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Article

Design and Reliability Analysis of Four-Legged Jacket Type Offshore Platform in North Java Sea

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Abstract. In ideal conditions, offshore platform design follows standardized international criteria such as the American Petroleum Institute Recommended Practice 2A-LRFD (API RP2A-LRFD) to ensure structural reliability and safety. However, the real conditions in the Java Sea present unique challenges, as environmental loading patterns and regional factors may differ from those assumed in global standards. This study proposes a comprehensive solution through combined structural analysis and reliability assessment using Monte Carlo simulation methods. The urgency of this research stems from the critical need to validate and potentially adjust design standards for regional applications, ensuring the long-term safety and reliability of offshore structures in Southeast Asian waters. The research objectives focus on evaluating the structural reliability of a four-legged jacket type platform using both deterministic and probabilistic approaches, specifically assessing the applicability of API RP2A-LRFD criteria to Java Sea conditions. Results demonstrate that while the structure meets basic design criteria, the reliability indices ($\beta = 16.70$ for LRFD, $\beta = 22.29$ for unfactored) suggest current load factors may be overly conservative for regional conditions.

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1. Introduction

Offshore platforms are used in oil and gas exploration and production and can be fixed to the seabed or float [1]. This project uses a four-legged jacket type structure fixed to the Java Sea seabed, with a water depth of 100 ft from the mean sea level (m.s.l.). The structure must meet the American Petroleum Institute Recommended Practice 2A-LRFD (API RP2A-LRFD) criteria [2], and therefore three analyses must be conducted: an inplace analysis, a seismic analysis, and a fatigue analysis [3]. Current research has emphasized the importance of comprehensive analysis approaches in offshore platform design, particularly in Southeast Asian waters [4-5].

An the Inplace analysis, Cross-sectional optimization is carried out on the structure, and a Reliability analysis is conducted to assess the structure's probability of failure (Pf) with the given load and structural resistance [6]. Recent studies have demonstrated the significance of regional wave patterns and environmental loading in structural reliability assessment [7-10]. This approach provides an initial indication of the API RP2A-LRFD design load factor in the Java Sea, and the structural members' reliability index (β) would be obtained. Figure 1 shows the platform location in the Java Sea.

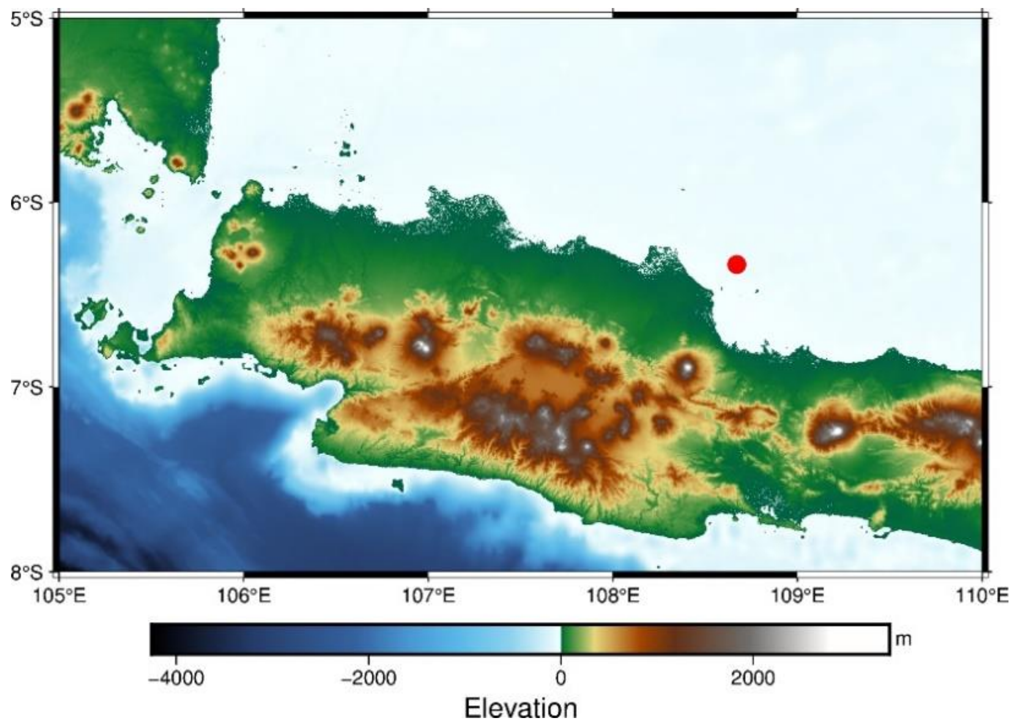

Figure 1. Platform location off the coast of the Java Sea (red dot). This map was rendered using PyGMT [11-12]

In this study, structural modeling was conducted using the Bentley Structural Analysis Computer System (SACS) Offshore Structure software to account for the structure, equipment, and environmental load. This software has proven to be used successfully to analyze and design offshore structures in various places in the world [11-14]. Modern analyses have validated its effectiveness in handling complex environmental conditions [15]. Furthermore, the design process was completed based on inplace analysis criteria and seismic and fatigue analysis [16]. Member stress checks, joint punching shears, and pile capacity checks were carried out. If there was a structural failure, a cross-section redesign was implemented to meet the API RP2A-LRFD design criteria [17]. Figure (2) summarizes the overall stages of this project.

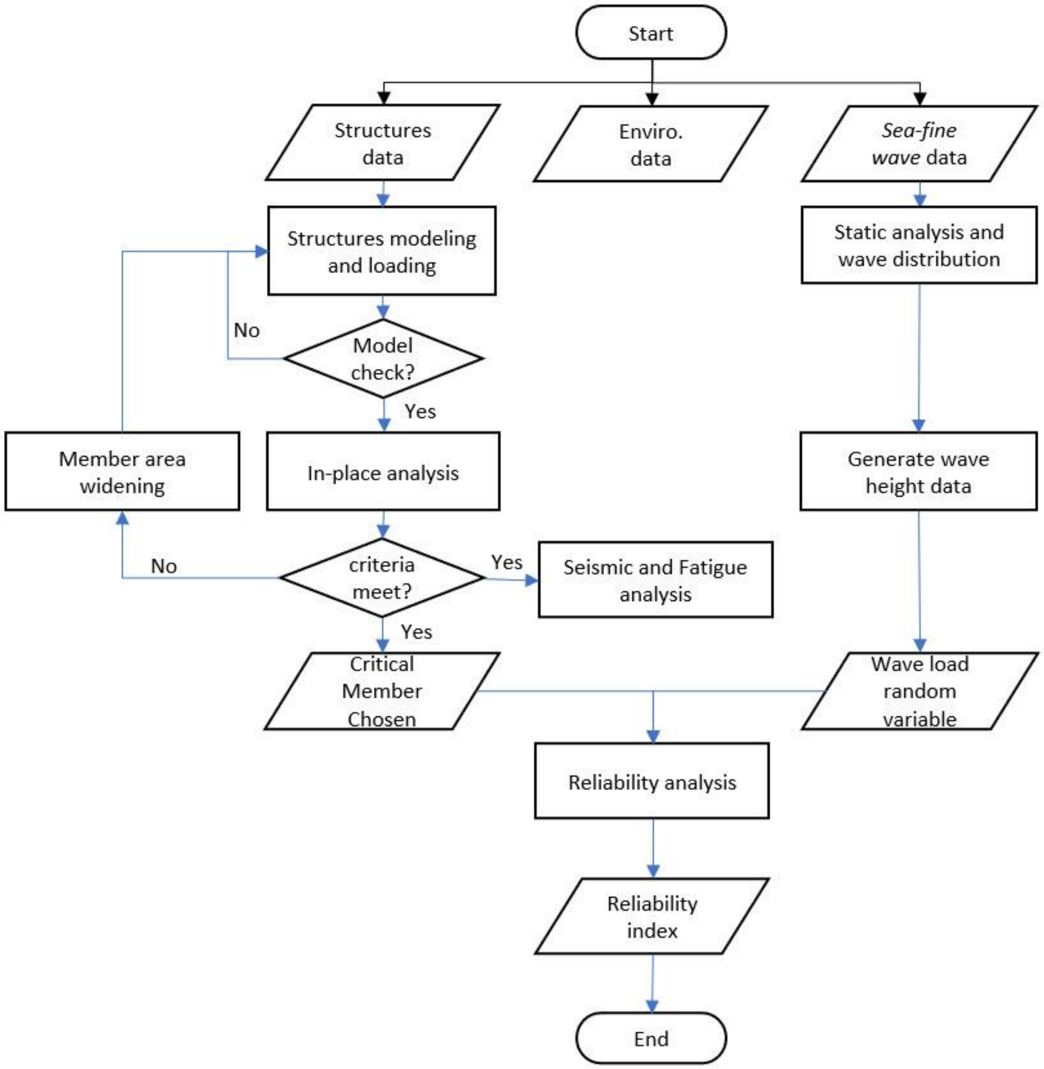

Figure 2. Project flowchart

This study analyzed an offshore platform structure with a four-legged jacket type. It was installed in the waters of the Java Sea, located at coordinates 108.671389ºE, 6.3375ºS. This location is in the northern part of Cirebon and the east of Indramayu, as shown in Figure 1. The water depth at this location is 100 ft from the datum m.s.l. to the seabed. Recent environmental studies have highlighted the unique characteristics of this region that affect structural design considerations [18-19].

2. Experimental Section

2.1. Structure and Environment Data

The platform structure has three decks: main deck at +45 ft, mezzanine deck at +31 ft, cellar deck at +25 ft. The working point is at +15 ft elevation, and the jacket walkway is at +10 ft elevation. Recent studies have emphasized the importance of proper deck configuration for operational efficiency and safety [20-21]. Figure 3 illustrates the structure of the bridge, showing the complete configuration of the platform.

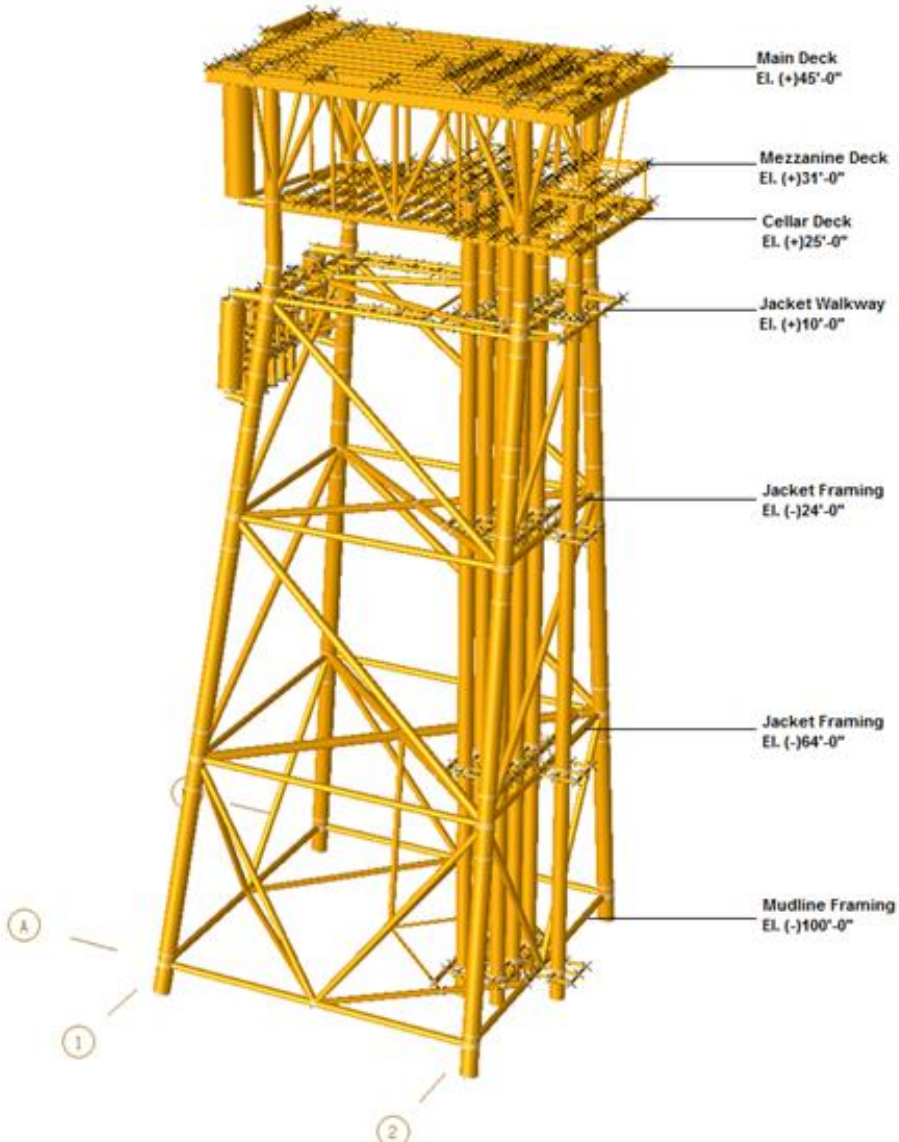

Figure 3. Four-legged jacket type structural model in Bentley SACS

Environmental data such as wind, current, and wave were used to perform the analysis, implementing modern environmental load assessment methods [22-23]. Table 1 shows the wind data used in the process. Since the flow data above is a single dataset on the water surface (0 m.s.l.), the current data must be distributed to generate distributed flow data (Table 2).

Table 1. Environmental data

Condition	Wind speed (ft/sec.)	Wave Hmax. (ft)	Wave Tmax. (ft)	Wave speed (ft/sec.)
1-year operating	42.19	14.83	8	2.07
100-year extreme	56.14	20.87	9.1	2.56

Table 2. Current distribution

Z (ft)	Operating UZ (ft/sec.)	Storm UZ (ft/sec.)
0	0.000	0.000
10	1.490	1.842
20	1.645	2.034
30	1.743	2.155
40	1.816	2.246
50	1.875	2.319
60	1.924	2.380
70	1.967	2.433
80	2.005	2.480
90	2.039	2.522
100	2.070	2.560

2.2. Analysis Methods

2.2.1. In-place Analysis

The inplace analysis in the design process included member stress checks, joint punching shear inspections, and pile axial capacity checks based on the API RP2A-LRFD criteria [24]. Two loading conditions were considered: Operating and Storm. Unity Check (UC) values were calculated, and a safe design criterion of UC less than 1 was applied. For the pile capacity inspection, the load on the pile must be below the factored pile capacity, with a factor of 0.7 for operating conditions and 0.8 for storm conditions [25-26]. The results of the inplace analysis for the respective operating and storm conditions are presented in Tables (3-6). All load values were below the factored capacity value, indicating that the structure meets the design criteria for both operating and storm conditions.

Table 3. UC member operating condition

Location	Member	Group	Property	UCmin.	UCmax.
Main Deck	M397- M030	MA2	W24×68	0.851	0.85
Cellar Deck	C024- C029	CL4	C 8×11.5	0.574	0.576
Mezzanine Deck	Z037- Z016	ME2	L4×4 ¼	0.963	0.964
Deck Leg	603L- C003	DL1	OD30”×1” WT	0.394	0.396
Deck Brace	C002- M015	TR1	OD10.75”×0.365” WT	0.685	0.678
Jacket Leg	0026-0038	LG2	OD34”×0.5” WT	0.375	0.363
Jacket Brace	304L-403L	DG2	OD16”×0.375” WT	0.582	0.605
Pile	301P-401P	PL1	OD30”×1” WT	0.377	0.357

Table 4. UC member storm condition

Location	Member	Group	Property	UCmin.	UCmax.
Main Deck	M054-M057	MA3	W16×21	0.734	0.727
Cellar Deck	C132-C133	CL1	C16×67	0.927	0.927
Mezza- nine Deck	0092-Z027	ME2	L4×4 ¼	0.664	0.663
Deck Leg	602L- C002	DL1	OD30”×1” WT	0.418	0.412
Deck Brace	C002- M015	TR1	OD10.75”×0.365” WT	0.623	0.614
Jacket Leg	0025-0037	LG2	OD34”×0.5” WT	0.483	0.483
Jacket Brace	304L-403L	DG2	OD16”×0.375” WT	0.818	0.842
Pile	301P-401P	PL1	OD30”×1” WT	0.555	0.537

Table 5. UC joint can inplace

Pile Joint	Capacity (QD) (Kips)	0.7(QD) (Kips)	DLE Load (Kips)	SLE Load (Kips)
001P	1432.35	1002.645	701.06	569.19
002P	1432.35	1002.645	370.47	328.88
003P	1432.35	1002.645	587.23	450.26
004P	1432.35	1002.645	778.38	637.39

Table 6. Pile capacity

Pile Joint	Capacity (QD) (Kips)	0.8 (QD) (Kips)	Operating		Storm	
			Water Level Max. (Kips)	Water Level Min. (Kips)	Water Level Max. (Kips)	Water Level Min. (Kips)
001P	1500.4	1200.32	690.5	711.5	787.3	806.4
002P	1506.2	1204.96	519	521.8	400	402.5
003P	1500.4	1200.32	599.8	611.6	723.2	733.4
004P	1506.2	1204.96	790.4	805.4	758.4	772.1

2.2.2. Seismic Analysis

Dynamic analysis was used to assess the seismic conditions of the structure [27]. The structure's natural period was determined to be 2.03 sec., with 90% of the mass participation in the 12th mode. Table (7) displays the value of each Pseudo Spectrum (PSV) of the two earthquake loads; Strength Level Earthquake (SLE, PGA = 0.159 g) and Ductility Level Earthquake (DLE, PGA = 0.239g).

Table 7. PSV Values for Earthquake Loads

Period	PSVSLE (in/s/g)	PSVDLE (in/s/g)
0.03	1.845	1.845
0.05	3.075	3.075
0.125	15.238	15.238
0.5	54.714	60.952
5	54.714	60.952
10	23.357	30.476

2.2.3. Fatigue Analysis

Fatigue analysis is a critical stage of the design analysis process [28-29]. It helps determine the service life of a joint structure by analyzing the effect of cyclic environmental loads on it. The analysis involves providing the system with different wave heights, wave periods, and directions [30-32]. The fatigue analysis output is the joint structure's service life, which is determined by the damage value of the design upon its exposure to cyclic loads.

2.2.4. Reliability Analysis

Reliability is defined as the probability of success (Ps) that meets the performance criteria expressed in the performance function as follows:

$$Z = g(X_1, X_2, \dots, X_n) \quad (1)$$

where X_i defines a random variable related to load and capacity parameters. Two random variables, structural strength and load, were selected to determine the performance failure parameters. Therefore, the performance function used was:

$$g(R, Q) = R - Q \quad (2)$$

where R defines the parameter of the strength of the structure, and Q is the parameter of the structure's load. The structure's failure probability is when $g(R, Q) < 0$.

$$T = 0.5409Hs + 3.843 \quad (3)$$

The probability of member failure can be determined from the PDF-UC curve by calculating the area under the PDF curve with a limit of $1 \leq UC \leq \infty$. Based on the results of the previous distribution, the calculation of the reliability index (β) was done using the following log normal equations,

$$P_f = 1 - \Phi\left(\frac{\lambda_{UC}}{\zeta_{UC}}\right) \quad (4)$$

$$P_f = 1 - P_s$$

$$P_s = \Phi - (\beta) \quad (5)$$

The value of the reliability index can be determined by:

$$\beta = \frac{\lambda_{UC}}{\zeta_{UC}} \quad (6)$$

The structural strength parameter selected was the yield stress of the structural material (Fy), and the load parameter was a wave load with significant wave height and period. Monte Carlo simulation [33-35] was used as the reliability analysis method, with 50 simulations carried out. To generate the wave data, 59 years of significant wave data from the Java Sea was used to determine the wave data distribution. Kolmogorov-Smirnov (K-S) method [36] was used to carry out the distribution test. This method was then used to generate 50 wave data pairs with parameters: H_{max}= 16.22 ft, mean = 3.45 ft, and standard deviation = 2.53 ft.

3. Results and Discussion

3.1. Wave Data Analysis and Distribution

The wave data distribution analysis was conducted using the Kolmogorov-Smirnov test method, with results shown in Figure 4. Recent studies have validated this approach for wave data analysis in Southeast Asian waters [37-38]. The log normal distribution demonstrated the best fit with the smallest $D_n$value of 0.0612, aligning with findings from similar regional studies [39].

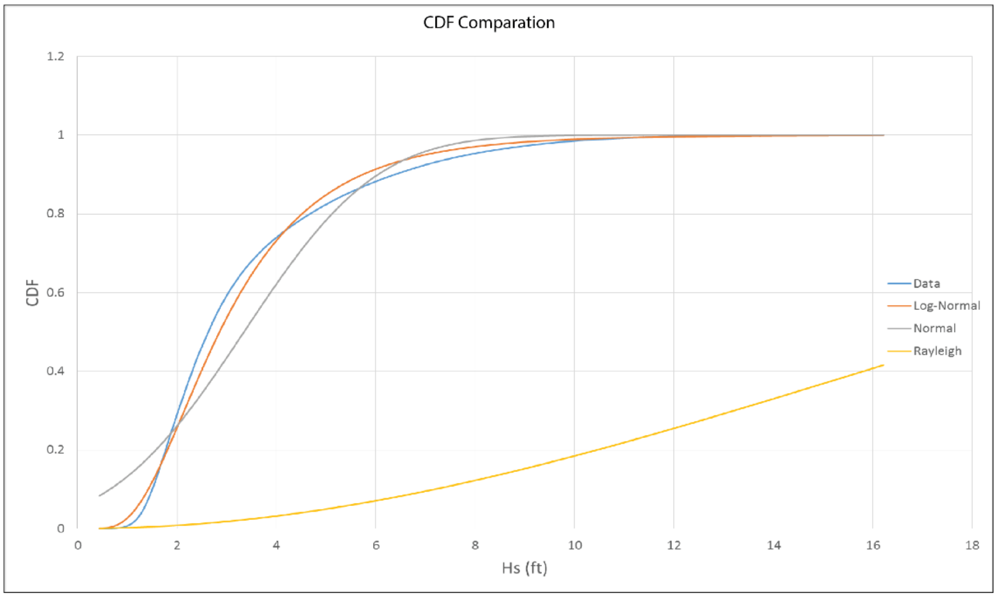

Figure 4. $\boldsymbol{H_s}$ wave K-S test results

3.2. Structural Performance Analysis

3.2.1. In-place Analysis Results

The inplace analysis results for operating and storm conditions demonstrated satisfactory performance of all structural components. Tables 8-10 display the results of the member stress UC, joint punching shear, and pile capacity checks for both SLE and DLE earthquake conditions. Recent research has emphasized the importance of these parameters in offshore structure assessment [40, 41]. The pile capacity met both operating and storm conditions for each maximum and minimum water level, as the working load remained below the factored capacity value, consistent with modern design standards [42].

Table 8. Seismic analysis member stress results

Joint	UCSLE	Joint	UCDLE
304L	0.688	404L	0.439
303L	0.421	403L	0.433
401L	0.386	401L	0.427
204L	0.334	402L	0.397

Table 9. Joint punching shear results

Location	Member	Group	Property	UCSLE	UCDLE
Main Deck	M021-M001	MA2	W24×68	0.503	0.555
Cellar Deck	C057-C085	CL4	C8×11.5	0.46	0.556
Mezzanine Deck	0092-Z027	ME2	L4×41/4	0.519	0.532
Deck Leg	602L- C002	DL1	OD30"×1"WT	0.31	0.406
Deck Brace	C003- M008	TR1	OD10.75"×0.365"WT	0.416	0.558
Jacket Leg	0026-0038	LG2	OD34"×0.5"WT	0.253	0.342
Jacket Brace	304L-403L	DG2	OD16"×0.375"WT	0.463	0.685
Pile	301P-401P	PL1	OD30"×1"WT	0.332	0.444

Table 10. Pile capacity verification results

Pile Joint	Capacity (QD) (Kips)	0.7(QD) (Kips)	DLE Load (Kips)	SLE Load (Kips)
001P	1432.35	1002.645	701.06	569.19
002P	1432.35	1002.645	370.47	328.88
003P	1432.35	1002.645	587.23	450.26
004P	1432.35	1002.645	778.38	637.39

3.2.2. Fatigue Analysis Results

The fatigue analysis results for the joint structure are presented in Tables 11-12. The damage value for the joint structure was above 1, indicating that further assessment of the jacket bracing members is necessary to achieve the desired service life of 52 years [43-44]. This finding aligns with recent studies on fatigue life assessment of offshore structures in similar environments [45].

Table 11. Joint fatigue damage results

Joint	Member	Group	Damage	Fatigue Life (year)
0006	102L-0006	BR3	1.67	31

Table 12. Additional joint fatigue life values

Joint	Member	Group	Damage	Fatigue Life (year)
003P	003P-103P	PL1	0.85	61.11
304L	202L-304L	DG3	0.64	81.27
304L	0032-304L	LG1	0.54	96.57
604L	504L-604L	PL1	0.53	98.06
0163	0165-0163	HR3	0.28	184.40
303L	303L-304L	HR1	0.21	248.80

3.3. Reliability Assessment

The PDF-UC factoring conditions for the main deck member are shown in Figure 5. Advanced reliability analysis techniques [46, 47] were employed to interpret these results. Tables 13 and 14 present the main statistical parameters of the UC obtained from the simulation results and the reliability index calculations for LRFD and non-factor loading conditions.

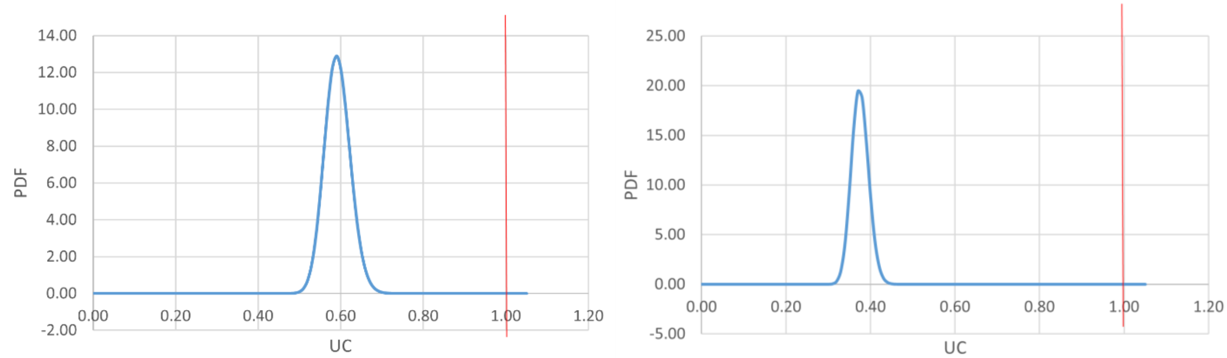

Figure 5. PDF of UC main beam: (left) LRFD and (right) unfactored.

Table 13. Main statistical parameters

Location	Factored		Unfactored	
Main Beam	Mean	0.5917	Mean	0.3753
	Standard Error	0.0044	Standard Error	0.0029
	COV	0.0525	COV	0.0540
Deck Leg	Mean	0.3197	Mean	0.2006
	Standard Error	0.0024	Standard Error	0.0016
	COV	0.0524	COV	0.0547
Jacket Leg	Mean	0.2615	Mean	0.1784
	Standard Error	0.0029	Standard Error	0.0021
	COV	0.0764	COV	0.0826
Pile	Mean	0.2552	Mean	0.1662
	Standard Error	0.0029	Standard Error	0.0021
	COV	0.0790	COV	0.0875

Table 14. Reliability index calculations

Location	LRFD			Unfactored		
	λ_{UC}	ζ_{UC}	β	λ_{UC}	ζ_{UC}	β
Main Beam	-0.53	0.05	10.03	-0.98	0.05	18.20
Deck Leg	-1.14	0.05	21.80	-1.61	0.05	29.44
Jacket	-1.34	0.08	17.62	-1.73	0.08	20.94
Pile	-1.37	0.08	17.35	-1.80	0.09	20.59
$\beta_{average}$			17.70			22.29

Recent studies by [48-49] recommend specific P_f and β values for different security classes, as shown in Table 15. The four members analyzed in this study fall within the high safety class category, with a recommended minimum reliability index of 3.72. The obtained reliability index values of 16.70 for factored load and 22.29 for unfactored conditions significantly exceed these recommendations, suggesting potential over-conservation in current design standards for regional conditions [50].

Table 15. Safety level recommendations

Safety Level	Target (P_f)	Safety (β)
Low	10-2	2.32
Normal	10-3	3.09
High	10-4	3.72

The analysis of this study has yielded several significant findings regarding the design and reliability of four-legged jacket type offshore platforms in the Java Sea environment. The structural analysis demonstrated compliance with design criteria for member stress, joint punching shear, and pile capacity according to the 1993 API RP2A-LRFD design criteria, aligning with recent regional structural assessment standards [51-52]. Fatigue analysis revealed critical insights into the structure's long-term performance, with one joint in the bracing showing a service life of 31 years, falling below the desired service life of 52 years, necessitating optimization through cross-section enhancement. This finding correlates with recent studies on fatigue life assessment of offshore structures in Southeast Asian waters [53-54], which emphasize the importance of regional environmental factors in structural longevity.

The Monte Carlo simulation method, employing 50 simulations of the four main member representatives using random variables in the form of significant waves, provided comprehensive reliability assessments. The mean reliability index (β) values of 16.70 for LRFD condition and 22.29 for unfactored condition significantly exceed the recommended minimum value of 3.72 for high-safety class structures [55]. This substantial margin suggests that current load factors may be overly conservative for Java Sea conditions, a finding supported by recent regional studies [56-57].

Based on these findings, this study strongly indicates the need for a more region-specific approach to load factor calibration for Indonesian waters, as supported by recent environmental studies [58-59]. Future research should incorporate detailed wave data analysis using maximum wave data and employ a minimum of 1000 Monte Carlo simulations to enhance result accuracy [60]. Furthermore, comprehensive studies across different Indonesian waters are essential to develop more appropriate environmental load factors for the API RP2A-LRFD application [61-62].

These findings contribute significantly to the growing body of knowledge regarding offshore structure design in Southeast Asian waters, particularly concerning the adaptation of international standards to regional conditions [63]. The results suggest that while current design standards ensure safety, they may lead to over-conservative designs that could be optimized through region-specific modifications [64-65]. This optimization could potentially lead to more efficient and economical designs while maintaining the required safety standards for offshore structures in the Java Sea region.

4. Conclusion

This article discusses the design and structural reliability analysis of a four-legged jacket-type offshore platform in the North Java Sea. The study highlights the importance of adapting international design standards, such as API RP2A-LRFD, to specific local environmental conditions.

Through deterministic and probabilistic analysis methods, including Monte Carlo simulations, this study evaluates the structure's resistance to environmental loads such as wind, waves, currents, and earthquakes. The analysis results show that the structure meets the basic design criteria, but the safety factor used may be too conservative for regional conditions. The obtained reliability index (β = 16.70 for LRFD and β = 22.29 for the unfactored condition) far exceeds the minimum recommended limit (β = 3.72).

These findings suggest that current design standards can be adjusted to optimize efficiency and cost without compromising safety. The main recommendations of this study are the need for load factor adjustment for Indonesian waters as well as further research with broader Monte Carlo simulations to improve the accuracy of the reliability analysis.

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