Load Directionality Impact on Jacket Platform Strength: A SACS Study

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***Abstract*—As a significant number of jacket platforms in the Asia-Pacific waters approach or exceed their design life, accurate ultimate strength assessment is crucial for their safe operation and life extension. Existing studies often focus on a single worst-case direction or treat extreme and operating conditions in isolation, lacking systematic investigation into the directional sensitivity of structures across multiple return periods. To address this gap, this study conducts a comprehensive high-fidelity nonlinear static analysis on a representative four-legged jacket platform using the industry-standard software SACS. The research incorporates the coupled effects of wave, current, and wind loads from eight directions (0°–315°) under two environmental regimes: the 100-year extreme storm and the 5-year operating condition. By quantifying the directional response, nonlinear scaling, and adverse combinations of bending moment, shear force, and axial force, the analysis reveals strong anisotropy and return-period dependency. In terms of engineering implications: (1) load parameters under extreme conditions are amplified by a factor of 3–4 compared to operating conditions, indicating that life extension assessments should not rely on linear extrapolation from operational loads but should directly incorporate long-return-period environmental parameters; (2) peak bending moment and shear occur at 90°/270°, while the most severe reverse bending is concentrated in the 135°–225° sector, suggesting that foundation and joint designs should account for positive and negative bending demands separately rather than assuming a single critical axis; (3) the maximum upward force peaks at 180°, whereas the maximum downward force reaches its extreme near 225°, implying that pile tension and compression designs should not adopt symmetric assumptions due to the decoupled directional behavior; (4) the sector from 135° to 225° experiences simultaneous high shear, substantial negative bending, and significant uplift, indicating that this combined load case should be given priority in overturning resistance and joint detailing checks. Based on these results, it is suggested that engineering practice adopt 360° directional load case screening, component-level directional load envelopes, and return-period-dependent amplification factors as references for integrity management of aging jacket platforms.**

***Keywords*—offshore jacket platform, environmental loads, structural response, ocean engineering, numerical simulation, waves**

I. Introduction

Fixed offshore jacket platforms are critical infrastructure assets within the global energy sector, serving as the primary structures for hydrocarbon exploration and production in shallow to intermediate water depths [1]. These complex steel lattice frameworks are engineered to endure a multitude of concurrent forces over operational lifespans that can exceed several decades. In addition to permanent gravity loads from topside facilities, they are perpetually subjected to severe, time-varying environmental actions, primarily stemming from wind, ocean currents, and—most significantly—waves [2–5]. Among these environmental factors, wave loading is often the most critical, as it induces complex hydrodynamic interactions and governs the extreme load effects on the submerged structural members [6, 7]. The accurate prediction of these dynamic loads and the corresponding nonlinear structural response is paramount for ensuring operational safety and structural integrity, as underestimation can precipitate catastrophic failures, leading to profound economic losses, environmental disasters, and potential loss of life [8–10].

In regions such as the Asia-Pacific, and specifically in Malaysian waters, hundreds of offshore platforms have been installed over the past few decades [11]. A significant portion of this offshore infrastructure is now approaching or has surpassed its original design life of approximately 25 years [12]. These aging platforms face cumulative challenges, including material degradation from corrosion and the increased hydrodynamic loading effects of marine growth, which can significantly reduce their structural reliability and performance [13, 14]. Consequently, there is a pressing need for robust structural integrity management and reassessment programs to ensure these platforms can continue to operate safely or to inform decisions regarding their life extension or decommissioning [15, 16]. To address these challenges, the offshore industry has progressively shifted from traditional linear-elastic analysis, which is often insufficient for capturing the full range of structural behavior, to more advanced nonlinear analysis techniques. The ultimate strength analysis, particularly the nonlinear static pushover method, has become a widely accepted and powerful tool for assessing the true capacity of a platform [17]. This method involves applying a progressively increasing lateral load pattern to a finite element model of the structure until it reaches a state of collapse. The outcome of this analysis provides critical insights into the platform's failure modes, ductility, and, most importantly, its Reserve Strength Ratio (RSR). The RSR, defined as the ratio of the structure's ultimate collapse load to its design load, serves as a key indicator of the platform's inherent safety margin [18]. Industry standards and guidelines, such as those from the American Petroleum Institute (API) and Det Norske Veritas (DNV), now widely recommend or require such nonlinear analyses for the assessment of existing platforms [19].

An extensive body of research has been dedicated to the ultimate strength analysis of jacket platforms. Studies have investigated the influence of various parameters on structural

capacity. For instance, the nonlinear behavior of the foundation, governed by Pile-Soil-Structure Interaction (PSSI), has been identified as a primary source of nonlinearity and a critical factor in the overall system's response. Researchers have demonstrated that an accurate PSSI model is essential, as foundation failure can often be a precursor to or a simultaneous event with the buckling of jacket members [20, 21]. Furthermore, sensitivity analyses have been conducted to determine the most influential variables affecting the platform's response. These studies have consistently shown that uncertainties in hydrodynamic coefficients (e.g., drag and inertia coefficients), marine growth thickness, and soil properties (like undrained shear strength) can significantly impact the predicted ultimate capacity [22]. To this end, advanced methods like Incremental Wave Analysis (IWA) have been developed to provide a more refined estimation of the platform's capacity against wave loading hazards by incrementally increasing wave heights until collapse [23]. Industry standards have increasingly adopted nonlinear static pushover analysis as the benchmark for ultimate strength assessment, with the Reserve Strength Ratio (RSR) serving as the key safety metric. While extensive research has explored factors like Pile-Soil-Structure Interaction (PSSI) and wave load modeling [21, 23], a significant gap remains in the systematic, integrated evaluation of directional sensitivity across multiple return periods. Most existing studies either focus on a single "worst-case" direction or treat extreme and operational conditions in isolation, thereby overlooking how directional vulnerability shifts with load intensity and how unfavorable combinations of load components (e.g., moment, shear, and axial force) may arise at non-intuitive angles [22].

This study addresses this gap by conducting a comprehensive, high-fidelity numerical investigation of a representative four-legged jacket platform. Using the industry-standard SACS software, we perform nonlinear pushover analyses for eight distinct wave directions (0° to 315°) under two defining environmental regimes: extreme storm conditions (100-year return period) and operating conditions (5-year return period). This dual-focus approach enables a detailed examination of: (1) the nonlinear amplification of key mudline load parameters (bending moment, shear force, and axial force) with return period; (2) the direction-dependent patterns of these parameters, visualized through both Cartesian and polar plots; and (3) the identification of critical directional zones where adverse load combinations may govern design. The primary objectives are to: (i) quantify the platform's directional and identify its weakest orientation; (ii) elucidate the phase differences between peak positive and negative load components; and (iii) provide a directionally-aware framework for the ultimate strength assessment and integrity management of jacket platforms, with direct implications for safe operation and life extension in this strategic region. The remainder of this paper is organized as follows: Section 2 elaborates on the research methodology, including finite element modeling of the platform, definition of material properties, multi-directional simulation of environmental loads (waves, current, wind), and the soil-structure interaction modeling. Section 3 systematically presents and discusses the structural response results under different return periods and wave directions, covering mudline load distributions, directional patterns, and identification of critical load combinations. Finally, Section 4 summarizes the main findings, and engineering implications.

II. Methodologies

This chapter systematically outlines the comprehensive research methodology adopted to assess the ultimate strength of the offshore jacket platform. The framework is built upon high-fidelity finite element modeling, encompassing structural geometric modeling, definition of material constitutive behavior, detailed characterization of multi-source environmental loads. The industry-standard software SACS was employed for modeling and simulation, with a focus on investigating the multidirectional combined effects of wave, current, and wind loads. By integrating different return periods (operating and extreme conditions), the study systematically evaluates the platform's nonlinear response characteristics and directional sensitivity under complex marine environments. The following subsections detail the platform configuration and modeling, material properties, load condition definitions, load case setups, and nonlinear finite element analysis procedures, collectively providing a robust methodological foundation for the subsequent results analysis and discussion.

A. Offshore Jacket Platform Configuration and Modelling

The subject of this investigation is a representative four-legged, fixed steel jacket platform installed at a nominal water depth of 60 m, designed to support a wellhead topside. The jacket structure is constructed from tubular steel members and incorporates five primary frame elevations, spanning from the mudline at EL (−) 58.32 m to the topside interface at EL (+) 19.2 m, as illustrated in Fig. 1 and summarized in Table 1. The topside consists of three deck levels: the cellar deck and the main deck.

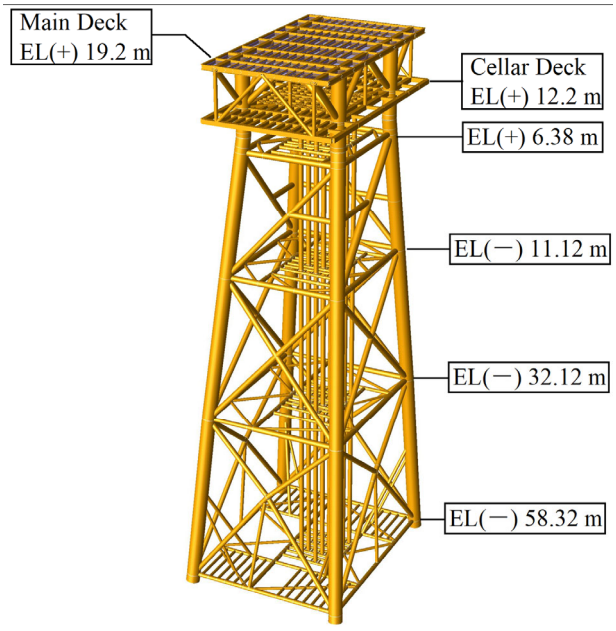


Fig. 1. Offshore jacket platform 3-Dimensional (3D) isometric view with elevation labelling.

To accurately assess the structural performance, a high-fidelity three-dimensional finite element model was developed using the industry-standard software SACS

(Structural Analysis Computer System) [24]. The model comprehensively includes all primary structural components, such as legs, braces (arranged in an X-bracing configuration within vertical frames), and piles. Secondary elements, including conductors and risers, are also incorporated to ensure an accurate representation of the platform's mass distribution and stiffness characteristics, thereby enabling precise simulation of load transfer and structural response.

Table 1. Elevations of the jacket offshore platform for this study

Level details	Platform Elevation
Main Deck Level	EL(+) 19.2 m
Cellar Deck Level	EL(+) 12.2 m
Level 1	EL(+) 6.38 m
Level 2	EL(−) 11.12 m
Level 3	EL(−) 32.12 m
Level 4 (Base/Mudline)	EL(−) 58.32 m

B. Offshore Jacket Platform Material Properties

The structural members of both the jacket and topside modules are fabricated from high-tensile steel. This grade of steel exhibits a nominal yield strength of 345 MPa, with the exact value depending on member thickness and specific functional requirements. To ensure the computational accuracy and reliability of the finite element model, the constitutive material properties and key mechanical parameters adopted in this study are strictly consistent with the design specifications and reflect actual engineering practice. The detailed material properties, including Young's modulus, shear modulus, density, Poisson's ratio, and yield strength, are summarized in Table 2, providing essential inputs for the subsequent nonlinear structural analysis.

Table 2. Material properties of the steel used in the jacket platform

Steel Details	Value
Young's Modulus, E	20000 kN/cm^2
Shear Modulus, G	8 000 kN/cm^2
Density in air	7850 kg/m^3
Poisson's ratio	0.30
Yield strength, f_y	34.5 kN/cm^2

C. Load Conditions

The platform is subjected to a combination of permanent gravity loads and variable environmental loads. The accurate definition of these loads is critical for the ultimate strength assessment.

1) Environmental loads

Environmental loads represent the primary source of lateral forces acting on jacket platforms. Based on their physical origins, these loads can be broadly classified into aerodynamic loads (wind) and hydrodynamic loads (wave and current) [25–27]. In this study, a conservative simultaneous loading assumption is adopted, where wind, waves, and currents are considered to act concurrently from the same direction, to evaluate the most adverse load combination effects. For slender offshore structures such as jackets, hydrodynamic forces induced by waves and currents typically constitute the vast majority (approximately 90%) of the total environmental load. Consequently, their accurate modeling is critical for reliable ultimate strength assessment.

2) Wave and current loads

Hydrodynamic forces generated by the combined action of ocean waves and currents constitute the most significant environmental loads on jacket platforms [17]. These forces arise from the complex interaction between the moving fluid and submerged structural members. Ocean currents, typically driven by wind or tidal effects, induce steady drag forces, while surface waves generate oscillatory drag and inertia forces due to the acceleration and deceleration of water particles. When waves propagate on a current, their characteristics such as wavelength and steepness are modified, which in turn influences the magnitude and distribution of wave-induced loads. Therefore, accounting for the coupled effects of waves and currents is essential in the analysis.

For structures composed of slender tubular members, such as jacket platforms, where the member diameter is generally small relative to the wavelength, hydrodynamic forces are commonly calculated using the Morison equation. This semi-empirical formula decomposes the total wave force per unit length on a cylinder into two components: an inertia force proportional to the water particle acceleration and a drag force proportional to the square of the water particle velocity.

Accurate estimation of wave loads depends on a precise description of underwater fluid kinematics. Various wave theories, including linear (Airy) and nonlinear (e.g., Stokes, cnoidal) wave theories, are available for modeling water particle motion, with their applicability determined by parameters such as water depth, wave height, and wave period [21, 28]. In this study, Stokes' fifth-order wave theory was adopted. This nonlinear theory is suitable for describing steep waves in intermediate to deep water, aligning well with the conditions of the 100-year extreme storm at the platform location. Compared to linear wave theory, the fifth-order Stokes formulation provides a more accurate representation of the wave profile, particularly capturing the higher crests and flatter troughs characteristic of steep nonlinear waves, thereby better reflecting wave geometry and kinematics.

Within the SACS software, the Stokes fifth-order wave is defined by the specified wave height (H) and wave period (T). The software employs a perturbation method to solve the nonlinear free-surface boundary conditions, generating the detailed fields of water particle velocities and accelerations required for the Morison equation. This approach effectively captures wave nonlinearities, leading to a more realistic estimation of hydrodynamic loading, which is crucial for ultimate strength assessment. The velocity potential adopted in this study is expressed as (Eq. (1)):

$$\Phi = \frac{L^2}{2\pi T}\sum_{n=1}^{5}\Phi_n' \cosh\left[2\pi n\left(\frac{z+d}{L}\right)\right]\sin\left[2\pi n\left(\frac{x}{L}+\frac{t}{T}\right)\right] \quad (1)$$

where the wave period T is related to the wavelength L by (Eq. (2)):

$$T = \sqrt{\frac{2\pi L}{gX\tanh\left(2\pi\frac{d}{L}\right)[1+\lambda^2 C_1+\lambda^4 C_2]}} \quad (2)$$

The constants, Φ_n', λ, C_1, and C_2 are known (are dimensionless) as functions of H, L, and d.

3) Wind

Wind loads act on the portions of the platform exposed to the atmosphere, including topside decks, equipment, and the above-water sections of the jacket structure. Although

generally less dominant than hydrodynamic loads induced by waves and currents for jacket platforms, wind forces constitute an important component of the total environmental load, particularly under extreme storm conditions. The calculation of wind loads in this study strictly adhered to internationally recognized industry standards, including the guidelines provided by the American Petroleum Institute [29] and the American Bureau of Shipping [30]. Wind load calculation is based on the wind pressure distribution over structural surfaces. The wind pressure acting on each member of the platform can be estimated using the following empirical formula (Eq. (3)):

$$p = 0.00338V^2C_hC_s \quad (3)$$

where p is the wind pressure in pounds per square foot, V is the wind speed in knots, C_h is the height coefficient, accounting for wind speed variation with elevation, and C_s is the shape coefficient, depending on the cross-sectional shape of the member (e.g., tubular or flat surfaces). According to API and ABS recommendations, the shape coefficient C_s is taken as 0.5 for circular tubular members and 1.5 for flat surfaces or other non-circular sections. The wind pressure p is applied as a uniformly distributed static load over the windward projected area of the member. The resultant wind force F acting on a platform member is calculated as follows (Eq. (4)):

$$F = pAsin\alpha \quad (4)$$

where, A is the projected area of the member normal to the wind direction, α is the angle between the wind direction and the axis of the member.

This formulation is recommended by both DNV and API standards and is applicable to the assessment of wind loads on inclined or horizontal members. In this study, the calculated wind forces were applied as static loads on the corresponding member surfaces within the finite element model.

4) Environmental loads' directionality

To identify the most critical loading direction that challenges the structural integrity of the platform, combined environmental loads were applied from multiple azimuths [31]. The directional analysis considered eight principal wave attack angles: 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°, as illustrated in Fig. 2. To simplify the analysis and adopt a conservative approach, wind, waves, and currents were assumed to be collinear and act concurrently from the same direction for each loading case. Although this assumption may overestimate the combined load effects in certain directions, it effectively captures the most adverse structural response under extreme environmental conditions, thereby providing a reliable basis for safety assessment.

5) Soil

The interaction between the foundation piles and the surrounding soil constitutes a critical source of nonlinearity in the overall structural response. The soil modeling in this study strictly followed the provisions of the American Petroleum Institute (API) recommended practice, API RP 2A-WSD: Planning, Designing, and Constructing Fixed Offshore Platforms—Working Stress Design. To accurately simulate the nonlinear soil behavior under cyclic loading, the pile-soil interaction was characterized using three types of empirical curves:

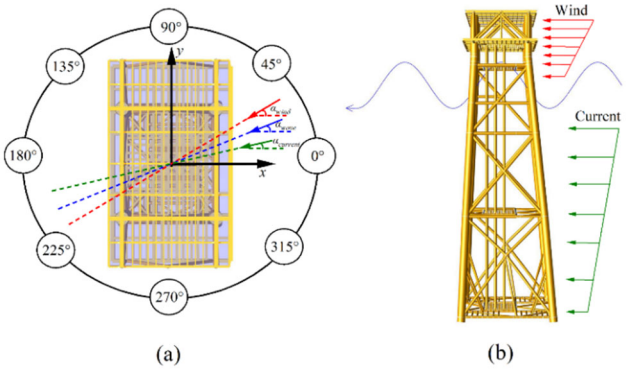


Fig. 2. Loading directionality and environmental loads of offshore jacket platform.

- *p–y* curves: describing the nonlinear lateral soil resistance against pile lateral displacement;
- *t–z* curves: representing the nonlinear axial skin friction along the pile shaft;
- *q–z* curves: defining the nonlinear end-bearing capacity mobilization with pile tip displacement.

These curves establish the nonlinear relationship between soil resistance and pile displacement, enabling the model to capture the progressive mobilization of foundation capacity under increasing lateral load. This approach provides a realistic representation of the overall stiffness and load-carrying behavior of the pile-soil system, thereby delivering reliable boundary conditions for ultimate strength assessment.

6) Gravity loads

Gravity loads consist of all permanent (dead) and temporary (live) loads acting on the platform, serving as the primary source of the initial stress state. Permanent loads include the self-weight of the jacket, piles, and topside structures, as well as the weight of permanently installed equipment, piping systems, and architectural components. Variable loads encompass time-dependent components such as personnel loads, consumable supplies, drilling equipment (where applicable), and temporary loads in designated laydown areas. In this study, all specified gravity loads were applied to the finite element model in SACS to establish an accurate initial stress and deformation state under self-weight prior to the application of lateral environmental loads. This step is crucial for the realistic prediction of structural response in subsequent nonlinear pushover analyses, ensuring that the results reflect the true mechanical behavior of the platform under in-service conditions.

D. Application of Operating and Extreme Load Condition

To evaluate the structural response of the platform throughout its service life, two representative environmental load cases were defined based on the probability of occurrence: the Operating Condition and the Extreme Condition. The following subsections describe each case in detail.

1) Operating condition

The operating condition represents the typical

environmental loading that the platform is expected to withstand during normal operations. The load parameters for this case were derived from metocean data corresponding to a 5-year return period. This analysis is essential for assessing the platform's performance and safety under frequently occurring, moderate environmental loads, providing a basis for operational maintenance and fatigue life evaluation.

2) Extreme condition

The extreme condition simulates the severe storm events that the platform must survive to ensure its ultimate structural integrity. Load parameters were based on metocean data for a 100-year return period. Nonlinear pushover analysis under this condition forms the basis for determining the platform's ultimate load-carrying capacity, and the failure modes, which is critical for evaluating the platform's safety margin against collapse under extreme events. To account for tidal variations and potential climate change effects, the two load conditions (operating and extreme) were further combined with design water depths, resulting in two primary analysis cases as summarized in Table 3. This approach ensures a comprehensive and robust structural assessment across varying water-level scenarios.

Table 3. Combination of environmental load cases for simulation

Case name	Set of Analyses
C1	Operating condition (5-year return period)
C2	Extreme condition (100-year return period)

E. Finite Element Analysis

To systematically investigate the nonlinear behavior and ultimate load-carrying capacity of the offshore jacket platform under complex marine environmental actions, this study employed advanced numerical simulation techniques based on the finite element method, utilizing the industry-recognized software SACS for integrated modeling and analysis. Developed by Bentley Systems, SACS is a comprehensive suite for offshore structural engineering that integrates modeling, load calculation, and nonlinear analysis, and has been widely validated and accepted in both engineering practice and academic research for ultimate strength assessment of marine structures. Through the development of a high-fidelity three-dimensional finite element model and based on the environmental load conditions (waves, current, and wind) and multi-directional loading patterns defined in Sections 2.3 and 2.4. The analysis fully accounted for the directional combination effects of environmental loads (applied from eight principal directions) and incorporated different return periods (operating and extreme conditions) and water-level variations (minimum and maximum design water depths) to establish a multi-case analysis framework. This systematic approach aims to identify the most critical response directions and structural vulnerabilities of the platform under varying environmental excitations and load combinations.

III. Results and Discussion

This section presents a systematic analysis of the structural response of the fixed offshore jacket platform under two distinct environmental regimes: an extreme condition corresponding to a 100-year return period and an operating condition representing a 5-year return period. These scenarios are defined to assess the platform's performance at the Ultimate Limit State (ULS) and the Fatigue State (FLS/SLS), respectively. The environmental design parameters governing these conditions are summarized in Table 4. For the 100-year storm, the significant wave height reaches 12.20 m with a period of 11.0 s, accompanied by a maximum wind speed of 40.0 m/s and a seabed current speed of 1.50 m/s. In contrast, the 5-year operational state is characterized by a significantly milder environment, with a wave height of 7.21 m, a period of 8.5 s, a wind speed of 13.0 m/s, and a reduced current speed of 0.49 m/s at the seabed. The substantial differences in these parameters establish a clear basis for evaluating the nonlinear scaling of structural loads with environmental severity and for examining the platform's directional sensitivity across a broad intensity spectrum. Subsequent sections delve into the detailed directional response of key load components—bending moment, shear force, and axial force—at the mudline, derived from nonlinear pushover analyses conducted for eight wave incidence angles (0° to 315°). The results are presented through a combination of Cartesian line graphs and polar coordinate plots, enabling a comprehensive evaluation of both load magnitude scaling with return period and the inherent anisotropy of the structural system.

Table 4. Environmental design parameters for different return periods

Return Period (years)	Wave Height (m)	Period (s)	Wind Speed (m/s)	Current Speed (5m depth, m/s)	Current Speed (30m depth, m/s)	Current Speed (60m depth, m/s)
100	12.20	11.0	40.0	0.40	0.80	1.50
5	7.21	8.5	13.0	0.13	0.26	0.49

A. Numerical Simulation

To accurately evaluate the structural response and performance of a fixed offshore jacket platform under various marine environmental conditions, a detailed three-dimensional (3D) Finite Element (FE) model was developed in this study. The model is based on a typical four-legged jacket platform installed in a water depth of 60 m. The geometric configuration of the model is depicted in Fig. 3 and Fig. 4, which present the front, side, and top views of the platform, respectively, comprehensively illustrating its spatial truss structure. The structure primarily consists of large-diameter vertical main legs, horizontal frames connecting these legs, and an extensive system of diagonal braces (X- and K-braces) that provide lateral stiffness and load-bearing capacity. The topside structure, which supports equipment and operational modules, transfers its weight through the main legs to the substructure. The base of the platform is connected to the seabed through a Pile-Soil Interaction (PSI) model, which simulates the restraining effects of the pile foundation under complex loading and provides firm support for the structure. The core of this investigation lies in assessing the structural integrity of the platform under environmental loads corresponding to two different design return periods, representing two critical design scenarios: extreme and operational conditions. The

color contours in the figures represent the Unity Check (UC) ratio of the structural members, which is the ratio of the actual stress in a member to its allowable stress. The UC value is a key indicator of structural safety, with colors ranging from blue (low UC value) to green, and then to yellow and red (high UC value). Typically, red indicates a UC value approaching or exceeding 1.0, signifying that the member's load-bearing capacity has reached or surpassed its design limit, thus highlighting an area requiring critical attention in the structural analysis.

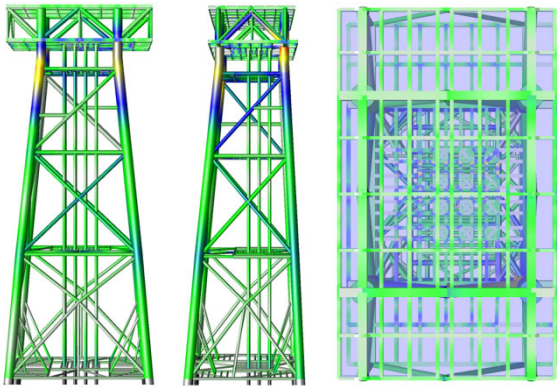


Fig. 3. Three-dimensional model of a fixed offshore jacket platform (Once in a century) (a) Front view, (b) Side view, (c) Top view.

Fig. 3 illustrates the UC value distribution on the platform under "once-in-a-century" extreme environmental conditions. In this Ultimate Limit State (ULS), the structure is subjected to the combined maximum forces of wind, waves, and currents expected during its design life. It is clearly observed from the figure that several areas exhibit high UC values, indicated by yellow and even red colors. These stress concentration "hot spots" are primarily located at: (1) the joints connecting the main legs and horizontal frames (K- or X-joints) in the upper and middle sections of the platform; and (2) certain diagonal braces subjected to high axial forces or bending moments. These red areas signify that under extreme loading, the stress levels in these critical members are approaching the material's allowable limit, constituting the weak links of the platform. Therefore, the design and fabrication quality control of these areas are of paramount importance, and they are also the primary focus for in-service structural health monitoring. Fig. 4, in contrast, displays the UC value distribution under "once-in-five-years" environmental conditions, a scenario typically used for Fatigue Limit State (FLS) or Serviceability Limit State (SLS) analysis. In stark contrast to Fig. 3, the entire structure in Fig. 4 is predominantly colored green and light blue, indicating that the UC values for all members are generally low and the structure possesses an ample safety margin. This is expected, as the five-year return period load is far less severe than the one-hundred-year extreme load. Although the overall stress level is not high, this type of frequently occurring operational loading is the main contributor to the accumulation of fatigue damage in the structure. Consequently, the analysis of this condition is equally indispensable for ensuring the platform's durability and reliability throughout its entire design life. By comparing the UC value distributions under these two scenarios, this study not only verifies the platform's survivability in extreme storms but also provides crucial input for its long-term fatigue performance assessment.

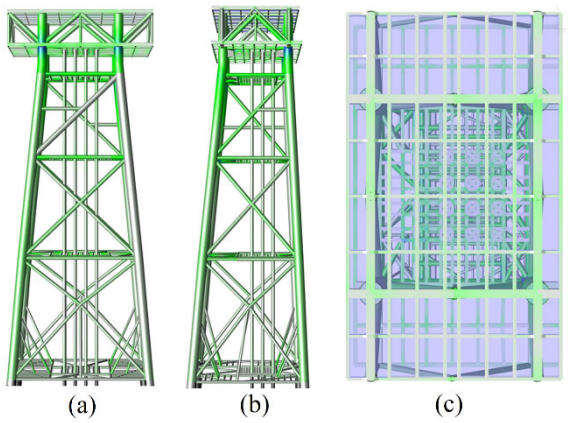


Fig. 4. Three-dimensional model of a fixed offshore jacket platform (Once in five years) (a) Front view, (b) Side view, (c) Top view.

B. Maximum and Minimum Moment about Mudline

This section investigates the bending moment response at the mudline of a jacket platform, a critical indicator for assessing the structural safety margin of both the pile foundation and the jacket-leg connection. The analysis employs Cartesian coordinate line graphs to systematically illustrate the sensitivity of the mudline maximum bending moment to wave incidence angle under two distinct return period conditions: the extreme "Once in a Century" event (Fig. 5a) and the more frequent "Once in Five Years" event (Fig. 5b).

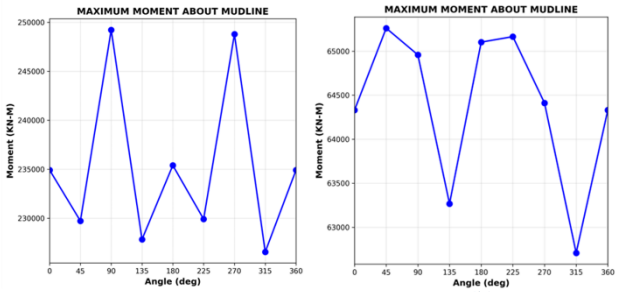
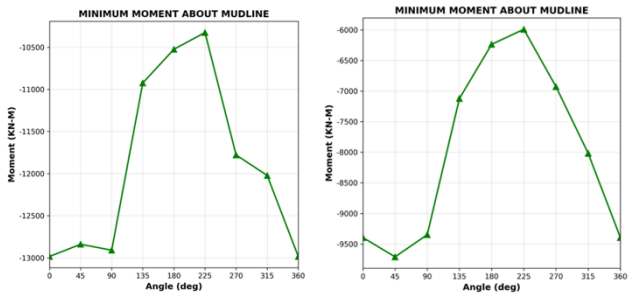


Fig. 5. Variation of maximum moment about mudline with wave direction (a) Once in a century, (b) Once in five years.

A prominent observation from Fig. 5 is the substantial magnitude scaling with return period. Under the 100-year condition, the maximum moment peaks at approximately 250,000 kN·m, occurring at wave angles near 90° and 270°. In contrast, the corresponding peak under the 5-year condition is markedly lower, at about 65,500 kN·m. This nearly fourfold increase underscores the non-linear intensification of hydrodynamic loading associated with extreme environmental states. Despite this significant difference in magnitude, both scenarios exhibit a highly consistent directional trend. The moment consistently reaches its maximum when waves approach perpendicular to the principal structural axes (around 90°/270°), while local minima are observed at oblique angles such as 45°, 135°,

225°, and 315°. This persistent pattern confirms that the platform's geometric configuration and stiffness distribution fundamentally govern its directional sensitivity, a characteristic that remains invariant across different load intensities.



(a) (b)

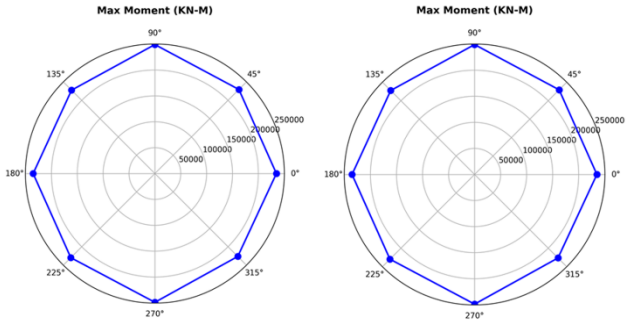
Fig. 6. Variation of minimum moment about mudline with wave direction (a) Once in a century, (b) Once in five years.

Fig. 6 presents the variation of the minimum bending moment (representing reverse or negative bending) with wave direction. The absolute values are approximately 13,000 kN·m for the 100-year event and 9500 kN·m for the 5-year event. Notably, while the minimum moment curve also exhibits periodic fluctuation, its peak distribution differs from that of the maximum moment. The most severe reverse bending does not align with the 90°/270° directions but is instead concentrated within the 135° to 225° sector. This phase shift indicates that the mechanisms driving peak positive and negative moments are distinct. Positive moments are maximized by direct, broadside wave attack on the jacket faces, whereas peak negative moments likely arise from complex combinations of wave loading, structural torsion, and the dynamic inertial response when waves impinge on the structure's corners or diagonals. Accurate quantification of this reverse bending is paramount for evaluating pile foundation tension capacity, joint integrity under cyclic loading, and long-term fatigue performance.

To provide a holistic view of directional dependency, Figs. 7 and 8 employ polar coordinate plots to visualize the omnidirectional distribution of the maximum moment and the absolute value of the minimum moment, respectively. These polar diagrams compellingly reveal a non-axisymmetric, polygonal response envelope. The contours distinctly deviate from a perfect circle, instead forming an octagonal or multi-lobed shape that mirrors the inherent structural symmetry (typically four- or eight-legged) of the jacket platform. This visual representation directly underscores the outcome of a comprehensive directional analysis: the structural response is intrinsically anisotropic. Consequently, adopting a unidirectional design approach based on a single, supposedly dominant wave direction is inadequate and potentially non-conservative. A rigorous assessment must consider environmental loads from all azimuths to ensure that the most critical load case, which may occur at a non-cardinal direction, is captured.

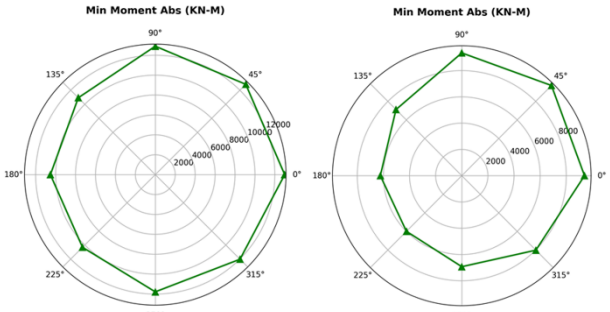
C. Maximum and Minimum Shear at Mudline

This section examines the distribution of shear force at the mudline, commonly termed base shear, a parameter of paramount importance for assessing the global lateral stability of the jacket platform and the lateral load-bearing capacity of the underlying pile foundation. The analysis delineates how both the peak positive and negative shear responses vary with wave incidence angle under contrasting environmental severities.



(a) (b)

Fig. 7. Polar distribution of maximum moment about mudline (a) Once in a century, (b) Once in five years.



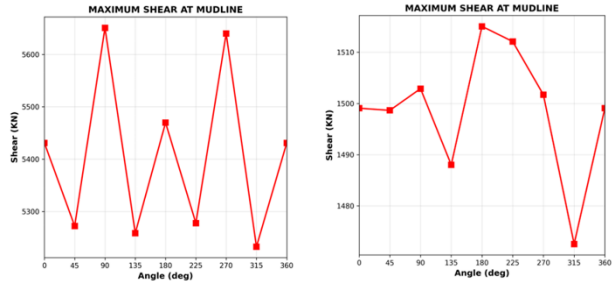
(a) (b)

Fig. 8. Polar distribution of minimum moment about mudline (a) Once in a century, (b) Once in five years.

Fig. 9 presents the variation of the maximum (positive) shear force with wave direction. A pronounced scaling effect analogous to that observed for bending moment is evident. Under the extreme 100-year condition (Fig. 9a), the maximum shear force attains a peak magnitude of approximately 5650 kN. In contrast, for the more frequent 5-year event (Fig. 9b), the peak value reduces significantly to about 1520 kN. This consistent reduction in intensity across return periods underscores a proportional relationship between hydrodynamic forcing and environmental severity. The directional variation pattern reveals a strong correlation with the moment response. The shear force maxima consistently occur at wave angles of 90° and 270°, coinciding precisely with the directions that generate the maximum bending moment. This synchronicity confirms that these orientations represent the most critical loading scenario, where the combined action of maximum lateral force and maximum overturning moment poses the greatest challenge to the foundation's stability. Secondary local maxima and the overall polygonal trend in the line graph further reflect the influence of the jacket's planar geometry and leg arrangement on distributing lateral loads.

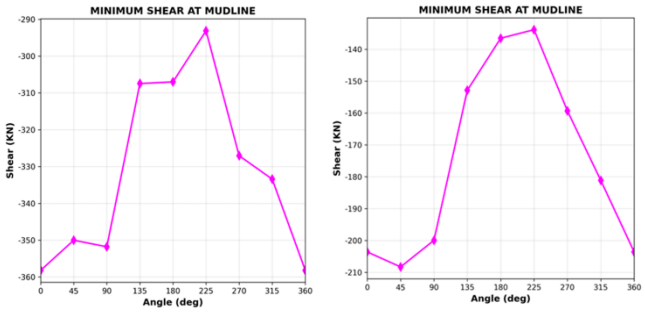
The behavior of the minimum shear force (representing shear in the opposite direction) is detailed in Fig. 10. The absolute values are approximately 360 kN for the 100-year condition (Fig. 10a) and 210 kN for the 5-year condition (Fig. 10b). While also scaled by return period, the directional distribution of the minimum shear exhibits a distinct characteristic: its most negative values (largest in absolute

terms) generally occur in angular regions offset from the peaks of the maximum shear. This phase shift indicates that the wave loading mechanism inducing peak positive shear (e.g., direct push on a face) differs from that causing peak negative shear (e.g., suction or loading on the opposing side during a different phase of wave interaction or from a different approach angle). This bidirectional shear characteristic is crucial for designing pile foundations and connections that must resist reversing loads, a key consideration for fatigue assessment under long-term cyclic wave action.



(a) (b)

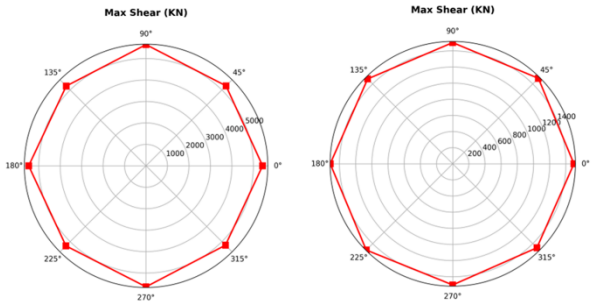
Fig. 9. Variation of maximum shear at mudline with wave direction (a) Once in a century, (b) Once in five years.



(a) (b)

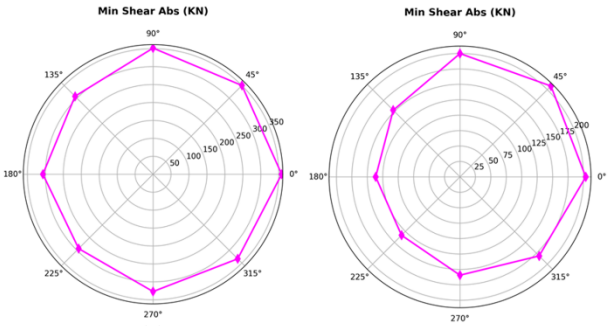
Fig. 10. Variation of minimum shear at mudline with wave direction (a) Once in a century, (b) Once in five years.

To comprehensively visualize the directional dependency, Figs. 11 and 12 employ polar coordinate representations for the maximum shear and the absolute value of the minimum shear, respectively. These polar plots vividly translate the line graph data into anisotropic load envelopes. The contours are distinctly non-circular, exhibiting a multi-lobed or polygonal shape that is a direct geometric mapping of the jacket structure's symmetry and its varied stiffness in different directions. Fig. 11 clearly shows lobes extending along the principal structural axes (near 0°, 90°, 180°, 270°), defining the envelope of maximum lateral load. Fig. 12, representing the reverse shear envelope, often shows lobes oriented between the primary axes, highlighting directions where the load reversal is most severe. These polar diagrams serve as powerful tools for design, compelling engineers to move beyond a unidirectional analysis. They explicitly define the directional load envelope that foundation and structural components must withstand, ensuring that design checks are performed for the controlling load case from any possible wave approach angle, thereby guaranteeing robustness against omnidirectional environmental actions.



(a) (b)

Fig. 11. Polar distribution of maximum shear at mudline (a) Once in a century, (b) Once in five years.

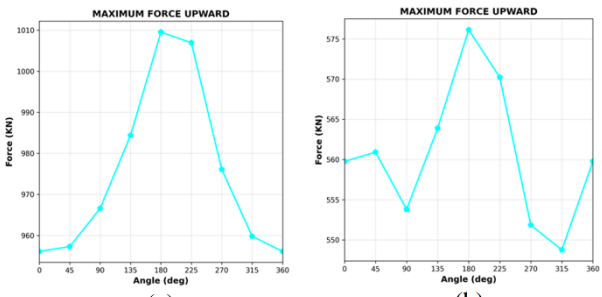


(a) (b)

Fig. 12. Polar distribution of minimum shear at mudline (a) Once in a century, (b) Once in five years.

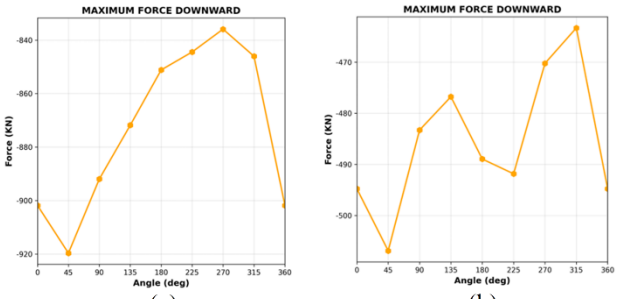
D. Maximum Force upward and Downward

This section investigates the axial force response of the jacket platform system by analyzing the maximum upward and maximum downward forces. These vertical load components are fundamental to the design of the pile foundation, directly governing its performance in tension (uplift resistance) and compression (bearing capacity). The analysis reveals distinct directional characteristics and load source dependencies for these opposing forces.



(a) (b)

Fig. 13. Variation of maximum force upward with wave direction (a) Once in a century, (b) Once in five years.



(a) (b)

Fig. 14. Variation of maximum force downward with wave direction (a) Once in a century, (b) Once in five years.

Fig. 13 illustrates the variation of the maximum upward force with wave incidence angle. A clear magnitude scaling is observed: the peak upward force under the 100-year condition (Fig. 13a) is approximately 1,010 kN, while under the 5-year condition (Fig. 13b), it reduces to about 575 kN. This scaling is consistent with the increased hydrodynamic loading in extreme events. More significantly, the upward force exhibits a pronounced directional concentration. The force reaches its global maximum in the vicinity of 180°, forming a distinct peak that contrasts with the relatively lower values at other angles. This pattern strongly suggests that the upward force is not merely a uniform buoyant component but is dominated by the vertical wave slam and lift forces that are maximized when waves approach from specific directions, likely related to the geometry of the submerged jacket structure and the phasing of wave kinematics relative to structural members.

Conversely, Fig. 14 presents the variation of the maximum downward force (absolute value). Its peak magnitudes are approximately 840 kN for the 100-year event (Fig. 14a) and 460 kN for the 5-year event (Fig. 14b). While also subject to return period scaling, the directional distribution of the downward force reveals a notable asymmetry compared to the upward force. Its maximum does not occur at 180° but is instead found around 225°, and the overall curve shape differs. This divergence is critical. The downward force is a composite of the constant load from the structure's self-weight and variable loads from deck operations, augmented by the downward-acting vertical components of wave and current loads (e.g., dynamic amplification, drag, and inertia). The different peak direction indicates that the wave mechanisms contributing most significantly to downward loading (e.g., wave trough passage, inertia forces) are distinct from those driving peak uplift, leading to a phase shift in their respective directional maxima.

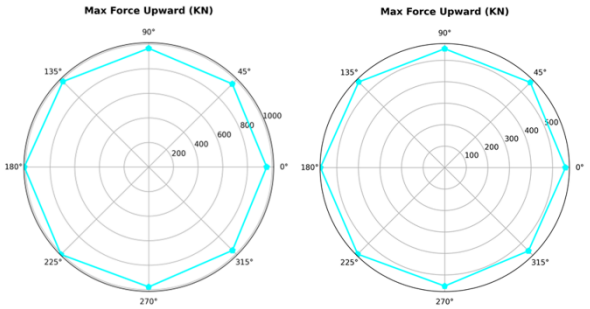


Fig. 15. Polar distribution of maximum force upward (a) Once in a century, (b) Once in five years.

The polar coordinate representations in Figs. 15 and 16 provide a holistic view of the omnidirectional axial load envelopes. Fig. 15, depicting the maximum upward force, shows a polygonally shaped envelope with pronounced lobes, confirming the force's strong directional bias rather than a uniform radial distribution. Fig. 16, representing the absolute maximum downward force, also displays a non-circular, multi-lobed contour, but its lobe orientation and prominence differ from those in Fig. 15. These polar plots are not merely visualizations; they are essential design tools that define the directional design space for axial loads. The upward force envelope (Fig. 15) identifies the critical directions for pile tension design and anchorage requirements. The downward force envelope (Fig. 16), combined with the constant gravity load, defines the maximum compressive demand on piles and the underlying soil. The fact that these envelopes are non-coincident and anisotropic underscores a key design principle: the foundation must be checked for the most severe combination of axial load from any direction, as the direction causing maximum compression is not the same as that causing maximum tension.

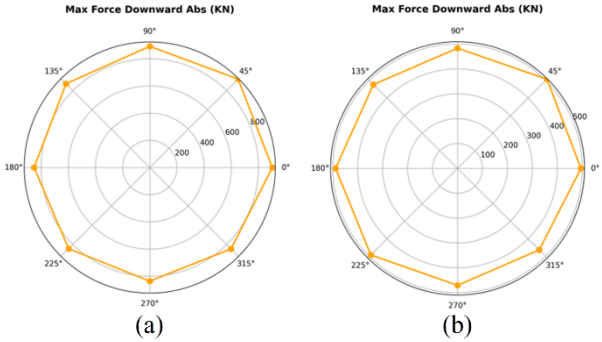


Fig. 16. Polar distribution of maximum force downward (a) Once in a century, (b) Once in five years.

E. Angle-dependent Load Parameter Summary

The comparative analysis presented in Fig. 17, supplemented by the quantitative data in Tables 5 and 6, reveals profound and systematic trends regarding the angular dependency and return period scaling of structural load parameters. A dominant and consistent observation is the overwhelming influence of the return period on the magnitude of all load components. The extreme values corresponding to the 100-year return period are ubiquitously amplified by a factor of 3 to 4 compared to their 5-year counterparts. This exponential escalation, exemplified by the maximum moment at 0° surging from 64,331 kN·m to 234,917 kN·m, underscores the non-linear intensification of environmental actions under extreme events. It unequivocally validates the engineering imperative of employing long-return-period criteria for the design of critical infrastructure, where safety margins must account for such drastic load amplification.

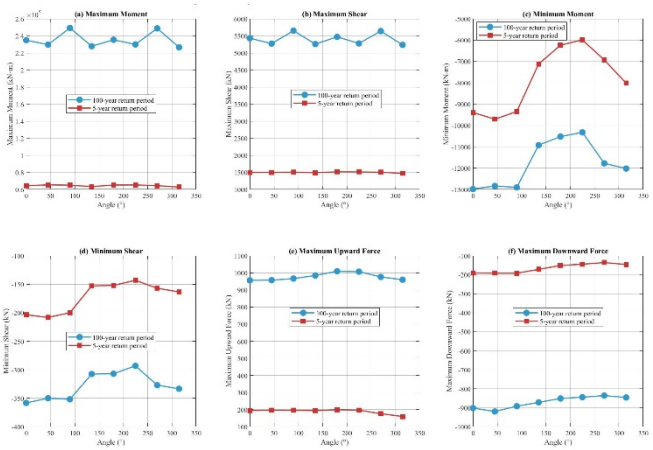


Fig. 17. Comparative analysis of load parameters under different return periods.

Beyond the scaling effect, the data delineates a clear and periodic pattern of directional sensitivity across all parameters, with a fundamental periodicity of 180°. The

maximum bending moment and maximum shear force exhibit a strong positive correlation, simultaneously attaining their global peaks in directions perpendicular to the structural axes, specifically at 90° and 270°. This identifies these orientations as the most critical for assessing the structure's resistance to bending and shear. In contrast, the most severe reverse bending actions, represented by the minimum moment (largest negative values), are concentrated within a distinct 90° sector spanning from 135° to 225°. This spatial shift in the critical region for negative moment suggests that the mechanisms governing peak positive and negative flexural demands are not simple opposites but are influenced by different aerodynamic or load-path interactions. The vertical force components further complicate the directional landscape. The maximum upward force peaks definitively at 180°, indicating a pronounced lift effect from that specific direction. Conversely, the maximum downward force finds its extremum not at the opposing 0° direction but is more significant near 0° and 45°, demonstrating an asymmetric distribution that likely arises from the coupled effects of wind pressure distribution and structural geometry.

Table 5. Angle−dependent load parameter summary (Once in a century)

Angle (°)	Maximum moment (KN·M)	Maximum shear (KN)	Minimum moment (KN·M)	Minimum shear (KN)	Maximum force upward (KN)	Maximum force downward (KN)
0	234917.469	5430.996	−12983.515	−358.183	956.130	−901.833
45	229716.109	5272.329	−12838.645	−350.011	957.281	−919.681
90	249225.703	5650.784	−12908.435	−351.788	966.601	−891.939
135	227839.016	5258.773	−10923.954	−307.465	984.362	−871.837
180	235389.734	5469.727	−10524.119	−307.006	1009.547	−851.153
225	229904.266	5277.925	−10325.278	−293.117	1006.944	−844.440
270	248776.172	5639.714	−11778.487	−327.061	976.082	−835.903
315	226560.797	5232.960	−12021.724	−333.419	959.798	−846.032

Table 6. Angle−dependent load parameter summary (Once in five years)

Angle (°)	Maximum moment (KN·M)	Maximum shear (KN)	Minimum moment (KN·M)	Minimum shear (KN)	Maximum force upward (KN)	Maximum force downward (KN)
0	64331.461	1499.073	−9394.924	−203.583	559.770	−494.776
45	65261.684	1498.652	−9709.850	−208.273	560.909	−506.915
90	64958.508	1502.892	−9348.075	−199.934	553.791	−483.288
135	63267.629	1488.016	−7121.561	−152.865	563.889	−476.771
180	65103.133	1515.054	−6236.517	−136.513	576.131	−488.959
225	65165.523	1512.096	−5990.999	−133.834	570.213	−491.853
270	64411.816	1501.707	−6928.583	−159.309	551.845	−470.239
315	62708.152	1472.563	−8019.110	−181.134	548.764	−463.301

The interplay between different load parameters at specific angles holds significant design implications. Crucially, the angles producing the maximum individual load effects do not coincide. While 90°/270° govern maximum moment and shear, the region from 135° to 225° emerges as a potentially more critical composite hazard zone. Within this sector, the structure may be subjected to a concurrent combination of notably high shear, substantial negative bending moment, and near-maximum uplift force. Such a combination can govern the design of foundations against overturning and uplift, the detailing of beam-column joints, and the moment capacity requirements in continuous systems. Furthermore, a meticulous examination of nominally symmetric angles (e.g., 0° vs. 180°, 45° vs. 225°) reveals subtle but consistent asymmetries in the reported values. These discrepancies, beyond numerical rounding, likely reflect inherent asymmetries in turbulent wind inflow, minor geometric irregularities, or modeling assumptions, advising against the uncritical use of perfectly symmetric load envelopes in design.

In conclusion, the structural response is characterized by a dual dependency on direction and return period. This necessitates a comprehensive design approach that moves beyond single-direction analysis. A full 360-degree evaluation is essential to identify all governing load cases, with particular vigilance for angles that generate adverse combinations of action effects. Simultaneously, the selection of the appropriate return period remains a fundamental decision, directly setting the intensity scale for these directional actions and anchoring the trade-off between structural reliability and economic feasibility.

F. Unity Check Distribution

The Unity Check (UC) distribution offers a direct measure of component-level structural integrity by comparing computed member stresses against allowable capacities, thereby revealing localized vulnerabilities and overall system robustness. Figs. 18 and 19 illustrate the UC distribution under extreme (100-year) and operational (5-year) conditions, respectively, providing critical insights into structural performance. Under the extreme 100-year condition (Fig. 18), the UC distribution exhibits pronounced stress concentrations, with several structural zones approaching or exceeding a UC value of 1.0 (indicated by red and yellow contours). These critical regions are primarily located at:

1. Particularly at the intersections of main legs and diagonal braces (X- or K-joints) in the upper and mid-height regions of the jacket, where stress intensification due to combined axial force, bending, and shear is most severe.
2. Selected diagonal braces: Certain braces subjected to high axial compression or tension under lateral wave loading show elevated UC values, indicating their role as primary load-carrying elements that may approach yield under extreme conditions.

The presence of these high-UC zones suggests that the platform's failure mechanism under extreme loading is likely governed by joint flexibility and brace buckling, underscoring the necessity for meticulous detailing, inspection, and potential reinforcement in these regions to

ensure collapse resistance.

In contrast, under the 5-year operational condition (Fig. 19), the UC distribution is predominantly characterized by low values, with no members approaching their capacity limits. This indicates substantial reserve strength under frequently occurring environmental loads. Although stress levels are uniformly low, the distribution pattern aligns with that under extreme conditions, suggesting that these locations remain susceptible to gradual degradation due to cumulative fatigue over time. The comparative analysis of UC distributions across the two return periods highlights a key structural insight: while the platform possesses adequate safety margins under operational loads, its ultimate limit state is critically governed by a limited number of highly stressed components. This duality necessitates a tiered integrity management strategy: for extreme conditions, emphasis should be placed on reinforcing, monitoring, and periodically assessing high-UC regions; for operational conditions, priority should be given to fatigue evaluation and crack inspection at these same critical locations to ensure long-term durability and prevent progressive damage accumulation.

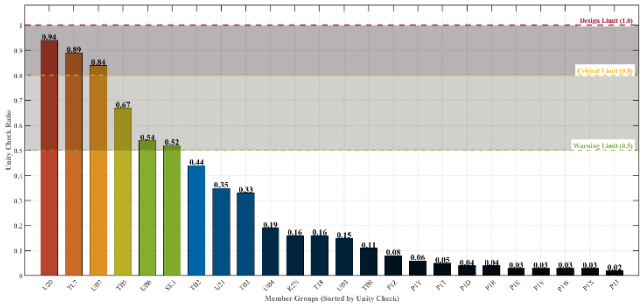


Fig. 18. Unity check distribution (Once in a century).

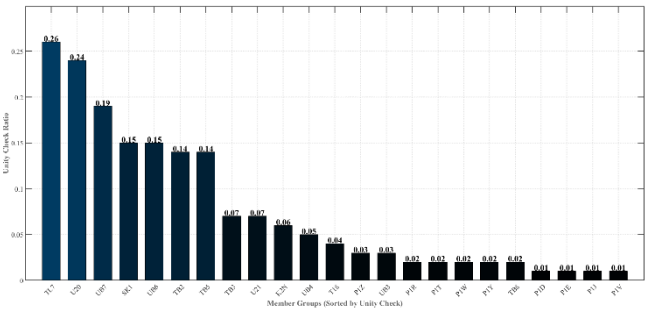


Fig. 19. Unity check distribution (Once in five years).

G. General Applicability of the Analysis Framework

It should be noted that the analytical procedure adopted in this study, comprising multi-directional load case combinations, dual-return-period comparisons, Morison-equation-based hydrodynamic load calculations, nonlinear static pushover analysis, and API-based pile-soil interaction modeling, is not, in its basic steps, contingent upon any specific platform configuration. However, it should be acknowledged that this study is based on a single four-legged platform, and the applicability of the procedure to other platforms requires further validation through additional case studies. For platforms with different configurations, the following aspects may be adjusted according to the specific conditions when applying this framework: (1) for a different number of legs (e.g., six or eight), the angular resolution may be refined (e.g., to 22.5° or 15° intervals) to better reflect the effects of structural symmetry; (2) for varying water depths, the choice of wave theory may be revisited (e.g., Stokes fifth-order or stream function theory for intermediate depths), and the drag and inertia coefficients in Morison's equation may be recalibrated with reference to KC number and Reynolds number; (3) for different soil conditions, replacing the corresponding *p-y*, *t-z*, and *q-z* curve parameters based on site data is sufficient, while the remaining analytical steps may remain unchanged. In summary, the methodological exploration presented in this study offers a preliminary reference, yet its adaptability to various platform conditions calls for further evaluation and refinement through comparative analyses in future work.

IV. Conclusion

This study presents a comprehensive numerical investigation into the ultimate strength and directional load-response characteristics of a representative four-legged jacket platform, employing advanced nonlinear static pushover analysis via the industry-standard SACS software. The research systematically evaluates the platform's structural behavior under two distinct environmental regimes: frequent operating conditions (5-year return period) and extreme storm conditions (100-year return period), with a particular focus on the omnidirectional sensitivity of key load parameters—bending moment, shear force, and axial force—at the critical mudline elevation. The primary findings and their implications are synthesized as follows:

1. A fundamental outcome of this study is the quantification of the nonlinear scaling relationship between environmental severity and structural demand. Load parameters under the 100-year extreme condition are consistently amplified by a factor of 3 to 4 compared to the 5-year operating condition. For instance, the maximum mudline moment escalates from approximately 65,500 kN·m to 250,000 kN·m, and the maximum base shear from about 1,520 kN to 5,650 kN. This exponential increase underscores the non-proportional intensification of hydrodynamic forces in extreme seas, driven by the higher-order terms in wave kinematics and drag forces. It unequivocally validates the engineering necessity of employing long-return-period criteria for ultimate limit state (ULS) design and reassessment, as safety margins must accommodate this drastic load amplification to prevent progressive collapse.
2. The analysis reveals that the platform's load response is intrinsically anisotropic, governed by its geometric configuration and stiffness distribution. The directional patterns, visualized through both Cartesian and polar plots, exhibit a clear 180° periodicity aligned with the structure's principal axes. Maximum bending moment and shear force consistently peak when waves attack perpendicular to the platform's faces (near 90° and 270°), identifying these as the most critical directions for lateral capacity. In contrast, the most severe reverse bending (minimum moment) is concentrated within a different sector (135° to 225°), indicating that the mechanisms governing peak positive and negative flexural demands are distinct, likely involving complex wave-structure interactions, torsion, and inertial effects at oblique angles.
3. The axial force response demonstrates a decoupled directional behavior between upward (tension) and

downward (compression) forces. The maximum upward force, dominated by wave slam and lift, peaks sharply at 180°. Conversely, the maximum downward force, a composite of gravity and downward-acting hydrodynamic components, attains its extreme at a different orientation (around 225°). This phase shift highlights that the wave kinematics and structural geometry interact differently to maximize vertical uplift versus downward loading. Consequently, the directional envelopes for tensile and compressive foundation design are non-coincident, necessitating separate checks.

4. Crucially, the angles producing peak individual load effects do not align. While 90°/270° govern maximum lateral loads, the sector from 135° to 225° emerges as a potentially more critical composite hazard zone. In this region, the structure may simultaneously experience high shear, substantial negative bending moment, and significant uplift force. This specific combination could dictate the design of pile foundations against overturning and pull-out, the detailing of critical joints, and the system's ductility requirements, underscoring the importance of load combination analysis beyond single-component maxima.

While this study provides valuable insights into the directional and nonlinear load-response characteristics of jacket platforms under extreme environmental conditions, several limitations should be acknowledged to contextualize the findings and guide future research. First, the analysis assumed collinear wind, wave, and current loads acting simultaneously from the same direction, which represents a conservative but simplified scenario. In reality, these environmental factors may exhibit directional misalignment and time-varying phase differences, potentially altering the resultant load combinations and structural response. Second, the study employed a single, deterministic soil profile and associated *p-y*, *t-z*, *q-z* curves based on API guidelines. The inherent spatial variability and uncertainty in soil properties, as well as potential cyclic degradation under long-term wave loading, were not explicitly modeled, which may influence the predicted foundation stiffness and system-level nonlinearity. Third, the material model assumed ideal elastoplastic behavior without accounting for potential strength degradation due to corrosion, fatigue damage accumulation, or strain-rate effects under dynamic loading. Finally, the study considered a fixed water depth and a specific platform geometry; the findings may not be directly generalizable to platforms with significantly different configurations, water depths, or situated in regions with distinct metocean characteristics.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Zeliang Yang: Conceptualization, methodology, software implementation, formal analysis, and writing—original draft. Shuixiang Huang: Data curation, investigation, and visualization of simulation results. Xinming Huang: Validation, supervision, and provision of resources. Suming Jing: Software validation, review, and editing of the manuscript. Junwei Ye: Conceptualization, overall supervision, project administration, funding acquisition, and writing—review & editing (corresponding author). All authors had approved the final version.

References

[1] S. E. Abdel Raheem, E. M. Abdel Aal, A. G. AbdelShafy, M. F. Fahmy, and M. H. Mansour, "In-place analysis for pile structural response of fixed jacket offshore platform," *Ships and Offshore Structures*, vol. 17, no. 6, pp. 1224–1237, 2022.

[2] ABS, "Guide for building and classing floating production installations," 2010.

[3] API, "API recommended practice 2A-WSD: Planning, designing, and constructing fixed offshore platforms—Working stress design," 2014.

[4] B. Asgarian, A. Aghakouchak, and R. Bea, "Nonlinear analysis of jacket-type offshore platforms using fiber elements," 2006.

[5] B. Asgarian and H. Agheshlui, "Reliability-based earthquake design of jacket-type offshore platforms considering pile-soil-structure interaction," *American Journal of Applied Sciences*, vol. 6, no. 4, 631, 2009.

[6] N. U. Azman, M. K. Abu Husain, N. I. Mohd Zaki, E. Mat Soom, N. A. Mukhlas, and S. Z. A. Syed Ahmad, "Structural integrity of fixed offshore platforms by incorporating wave-in-deck," *Journal of Marine Science and Engineering*, vol. 9, no. 9, 1027, 2021.

[7] D. Cao and H. Chen, "Probabilistic analysis of irregular wave runup on a fixed and truncated surface-piercing vertical cylinder," *Marine Structures*, vol. 88, 103360, 2023.

[8] D. Cao, J. He, and H. Chen, "Empirical predictions on wave overtopping for overtopping wave energy converters: A systematic review," *Processes*, vol. 12, no. 9, 1940, 2024.

[9] D. Cao, Z. Huang, F. He, W. Jian, and E. Y.-M. Lo, "An improved prediction for wave runup on a circular cylinder," *Coastal Engineering Journal*, vol. 59, no. 3, 1750013, 2017.

[10] D. Cao, W. Jian, Z. Huang, and E. Y. Lo, "Prediction of wave runup on columns of two semi-submersibles models," *Journal of Coastal Research*, no. 85, pp. 1031–1035, 2018.

[11] D. Cao, E. L. Yat-Man, W. Jian, and Z. Huang, "An experimental study of wave runup: Cylinder fixed in waves versus cylinder surging in still water," *International Journal of Engineering and Technology*, vol. 9, no. 2, 124, 2017.

[12] D. Cao *et al.*, "A numerical investigation of irregular wave overtopping on a 2D fixed overtopping wave energy converter," *Engineering Applications of Computational Fluid Mechanics*, vol. 19, no. 1, 2446658, 2025.

[13] K. A. Digre and F. Zwerneman, "Insights into using the 22nd edition of API RP 2A recommended practice for planning, designing and constructing fixed offshore platforms-working stress design," in *Proc. Offshore Technology Conference (OTC)*, 2012.

[14] M. A. El-Reedy, *Offshore Structures: Design, Construction and Maintenance*. Gulf Professional Publishing, 2019.

[15] J. D. Fenton, "Nonlinear wave theories," *The Sea*, vol. 9, no. 1, pp. 3–25, 1990.

[16] A. Golafshani, V. Bagheri, H. Ebrahimian, and T. Holmas, "Incremental wave analysis and its application to performance-based assessment of jacket platforms," *Journal of Constructional Steel Research*, vol. 67, no. 10, pp. 1649–1657, 2011.

[17] Z. Henry, I. Jusoh, and A. Ayob, "Structural integrity analysis of fixed offshore jacket structures," *Jurnal Mekanikal*, 2017.

[18] M. Hezarjaribi, M. Bahaari, V. Bagheri, and H. Ebrahimian, "Sensitivity analysis of jacket-type offshore platforms under extreme waves," *Journal of Constructional Steel Research*, vol. 83, pp. 147–155, 2013.

[19] A. Kharade and S. V. Kapadiya, "Offshore engineering: An overview of types and loadings on structures," *International Journal of Structural and Civil Engineering Research*, vol. 3, pp. 16–28, 2014.

[20] Y. Liu *et al.*, "Satellite data lift the veil on offshore platforms in the South China Sea," *Scientific Reports*, vol. 6, no. 1, 33623, 2016.

[21] T. Moan, Ø. Hellan, and M. Emami Azadi, "Nonlinear dynamic versus static analysis of jacket systems for ultimate limit state check," in *Proc. International Conference on Advances in Marine Structures III*, Dunfermline, Scotland, 1997.

[22] M. Mohd, M. Zalaya, M. Latheef, H. Choi, M. Rahman, and D. Kim, "Ultimate bending capacity of aged fixed platform by considering the effect of marine fouling," *Latin American Journal of Solids and Structures*, vol. 16, no. 5, e182, 2019.

[23] A. C. S. Nalawade and N. Khadake, "Review on analysis of offshore structure," 2020.

[24] N. A. Othman and M. H. Mohd, "Response of the offshore jacket platform at its ultimate strength under operating and extreme loads: A Malaysian waters case study," *Ships and Offshore Structures*, vol. 19, no. 11, pp. 1805–1826, 2024.
[25] N. A. Othman, M. H. Mohd, M. A. A. Rahman, M. A. Musa, and A. Fitriadhy, "Investigation of the corrosion factor to the global strength of aging offshore jacket platforms under different marine zones," *International Journal of Naval Architecture and Ocean Engineering*, vol. 15, 100496, 2023.
[26] S. E. A. Raheem, "Nonlinear response of fixed jacket offshore platform under structural and wave loads," *Coupled Systems Mechanics*, vol. 2, no. 1, pp. 111–126, 2013.
[27] E. M. Soom, M. A. Husain, N. M. Zaki, M. M. Nor, M. Ayob, and G. Najafian, "Global ultimate strength assessment (GUSA) for lifetime extension of ageing offshore structures," in *Proc. ISOPE International Ocean and Polar Engineering Conference*, 2015.
[28] A. Stacey, M. Birkinshaw, and J. Sharp, "Life extension issues for ageing offshore installations," in *Proc. International Conference on Offshore Mechanics and Arctic Engineering*, 2008.
[29] S. S. Sunder and J. Connor, "Sensitivity analyses for steel jacket offshore platforms," *Applied Ocean Research*, vol. 3, no. 1, pp. 13–26, 1981.
[30] B. Systems, "SACS offshore structure design and analysis software," 2020, Accessed: Sep. 8, 2022.
[31] T.-T. Tran, E. Kim, and D. Lee, "Development of a 3-legged jacket substructure for installation in the southwest offshore wind farm in South Korea," *Ocean Engineering*, vol. 246, 110643, 2022.

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