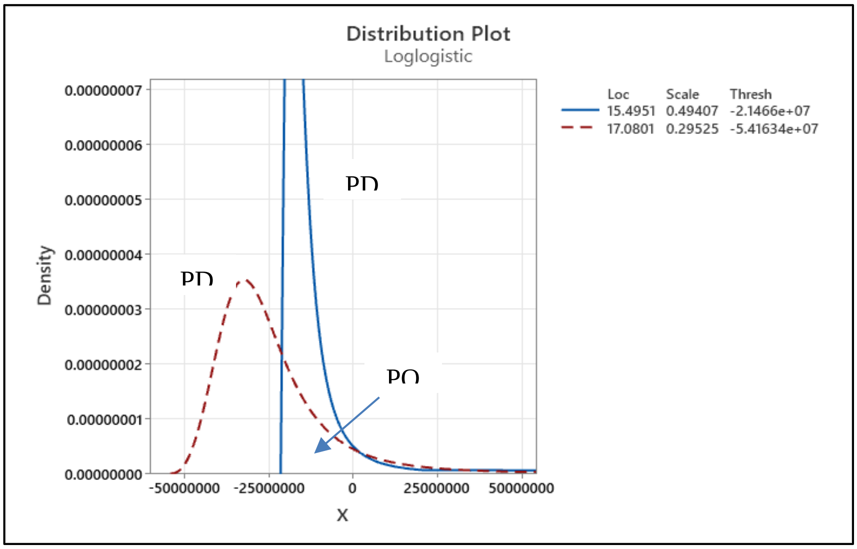

Figure 3. Sample of 270° direction of 4 tail bell curve distributions using equation (2) for 4 legged platform

3.4 Comparison between ISOs and PETRONAS in accordance with Industry Requirements

For existing platforms, API provides a common risk classification for the output of their exposure category and their POF classification (API, 1977, 1985). The exposure classification of an ageing platform is defined as relating to life safety exposure classes and failure consequence classes, taking into consideration potential environmental and economic consequences (API, 1993a, 1993b). The exposure classification matrix can be referred to in detail in ISO (2007). The life safety or consequence of failure should be established using the more restricted method. The offshore structure is categorised as the structure's exposure level (L1 - high, L2 - medium, L3 - low). Exposure levels are determined based on the life safety category and consequence category. For example, at the outset of the design process, offshore platforms should be classified as S1 - manned non-evacuated, S2 - manned evacuated, and S3 - unmanned, in addition to C1 – high consequence, C2 - a medium consequence, and C3 - low consequence.

Test samples of two (2) platforms, i.e., a braced monopod and 4-legged platforms, tested at 124 degrees and 270 degrees, respectively. Both platforms fall into the consequence category C2, whereas the life-safety category is S2. As a result, this platform fell short of the L2 reliability target. In Table 3, it can be seen that POF for braced monopod is 2.66 × 10-5 while POF for 4-legged platforms is 3.99 × 10-7. According to ISO 19902, Table 3, the maximum exposure level L2 is 5.00×10^{-4} probability of failure, and the exposure level L2 exceeded the acceptable limit of 2000 years return period from a design perspective. ISO 19901 indicated in the same table that the probability of failure for L2 is 4.00×10^{-4} (medium) under the inspection interval. According to PETRONAS, the authority recommended in this table, the probability of failure under unmanned design is 1.00×10^{-3}.

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Table 3. Probability of failure comparison measure (POF)

Risk Ranking	Probability of Failure (POF)	ISO 19902:2007 Amendment - 19902:2013 Design Target POF		ISO 19901-9:2019 Inspection Interval POF		PETRONAS Recommendation (Ayob *et al*, 2014)	
Very High	1.00		L1/L2: Critical Condition		L1: 1-3 years L2: 3-5 years		For Risk Mitigation
	1.00×10^{-2}						
	1.00×10^{-3}					Unmanned Design	
	5.00×10^{-4}	L2 @ 1/2000					
	4.00×10^{-4}		L1/L2: Good Condition	Medium	L1/L2: 3-5 years		
	1.00×10^{-4}			Low		Manned Design and Inspection	For Monitoring
	3.00×10^{-5}	L1 @ 1/33000			L1: 3-5 years L2: 6-10 years		
	Braced Monopod 2.66×10^{-5}		L1/L2: Best Condition				
Very low	1.81×10^{-6}						
	4-Legged 3.99×10^{-7}						
	0.00						

Following the development of the method, conclusions regarding the result of POF obtained using the stress-strength interference method may be derived by comparing it to the result calculated using Equation (3) and Equation (6) in comparison to ISO 19902 in terms of target reliability of design perspective, ISO 19901-9 in terms of inspection interval frequency and PETRONAS in terms of risk to consider as an authority (refer Figure 4 and Figure 5).

The results of the POF calculation (overlap) for 12 directions and 8 directions of wave impact between probability density function (PDF) and probability distribution function (PDF*) were obtained using the Equation (3) and Equation (6) approaches. As shown in Figure 4 and Figure 5, the result is based on the sum of load and strength distributions using the applied integral equation. The results of the study were compared against three different sets of standards: ISO 19902, ISO 19901, and PETRONAS recommendations, which are the regulatory authorities for Malaysia. ISO standards are one of the main references used by key players in the Malaysian oil and gas industry.

The study plotted the outer layer was the PETRONAS requirement, followed by ISO 19902 and ISO 19901. The estimated Probability of Failure (POF) values remained within the allowed range specified in the aforementioned standards (refer to Figure 4 and Figure 5), indicating that the braced monopod and 4-legged platforms were still in good condition. Specifically, the design outcome of ISO 19902 was L2, the best condition from a design perspective, while the inspection interval specified by ISO 19901 was between 6 and 10 years. PETRONAS, on the other hand, required monitoring for risk mitigation, which both platforms satisfied. Thus, these results indicate that both platform conditions were still intact with a low risk for the probability of failure, and it was deemed fit for service according to the standards.

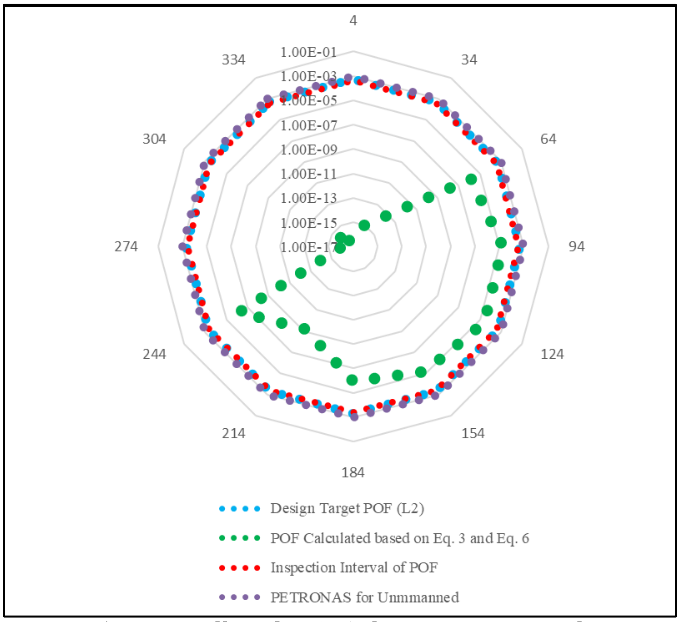

Figure 4. All twelve (12) directions POF result

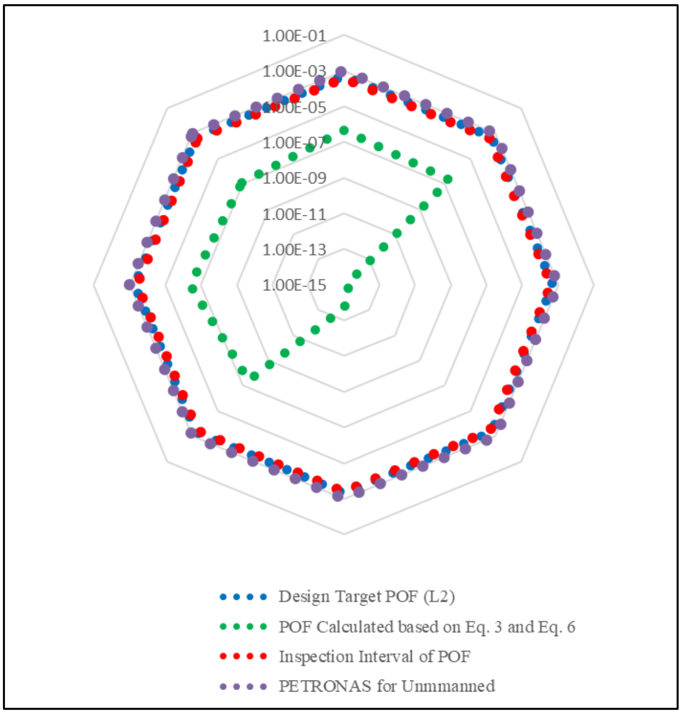

Figure 5. All eight (8) directions POF result

3. Conclusion

Safety is measured based on statistical judgement, while structural reliability is based on engineering methodology. The concepts of demand and supply or load and strength were applied in this simplified, reliable analytical procedure to determine the probability of failure of the test structures subjected to extreme storm conditions.

The probabilistic model used is a combination of the load model and strength model. All results from the applied global static under stress-strength interference theory analyses are acceptable and comply with the standard compliance of value delivery and classification of benefits to the platform operator. It is beneficial economically in terms of resource optimisation and the platform's reassessment.

This recent analysis is important to oil and gas industry standards as it involves quality, safety, and cost, especially when the platform's collapse potentially involves the loss of life, and damage to the assets and the environment. Overall, these findings underscore the critical role of direction in determining the integrity of offshore structures and highlight the importance of incorporating comprehensive reliability analyses in designing and maintaining such structures.

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Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

References

Abu Husain, M. K., Mohd Zaki, N. I., Lambert, L., Wang, Y., & Najafian, G. (2013). *Long-term probability distribution of extreme offshore structural response via an efficient time simulation method*. *55324*, V02AT02A050.

Abu Husain, M. K., Mohd Zaki, N. I., & Najafian, G. (2017). Various Methods of Simulating Wave Kinematics on the Structural Members of the 100-year Responses. *Journal of Mechanical Engineering and Sciences*, *11*(4), 18. https://doi.org/10.15282/jmes.11.4.2017.27.0293

Alati, N., Nava, V., Failla, G., Arena, F., & Santini, A. (2013). *Fatigue analysis of offshore wind turbines on fixed support structures*. *569*, 539–546.

Ang, A. H.-S., & Tang, W. H. (1984). *Probability Concepts in Engineering Planning and Design*.

Animah, I., Shafiee, M., Simms, N., Erkoyuncu, J. A., & Maiti, J. (2018). Selection of the most suitable life extension strategy for ageing offshore assets using a life-cycle cost-benefit analysis approach. *Journal of Quality in Maintenance Engineering*, *24*(3), 311–330. https://doi.org/10.1108/jqme-09-2016-0041

API. (1977). *API Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms*. American Petroleum Institute.

API. (1985). Manual of Petroleum Measurement Standards, Chapter 13, Statistical Aspects of Measuring and Sampling, Part 1. In *Statistical Concepts and Procedures in Measurement* (2rd ed.). API Publications.

API. (1993a). *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms—Load And Resistance Factor Design*. American Petroleum Institute.

API. (1993b). *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms—Working Stress Design*. American Petroleum Institute.

Ayob, M. S., Kajuputra, A. E., Mukherjee, K. B., & Wong, S. (2014). Requalification of Offshore Jacket Structures in Malaysia Waters. *Offshore Technology Conference-Asia*, 25021-.

Ayyub, B. M., & McCuen, R. H. (2016). *Probability, Statistics, and Reliability for Engineers and Scientists*. CRC press.

Azman, N. U., Abu Husain, M. K., Mohd Zaki, N. I., & Mat Soom, E. (2017). The Effect of Wave-in-deck in Conventional Pushover Analysis'. *International Conference on Computational Methods in Marine Engineering*. Marine 2017, Nantes, France.

Barltrop, N. D., & Adams, A. J. (2013). *Dynamics of fixed marine structures* (Vol. 91). Butterworth-Heinemann.

Bea, R. G. (1992). *Structural Reliability: Design and Requalification of Offshore Platforms*. 41–67.

Bea, R. G., & Mortazavi, M. (1992). *Experimental Validation of the ULSLEA with Results from Frame Tests*. 7th International Offshore and polar Engineering Conference. Honolulu. Hawaii. May.

Benjamin, J. R., & Cornell, C. A. (1970). *Probability, statistics, and decision for civil engineers: Solutions manual*. McGraw-Hill.

Bjerager, P. (1990). On Computation Methods for Structural Reliability Analysis. *Structural Safety*, *9*(2), 79–96.

Brebbia, C. A., & Walker, S. (2013). *Dynamic analysis of offshore structures*. Newnes.

Chakrabarti, S. (2005). *Handbook of Offshore Engineering (2-volume set)*. Elsevier.

Chakrabarti, S. K. (1987). *Hydrodynamics of Offshore Structures*. WIT press.

Chandrasekaran, S. (2017). *Offshore Structural Engineering: Reliability and Risk Assessment*. CRC Press.

Chandrasekaran, S., & Nagavinothini, R. (2020). *Offshore Compliant Platforms: Analysis, Design, and Experimental Studies*. John Wiley & Sons.

Chang, B., Abraham, M., & Peng, B.-F. (2005). *Comparison of ISO and API seismic design guidelines using three existing offshore platforms*. Offshore Technology Conference.

Coccon, M. N., Song, J., Ok, S.-Y., & Galvanetto, U. (2017). A New Approach to System Reliability Analysis of Offshore Structures Using Dominant Failure Modes Identified by Selective Searching Technique. *KSCE Journal of Civil Engineering*, *21*(6), 2360–2372.

Cremona, C. (2012). *Structural Performance: Probability-based Assessment*. John Wiley & Sons.

Dyanati, M., & Huang, Q. (2014). *Seismic Reliability of a fixed offshore platform against collapse*. *45431*, V04BT02A020.

Ebrahimian, H., Jalayer, F., De Dominicis, R., & Manfredi, G. (2014). Probability-Based Assessment of Jacket-Type Offshore. *In EUROSTEEL*.

Efthymiou, M., & Van de Graaf, J. W. (2011). Reliability and (Re)Assessment of Fixed Steel Platforms. *Proceedings of the ASME 30th International Conference on Ocean, Offshore and Arctic Engineering*. OMAE 2011, Rotterdam, The Netherlands.

Elsayed, T., El-Shaib, M., & Gbr, K. (2016). Reliability of fixed offshore jacket platform against earthquake collapse. *Ships and Offshore Structures*, *11*(2), 167–181.

Faber, M. H., & Stewart, M. G. (2003). Risk assessment for civil engineering facilities: Critical overview and discussion. *Reliability Engineering & System Safety*, *80*(2), 173–184.

Fayazi, A., & Aghakouchak, A. (2015). *Reliability Based Assessment of Existing Fixed Offshore Platforms Located in the Persian Gulf*.

Gnedenko, B., Pavlov, I. V., & Ushakov, I. A. (1999). *Statistical reliability engineering*. John Wiley & Sons.

Haritos, N. (2007). Introduction to The Analysis and Design of Offshore Structures–An Overview. *Electronic Journal of Structural Engineering*, *7*(Special Issue: Loading on Structures), 55–65.

Hørte, T., & Sigurdsson, G. (2017). *On The Application of Structural Reliability Analysis*. Proceedings of the 36th International Conference on Ocean, Offshore and Arctic Engineering. https://doi.org/10.1115/OMAE2017-62717

ISO 19901-2. (2004). *Petroleum and Natural Gas Industries–Specific Requirements for Offshore Structures–Part 2: Seismic Design Procedures and Criteria*.

ISO 19902. (2007). *Petroleum and natural gas industries—Fixed steel offshore structures*.

Jalayer, F. (2003). *Direct Probabilistic Seismic Analysis: Implementing Non-Linear Dynamic Assessments*. PhD Thesis, Stanford University.

Kajuputra, A. E., Shiiun, W. B., & Shamsuddin, M. A. (2016). *The Importance of SIMS in Structural Integrity Review and Life Extension Requirement for Existing Fixed Offshore Structure*. Proceedings of the Offshore Technology Conference Asia.

Karimi, H. R., KaramZadeh, N. S., & Golami, E. O. R. (2017). Effect of elevational and member damage on jacket strength: Sensitivity and reliability review of South Pars phase-20 jacket, using push-over analysis. *Ocean Engineering*, *143*, 209–216.

Khan, R., Luong Ann, L., Wayne Nichols, N., Bucknell, J., Chen, K., & Chen, J. (2020). System-based calibration of offshore Malaysia environmental action factors for the ISO 19902 PETRONAS offshore fixed platforms. *Journal of Marine Engineering & Technology*, *19*(2), 78–101.

Kolios, A., & Brennan, F. (2009). *Reliability Based Design of Novel Offshore Structures*. Proceedings of the 3rd International Conference on Integrity, Chengdu, China.

Krawinkler, H., & Deierlein, G. G. (2014). Challenges towards achieving earthquake resilience through performance-based earthquake engineering. In *Performance-based seismic engineering: Vision for an earthquake resilient society* (pp. 3–23). Springer.

Krawinkler, H., Zareian, F., Medina, R. A., & Ibarra, L. F. (2006). Decision support for conceptual performance-based design. *Earthquake Engineering & Structural Dynamics*, *35*(1), 115–133.

Kurian, V. J., Goh, S. S., Abdul Wahab, M. M., & Liew, M. S. (2014). *Reliability Assessment Model for Aging Jacket Structures in Malaysian Waters*. *567*, 283–288.

Kurian, V. J., Goh, S. S., Wahab, M. M. A., & Liew, M. S. (2015). Component reliability assessment of offshore jacket platforms. *Research Journal of Applied Sciences, Engineering and Technology*, *9*(1), 1–10.

Leimeister, M., & Kolios, A. (2018). A review of reliability-based methods for risk analysis and their application in the offshore wind industry. *Renewable and Sustainable Energy Reviews*, *91*, 1065–1076.

Low, B. K. (2017). Insights from Reliability-Based Design to Complement Load And Resistance Factor Design Approach. *Journal of Geotechnical and Geoenvironmental Engineering*, *143*(11), 04017089.

Manuel, L., Schmucker, D. G., Cornell, C. A., & Carballo, J. E. (1998). A reliability-based design format for jacket platforms under wave loads. *Marine Structures*, *11*(10), 413–428.

Mat Soom, E. (2018). *Efficient Load Coefficient Method for Structural Reliability Assessment of Ageing Offshore Platforms* [PhD Thesis,]. Universiti Teknologi Malaysia.

Mat Soom, E., Abu Husain, M. K., Mohd Zaki, N. I., Azman, N. U., Mukhlas, N. ‘Azizah, & Syed Ahmad, S. Z. A. (2023). *Structural Reliability Fundamentals and Their Application To Offshore Platforms* (1st ed.). Penerbit UTM Press.

Mat Soom, E., Abu Husain, M. K., Mohd Zaki, N. I., Azman, N. U., & Najafian, G. (2016). *Reliability-Based Design and Assessment for Lifetime Extension of Ageing Offshore Structures*. V003T02A044-V003T02A044.

Mat Soom, E., Abu Husain, M. K., Mohd Zaki, N. I. M., & Azman, N. U. (2020). A Reliable Approach for Fixed Offshore Structures Probability of Failure Determination. *International Journal of Advanced Research in Engineering and Technology (IJARET)*, *11*(5), 469–475. https://doi.org/10.34218/IJARET.11.5.2020.048

Mat Soom, E., Abu Husain, M. K., Mohd Zaki, N. I., Mohd Nor, K., Ayob, M. S., & Najafian, G. (2015). *Global Ultimate Strength Assessment (GUSA) for Lifetime Extension of Ageing Offshore Structures*.

Mat Soom, E., Mohd Zaki, N. I., Azman, N. U., & Abu Husain, M. K. (2019). Structural Reliability Analysis for Fixed Offshore Platforms. *Buletin Jurutera, IEM*.

Melchers, R. E., & Beck, A. T. (2018). *Structural Reliability Analysis and Prediction*. John Wiley & Sons.

Mirzadeh, J., Kimiaei, M., & Cassidy, M. J. (2015). A Framework to Efficiently Calculate the Probability of Failure of Dynamically Sensitive Structures in A Random Sea. *Ocean Engineering*, *110*, 215–226.

Moehle, J. P., & Deierlein, G. G. (2004). A Framework Methodology for Performance Based Earthquake Engineering. *13th World Conference on Earthquake Engineering.*

Mohd Zaki, N. I., Abu Husain, M. K., & Najafian, G. (2016). Extreme Structural Response Values from Various Methods of Simulating Wave Kinematics. *Ships and Offshore Structures*, *11*(4), 369–384. https://doi.org/10.1080/17445302.2014.987947

Mohd Zaki, N. I., Abu Husain, M. K., & Najafian, G. (2017). *Long-term probability distribution of fixed offshore structuralresponse using animproved version of finite memory nonlinear system procedure*. 485–495.

Mourão, A., Correia, J. A., Ávila, B. V., de Oliveira, C. C., Ferradosa, T., Carvalho, H., Castro, J. M., & De Jesus, A. M. (2020). *A fatigue damage evaluation using local damage parameters for an offshore structure*. *173*, 43–57.

Mukhlas, N. ‘Azizah, Shuhaimy, N. A., Johari, M. B., Mat Soom, E., Abu Husain, M. K., & Mohd Zaki, N. I. (2016). Design and Analysis of Fixed Offshore Structure–An Overview. *Malaysian Journal of Civil Engineering*, *28*(3), 503–520.

Negra, N. B., Holmstrom, O., Bak-Jensen, B., & Sorensen, P. (2007). Aspects of relevance in offshore wind farm reliability assessment. *IEEE Transactions on Energy Conversion*, *22*(1), 159–166.

Nizamani, Z. (2015). *Environmental Load Factors and System Strength Evaluation of Offshore Jacket Platforms* (Vol. 4). Springer.

Onoufriou, T., & Forbes, V. J. (2001). Developments in Structural System Reliability Assessments of Fixed Steel Offshore Platforms. *Reliability Engineering & System Safety*, *71*(2), 189–199.

Palkar, S., & Markeset, T. (2011). Extending the service life span of ageing oil and gas offshore production facilities. *IFIP International Conference on Advances in Production Management Systems*, 213–221.

Papoulis, A., & Pillai, S. U. (2002). *Probability, random variables, and stochastic processes*. Tata McGraw-Hill Education.

Paulo Mendes, José A. F. O. Correia, António Mourão, Rafael Pereira, Nicholas Fantuzzi, Abílio De Jesus, & Rui Calçada. (2021). Fatigue Assessments of a Jacket-Type Offshore Structure Based on Static and Dynamic Analyses. *Practice Periodical on Structural Design and Construction*, *26*(1), 04020054. https://doi.org/doi:10.1061/(ASCE)SC.1943-5576.0000533

Rao, A. R., Rao, S. S., Sharma, T., & Krishna, K. R. (2012). *Asset integrity management in onshore & offshore-enhancing reliability at KGD6*. SPE Oil and Gas India Conference and Exhibition.

Rao, S. S. (1992). *Reliability Based Design* (1st Edition). McGraw – Hill.

Rao, S. S., & Annamdas, K. K. (2013). A comparative study of evidence theories in the modeling, analysis, and design of engineering systems. *Journal of Mechanical Design*, *135*(6), 061006.

Rathod, V., Yadav, O. P., Rathore, A., & Jain, R. (2011). Probabilistic modeling of fatigue damage accumulation for reliability prediction. *Journal of Quality and Reliability Engineering*, *2011*.

Ribeiro, T., Rigueiro, C., Borges, L., & Sousa, A. (2020). A comprehensive method for fatigue life evaluation and extension in the context of predictive maintenance for fixed ocean structures. *Applied Ocean Research*, *95*, 102050.

Salgado, R., & Kim, D. (2014). Reliability analysis of load and resistance factor design of slopes. *Journal of Geotechnical and Geoenvironmental Engineering*, *140*(1), 57–73.

Shen, M., Khoshnevisan, S., Tan, X., Zhang, Y., & Juang, C. H. (2019). Assessing characteristic value selection methods for design with load and resistance factor design (LRFD)—Design robustness perspective. *Canadian Geotechnical Journal*, *56*(10), 1475–1485.

Shittu, A. A., Kolios, A., & Mehmanparast, A. (2021). A systematic review of structural reliability methods for deformation and fatigue analysis of offshore jacket structures. *Metals*, *11*(1), 50.

Shittu, A. A., Mehmanparast, A., Wang, L., Salonitis, K., & Kolios, A. (2020). Comparative study of structural reliability assessment methods for offshore wind turbine jacket support structures. *Applied Sciences*, *10*(3), 860.

Srikanth, I. (2016). *Nonlinear Static and Dynamic Analyses of Jacket-type Offshore Platform*. Master Thesis, Anna University.

Stacey, A., & Sharp, J. V. (2007). Safety factor requirements for the offshore industry. *Engineering Failure Analysis*, *14*(3), 442–458.

Starokon, I. V. (2019). *Methods for solving the problems of extending the resource of offshore stationary platforms: Case study*. *1399*, 055087.

Stewart, G., & Manzocchi, M. (2018). Recent Developments in Probabilistic Pushover Models for The Reliability Re-Assessment of Fixed Offshore Structures. *Safety and Reliability*, *38*(1–2), 3–31. https://doi.org/10.1080/09617353.2018.1545416

Sundararajan, C. R. (2012). *Probabilistic Structural Mechanics Handbook: Theory and Industrial Applications*. Springer Science & Business Media.

Syed Ahmad, S. Z. A., Abu Husain, M. K., Mohd Zaki, N. I., Mohd, M. H., & Najafian, G. (2019). *Offshore Responses Using an Efficient Time Simulation Regression Procedure*. 12.

Tofik, H. (2019). *Fatigue assessment of existing offshore wind turbine support structures for lifetime extension*.

Trivedi, K. S., & Bobbio, A. (2017). *Reliability and availability engineering: Modeling, analysis, and applications*. Cambridge University Press.

Veritas, D. N., & Lloyd, G. (2010). Fatigue design of offshore steel structures. *DNV Recommended Practice DNV-RP-C203*.

Verma, A. K., Ajit, S., & Karanki, D. R. (2016). *Reliability and safety engineering*. London : Springer-Verlag.

Vonta, I., & Ram, M. (2018). *Reliability Engineering: Theory and Applications*. CRC Press.

Wang, Y. G., & Xia, Y. Q. (2012). Simulating Mixed Sea State Waves for Marine Design. *Applied Ocean Research*, *37*, 33–44. https://doi.org/10.1016/j.apor.2012.03.003

Wehunt, C. D., Burke, N. E., Noonan, S. G., & Bard, T. R. (2003). Technical challenges for offshore heavy oil field developments. *Offshore Technology Conference*.

Yak, X. C., Mat Soom, E., Quen, L. K., Abu Husain, M. K., & Mohd Zaki, N. I. (2021). Data science application in structural integrity analysis of fixed offshore jacket platform. *Journal of Physics*. 9th Conference on Emerging Energy & Process Technology (CONCEPT 2021), Kuala Lumpur.

Zakikhani, K., Nasiri, F., & Zayed, T. (2020). A Review of Failure Prediction Models for Oil and Gas Pipelines. *Journal of Pipeline Systems Engineering and Practice*, *11*(1), 03119001.

Zentuti, N. A., Booker, J. D., Hoole, J., Bradford, R. A. W., & Knowles, D. (2018). *Probabilistic Structural Integrity*. Proceedings of the TAGSI-FESI Symposium on Probabilistics.