

Article

Directional Response and Strength Assessment of Truss-Type Legs for a Wind Turbine Installation Vessel Under Crane Angles and Wave Loads

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Abstract

With the rapid development of offshore wind energy toward deep water, the structural safety of truss-type legs for jack-up wind turbine installation vessels (WTIVs) under complex operational and environmental loads has become a key concern. This study focuses on the directional coupling effect between crane slewing angles and wave directions, which has rarely been systematically investigated in previous research. A finite element model of a 1500 t-class WTIV truss leg is established using SESAM, and its reliability is verified by mesh convergence analysis and literature comparison. The influences of crane slewing angle, wave direction, and their coupling on structural displacement and stress are analyzed quantitatively, and strength evaluation is carried out under typical working conditions in accordance with classification society rules. The results show that the structural response presents significant directional dependence and stiffness anisotropy. The peak displacement and stress occur at a crane slewing angle of 270°, with the maximum displacement approximately 33% higher than the minimum value. Obvious response amplification is observed when the crane slewing angle and wave direction are aligned within 225–270°, which constitutes the most unfavorable loading combination. The strength assessment demonstrates that all conditions meet the specification requirements, and the survival condition is the most critical, with a maximum stress of 289.66 MPa and a maximum displacement of 338.6 mm. This study reveals the coupling mechanism between operational loads and environmental loads and identifies the critical dangerous angle sector. The research findings can provide reasonable references for offshore lifting operation management and operational planning of marine truss leg structures.

Keywords: wind turbine installation vessel; truss-type leg; crane slewing angle; directional response; load coupling; strength assessment



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1. Introduction

Driven by global carbon-reduction strategies, offshore wind power has rapidly emerged as a pivotal clean energy source, drawing extensive attention from both academia and industry [1]. In recent years, the continuous scaling up of individual wind turbine rated capacities has imposed unprecedented demands on the operational capabilities and

structural performance of installation equipment [2]. Self-elevating jack-up wind turbine installation vessels (WTIVs) have expanded into deeper waters as the primary equipment for far-shore wind farm construction due to their exceptional stability and strong operational adaptability [3]. These units typically utilize specialized truss-type leg structures and heavy-duty, high-capacity cranes to accomplish offshore hoisting tasks. As the primary load-bearing and supporting system, the structural integrity of the truss-type leg is directly tied to the overall service performance and operational reliability of the vessel [4]. In practical operations, the leg structure is subjected to the combined effects of multiple complex loads, including crane operational loads, hydrodynamic loads induced by waves and ocean currents, and structural self-weight [5]. Crane slewing operations introduce significant directional loading, while environmental loads further increase the complexity of the structural response, resulting in pronounced spatial non-uniformity in the leg structural response. Therefore, it is necessary to conduct a systematic investigation into the response characteristics of WTIV leg structures under complex loading conditions.

In recent years, systematic progress has been made in the study of the structural configuration, environmental loading, and operational loading of jack-up platform leg structures.

Ren et al. [6] focused on the effects of different truss configurations on structural load distribution characteristics. Their results indicated that various truss layouts, such as X-type, K-type, and inverted K-type configurations, significantly alter the internal force transfer paths within the structure. Among them, the inverted K-type configuration enables a more uniform load distribution under complex loading conditions, thereby improving the overall load-carrying efficiency and structural stability.

Cao et al. [7] investigated the dynamic response characteristics of leg structures under wave loading. Their findings showed that resonance may occur when the structural natural frequencies approach the dominant wave frequencies, leading to significant dynamic amplification of the structural response. Meanwhile, geometric parameters of the legs, such as chord spacing and bracing inclination, were found to have a pronounced influence on the modal characteristics and dynamic behavior of the structure under environmental loading conditions.

Liu et al. [8] combined wind tunnel experiments with numerical simulations to systematically investigate the influence of different wind directions on the load distribution of key components in jack-up platforms. The results indicated that wind direction is one of the key factors governing the variation in wind load distribution and structural response, and also revealed that current design codes may exhibit certain discrepancies under specific directional conditions.

Tran et al. [9] further examined the directional variation in the bending resistance of a four-leg jacket foundation. Their findings showed that the structural stiffness distribution varies significantly with loading direction, leading to markedly different mechanical responses and indicating strong directional sensitivity, which also exhibits a certain periodicity with respect to load orientation.

Mirzadeh et al. [10] investigated structural responses under stochastic directional wave conditions by considering wave directional spreading effects. The results demonstrated that both wave propagation direction and its directional distribution significantly influence the structural response. Directional random waves provide a more realistic representation of actual sea states than conventional unidirectional regular wave models and can modify the spatial distribution characteristics of response peaks.

Yi and Park [11] performed parametric sensitivity analyses to investigate the effects of wave height, wave period, wind speed, and air gap on the global strength and leg stability of jack-up rigs. The results confirmed that wave height and wind speed represent the most dominant environmental factors governing structural responses, while the quasi-static

framework and dynamic amplification corrections were adopted to ensure compliance with industrial code requirements.

Ghazi et al. [12] evaluated the dynamic performance of jack-up platforms under combined wave, wind, earthquake, and tsunami loads. Numerical comparisons revealed that platform elevation significantly influences global displacements, and the most adverse responses were observed under seismic excitations and multi-directional tsunami impacts, highlighting the sensitivity of jack-up structures to multi-hazard environmental coupling effects.

Xie et al. [13] carried out systematic hydrodynamic model tests on truss-type legs and quantified the drag and inertia coefficients under combined wave and current loads. The pile-group effect, shielding interference, and inflow directionality were explicitly addressed, and the results demonstrated that leg-to-leg interactions and incident wave directions considerably modify hydrodynamic loads, providing valuable coefficients for engineering design.

Hannan and Bai [14] developed a fully three-dimensional nonlinear time-domain model based on the boundary element method (BEM) and conducted a systematic study on a fully submerged payload suspended from an offshore crane vessel. The results indicated that, under the coupled effects of wave excitation and vessel motions, the payload exhibits pronounced nonlinear dynamic characteristics, including subharmonic responses and period-doubling phenomena. The dynamic stability of the system under complex sea states was further revealed through phase portraits, bifurcation diagrams, and Poincaré maps.

Fang et al. [15] addressed the operational control problem of offshore crane systems by establishing a Lagrangian-based dynamic model that accounts for the coupling effects between the crane boom and the payload. A corresponding nonlinear control strategy was proposed. The results demonstrated that by introducing a high-performance nonlinear control law, the oscillation of the payload induced by vessel motions can be effectively suppressed, thereby significantly enhancing the disturbance rejection capability and operational stability of the system under severe sea conditions.

Chai et al. [16] carried out comprehensive strength and fatigue analyses on the truss-type legs and spudcan connections of a jack-up wind turbine installation vessel. A variety of typical operating conditions were adopted, including preloading, storm survival, crane operation, and non-operation. Although crane loads were involved in the analysis, the influence of varying crane slewing angles was not considered. Only the difference between operating and non-operating states was discussed, while the directional effect and coupling characteristics of crane boom orientation remain unclear.

Despite substantial research efforts devoted to the structural analysis of jack-up platforms and truss-type leg systems, several important issues remain insufficiently understood in practical offshore operations. Existing studies have primarily focused on structural configurations, environmental parameter sensitivity, and environmental loading effects, whereas operational loads induced by crane slewing and their directional characteristics have received relatively limited attention in global structural assessments. In particular, although the directional effects of wind and waves have been widely discussed, the coupling mechanism between crane boom orientation and environmental load direction has not yet been systematically clarified. In addition, previous studies involving crane operational loads mainly distinguished between operating and non-operating conditions, while the continuous variation in structural responses with crane slewing angle has rarely been quantitatively investigated. Under practical offshore installation conditions, variations in crane boom azimuth may significantly alter load eccentricity, internal force redistribution, and the alignment between loading direction and structural stiffness distribution, thereby lead-

ing to pronounced directional response characteristics. However, the critical unfavorable directional sectors governing the structural safety of WTIV legs remain unclear.

Therefore, this study investigates the directional response and strength performance of truss-type legs for a self-elevating WTIV under combined crane operational loads and environmental loads. A refined global finite element model is established using SESAM to evaluate the effects of the crane boom slewing angle and wave direction on the displacement and stress responses of the leg structure. The coupling amplification mechanism between operational and environmental loads is analyzed, and the critical unfavorable loading combinations are identified. Furthermore, representative operating conditions, including preloading, crane operating, non-operating, and survival conditions, are assessed according to BV classification rules to provide practical guidance for on-site operation, safety control, and operational decision-making during wind turbine installation.

The main contributions of this study can be summarized as follows:

- (1) A systematic directional response assessment of WTIV truss-type legs under varying crane slewing angles is conducted, with emphasis on the influence of operational load directionality on structural responses.
- (2) The coupling effect between crane boom orientation and environmental load direction is quantitatively investigated, and the corresponding unfavorable directional sectors governing stress and displacement amplification are identified.

2. Theoretical Analysis

2.1. Hydrodynamic Model Simplifications

The hydrodynamic loading on the truss-type leg structure is evaluated using a Morison-equation-based formulation combined with fifth-order Stokes wave theory, which is widely adopted in offshore engineering practice for global structural response analysis of slender members [7].

In this study, a deterministic regular wave based on fifth-order Stokes theory is adopted [17]. This choice is consistent with the objective of the present work, which focuses on the directional coupling effects between crane slewing angles and wave directions, and on identifying critical structural response conditions under controlled environmental parameters. The use of regular waves ensures consistency and comparability across different directional cases, avoiding additional variability associated with stochastic wave realizations. In addition, the design wave approach using regular waves is widely adopted in offshore engineering practice for Ultimate Limit State (ULS) and global strength assessments, as recognized in major classification rules (e.g., DNV, BV, and SNAME), where irregular sea states are often represented by equivalent extreme design conditions [11,18]. Finally, the stochastic characteristics of irregular waves are mainly relevant for fatigue analysis and long-term statistical response evaluation [19–21]. Since the present study focuses on global structural response under extreme conditions and directional sensitivity rather than fatigue-life prediction, the deterministic wave approach is considered appropriate.

The hydrodynamic coefficients are defined in accordance with established offshore design standards, including DNV-RP-C104 and SNAME recommendations [11]. The chord sections are idealized as generalized flat bar profiles with equivalent dimensions, and the corresponding hydrodynamic coefficients are determined in accordance with DNV-RP-C104, with $C_d = 1.9$ and $C_m = 2.0$ [22]. For tubular brace and strut members, the coefficients are adopted as $C_d = 0.65$ and $C_m = 2.0$, as recommended by SNAME [23]. The hydrodynamic coefficients for chord members are assumed to be constant and independent of flow direction. This assumption is consistent with standard engineering practice for global strength assessment of offshore structures and is considered conservative [24]. In addition, wake effects, shielding effects, and detailed hydrodynamic interactions between individual

members within the leg structure are not explicitly modeled in the present analysis. This simplification is consistent with the Morison-equation-based approach commonly adopted in offshore engineering practice for global structural response and strength assessment. In such global analyses, the influence of shielding is typically accounted for in an implicit and conservative manner, since downstream members are assumed to be fully exposed to the incoming flow without velocity reduction [11].

2.2. Environmental Load Assessment

Environmental loads are calculated in accordance with the DNVGL-RP-C104 recommended practice [25]. In this study, the Wajac module within the SESAM software system (Version V6.6-02) is employed to compute wave and current loads on the leg structure. By defining environmental parameters and wave conditions during the preprocessing stage, the hydrodynamic analysis is carried out, and the resulting equivalent nodal forces are automatically transferred to the finite element model for subsequent structural response and strength assessments.

2.2.1. Wind Load

Wind load is one of the primary external actions that must be considered in the structural design of jack-up platforms. According to the DNV standard, the averaging period of the mean wind speed is taken as 1 min and is closely related to the reference wind speed at a height of 10 m above the mean sea level [8,12,26]. The variation in wind speed with elevation for a jack-up platform under different operational conditions can be expressed as

$$V_Z = V_R \left(\frac{Z}{Z_0} \right)^{\frac{1}{n}} \quad (1)$$

where V_R (m/s) is the reference wind speed at the reference height $Z_0 = 10$ m; Z is the elevation of the point above the still water level (m); and n is the state-dependent exponent, taken as 11 for the elevated (jack-up) condition and 14 for the transit condition.

Under the mean wind speed, the wind action on the above-water structure can be treated as a static load, and the corresponding wind load can be calculated using the following expression:

$$F = \frac{1}{2} \rho C_S A V_Z^2 \quad (2)$$

where ρ is the air density, taken as $\rho = 1.225$ kg/m³ for dry air; A is the projected area of the structure normal to the wind direction (m²); V is the design wind speed obtained from the height correction formula above; and C_S is the shape coefficient. For a conservative estimation, the shape coefficient for both the hull and the legs is taken as 1.5, and the shielding effect between the legs is neglected. The calculated wind loads are finally applied to the structure in the form of concentrated nodal forces for subsequent structural analysis.

2.2.2. Wave Load

Based on the environmental parameters, such as the specified wave period, the wave loads are evaluated using the fifth-order Stokes wave theory [27]. The corresponding expressions for the free surface elevation, wavelength, and velocity potential are given as follows:

$$\eta = \frac{1}{k} \sum_{i=1}^5 \eta_i \cos(i\theta) \quad (3)$$

$$\frac{\pi H}{d} = \frac{\lambda + \lambda^3 B_{ij} + \lambda^5 (B_{ij} + B_{ij})}{d/L} \quad (4)$$

$$\frac{d}{L_0} = \frac{d}{L} \tanh(kd)(1 + \lambda^2 C_1 + \lambda^4 C_2) \quad (5)$$

$$\phi = \frac{L}{kT} \sum_{i=1}^5 \phi_i \cosh(iks) \sin(i\theta) \quad (6)$$

where d is the water depth; H is the wave height; T is the wave period; L_0 is the wavelength; k is the wave number; θ is the phase angle; λ is the wave steepness parameter; B_{ij} and C_i are coefficients; η_i denotes the free surface elevation coefficients; and ϕ_i represents the velocity potential coefficients.

In addition, the wave loads are calculated using the Morison equation, in which the total wave force is typically decomposed into a drag component and an inertia component [18]. The corresponding formulation is given as follows:

$$F = F_D + F_I = C_d \rho A \mu |\mu| + C_m \rho V \frac{\delta u}{\delta t} \quad (7)$$

where F is the hydrodynamic force vector acting normal to the member axis; F_D is the drag force component acting in the plane formed by the member axis and the velocity μ , and perpendicular to the member axis; F_I is the inertia force component acting in the plane formed by the member axis and the fluid acceleration du/dt , and perpendicular to the member axis; μ is the fluid particle velocity component normal to the member axis; du is the fluid particle acceleration vector; dt is the unit vector along the member axis; C_d is the drag coefficient; C_m is the inertia coefficient; A is the projected area per unit length of the member; V is the displaced volume per unit length of the member; and ρ is the water density.

2.2.3. Current Load

Current load is one of the key design loads for offshore submerged structures, primarily influenced by wind, temperature, and salinity. It is typically expressed as a function of the current velocity, and can be calculated as follows:

$$F = \rho / 2 C_d V^2 A \quad (8)$$

where V is the design current velocity; C_d is the drag coefficient; A is the projected area of the member normal to the current direction; and the seawater density is taken as $\rho = 1.027 \text{ g/cm}^3$. Under calm sea conditions, the current velocity can be approximated by the steady (still-water) current velocity. However, in severe sea states, it is inaccurate to represent the current solely by the still-water component, and the wind-induced current should be taken into account. The corresponding formulation is given as follows:

$$V_C = V_T \left(\frac{h-z}{h} \right)^{\frac{1}{7}} + V_w \left(\frac{h_0-z}{h_0} \right) \quad (9)$$

where V_T is the steady (still-water) current velocity; h_0 is the reference depth for the wind-induced current, taken as 50 m; V_w is the wind-induced current velocity, approximately equal to 0.017 times the wind speed measured at 10 m above the sea surface with a 1 min averaging period; h is the total water depth measured from the still water level to the seabed; and z is the depth of the current measured from the still water level. In this study, the current velocity is assumed to be uniform along the water depth, and the maximum design value at the water surface is adopted for the structural strength assessment of the leg system.

2.2.4. Inertial Load

The truss-type leg of the jack-up WTIV is essentially a dynamic system, which will generate obvious vibration, sway, and inertial responses under periodic wave excitation. A full-time-domain dynamic analysis can capture detailed transient behaviors and complex wave-structure interactions, yet it involves high computational cost. The primary objective of this study is to evaluate the global structural performance and directional sensitivity of the leg under extreme combined loads, and to identify critical loading conditions. For this purpose, we adopt a quasi-static framework augmented by the Dynamic Amplification Factor (DAF) as an equivalent dynamic method [28]. The DAF quantifies the dominant dynamic amplification effect induced by waves and converts dynamic inertial loads into equivalent static loads. This approach can effectively reflect the peak structural response without solving full transient dynamic equations. The quasi-static plus DAF method is a well-established technique explicitly recommended by DNV, BV, and SNAME for Ultimate Limit State (ULS) assessment of jack-up units and WTIVs [11,29]. Given the large number of working cases with various crane slewing angles and wave headings in this paper, this equivalent scheme ensures good computational efficiency and consistent comparative analysis results. It should be noted that this method focuses on global peak response rather than fine transient vibration characteristics. When the ratio of the natural period of the structure T_n to the wave period T falls outside the range of 0.9–1.1, the DAF can be calculated as follows:

$$DAF = 1 / \sqrt{\left[1 - \left(\frac{T_0}{T}\right)^2\right]^2 + \left(2\zeta \frac{T_0}{T}\right)^2} \quad (10)$$

$$F = 1.1(DAF - 1)\tau \quad (11)$$

where T_0 is the natural period of the structure; T is the wave period; ζ is the damping ratio, taken as 7% in this study; and τ is the maximum base shear of the leg structure under the self-weight condition. In this study, the minimum value of the DAF is taken as 1.2. The resulting inertia loads are finally applied as concentrated nodal forces at the connections between the leg structure and the main hull.

2.2.5. P-Δ Effect

In the analysis of stability and structural response of jack-up platforms, the second-order gravity effect (P-Δ effect) is an important factor that must be considered [30]. The P-Δ effect refers to the additional moments and stresses induced by structural deformation under external loads such as wind, waves, and earthquakes. These effects lead to increased structural displacements, particularly in long, slender legs subjected to horizontal loads, which may cause lateral displacement of the main hull and consequently generate significant additional bending moments. Such additional bending moments not only affect the strength of the legs but also introduce secondary stresses in the leg cross-sections, making the P-Δ effect a critical consideration in structural design. This influence becomes even more pronounced in deep-water operating conditions. Under these circumstances, conventional linear elastic small-deformation finite element analysis may no longer be adequate, as it assumes limited structural deformation and neglects geometric nonlinearity. Therefore, the P-Δ effect is typically evaluated using large-deformation analysis methods or geometric stiffness formulations.

In this study, the geometric stiffness method is adopted, in which the stiffness matrix is updated by accounting for changes in structural configuration under large deformations, thereby more accurately capturing the influence of geometric nonlinearity on the structural mechanical behavior. The linear elastic displacements are amplified to approximate the

actual structural response under large deformation conditions. For the linear buckling analysis of the leg structure, the Sestra module is employed. This module determines the buckling modes Φ and corresponding eigenvalues λ through a static eigenvalue analysis. The governing equation is expressed as follows:

$$(K - \lambda K_g)\Phi = 0 \quad (12)$$

where K is the linear stiffness matrix and K_g is the geometric stiffness matrix. Based on the calculated eigenvalue λ , the amplification factor α for the horizontal load can be determined, thereby enabling an approximate evaluation of the P- Δ effect. The corresponding expression is given as follows:

$$\alpha = 1 / \left(1 - \frac{P}{P_E} \right) \quad (13)$$

$$\Delta = \delta_g \alpha \quad (14)$$

where Δ is the displacement including the P- Δ effect, δ_g is the first-order linear elastic displacement of the structure, P is the axial load of the leg, and P_E is the Euler buckling load of the leg. By reapplying the horizontal loads using the obtained amplification factor, the actual stress and displacement responses of the leg under large deformation conditions can be effectively captured, thereby ensuring the completeness and accuracy of the analysis results.

2.3. Strength Assessment

In accordance with the requirements of the BV Rules, under the specified loading conditions, the truss-type leg members subjected to axial tension or compression shall be assessed separately for tensile and compressive stresses [31]. The axial stress must satisfy the following criterion:

$$\sigma_t \leq \alpha \sigma_{at} \quad (15)$$

$$\sigma_c \leq \alpha \sigma_{ca} \quad (16)$$

where σ_t and σ_c are the axial tensile and compressive stresses of the member (MPa), respectively; σ_{at} and σ_{ca} are the allowable tensile and compressive stresses of the material (MPa), respectively; and α is the allowable stress reduction factor, taken as 0.8. The allowable stresses for each structural component are listed in Table 1.

Table 1. Allowable stress of each structural component.

Structure	Chord	Brace	Span Breaker
Yield Strength (MPa)	690	690	355
Allowable Stress (MPa)	521	521	268

3. Finite Element Modeling and Load Application of the Truss-Type Leg

3.1. Geometric Modeling

This study considers a self-propelled jack-up WTIV with a lifting capacity of 1500 t (as shown in Figure 1a). The platform mainly consists of a hull, four truss-type legs, four hydraulic jacking systems, and a DP-2 dynamic positioning system. A 1500 t main crane is installed near the starboard aft leg. The principal dimensions of the hull are 136.3 m in length, 50 m in width, and 10 m in depth, with a draft of 6.6 m. The total length of each truss-type leg is 120 m, with a longitudinal spacing of 75 m and a transverse spacing of 35.6 m between legs. Each leg is composed of main chords, braces, and span breakers. Each leg segment contains three chord members, with a spacing of 10 m between adjacent

chords and a segment height of 5 m. The main chord is composed of a tubular section combined with a rack plate. Due to the absence of such composite cross-sections in the GeniE module, an equivalent stiffness approach is adopted, whereby the chord is modeled as a circular tubular beam with equivalent cross-sectional properties. The main chord has a diameter of $\text{Ø}950$ mm and a thickness of 80 mm, forming a K-type bracing configuration with the diagonal members. Both diagonal and span breakers are tubular members. The span breakers, with dimensions of $\text{Ø}168.3 \times 11$ mm, are connected to the braces in a T-type configuration to enhance structural stability. The detailed joint configuration of the leg structure is illustrated in Figure 1b, and the material properties of each component are listed in Table 2.

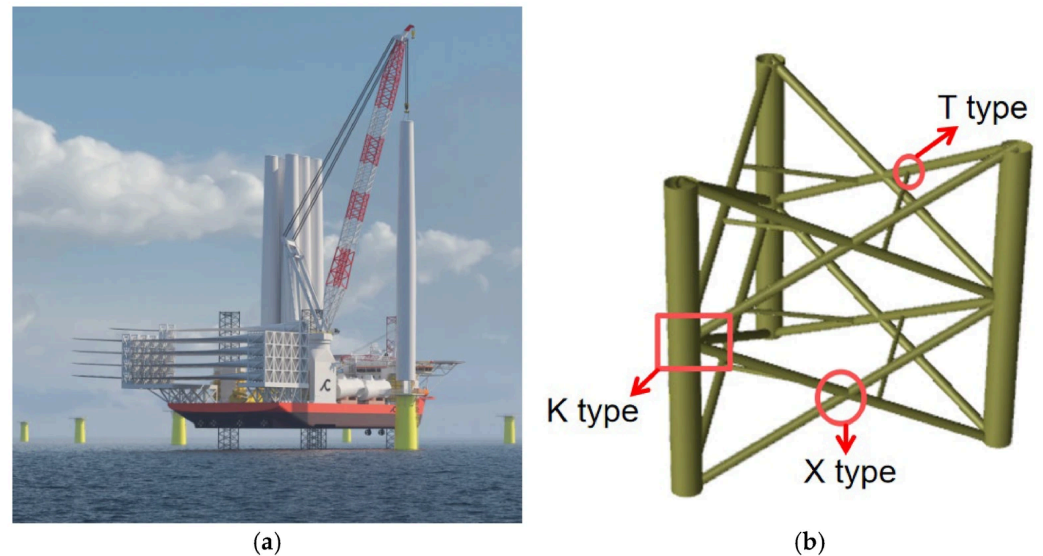


Figure 1. Configuration of the WTIV and detailed leg joint connections: (a) overall view of the WTIV; (b) detailed configuration of leg joints.

Table 2. Material properties of structural components.

Member	Density (kg/m^3)	Young's Modulus (MPa)	Shear Modulus (MPa)	Poisson's Ratio	Yield Strength (MPa)
Chord	7850	205,000	78,846	0.3	690
Brace					355
Span Breaker					355

A global finite element model of the WTIV is established using a combination of shell and beam elements. Shell elements are employed to model the primary hull structures, including the outer shell, longitudinal bulkheads, and transverse bulkheads, while beam elements are mainly used to represent the truss-type leg system. In the mesh generation, four-node quadrilateral shell elements are predominantly adopted, with three-node triangular elements applied in transition regions to ensure mesh compatibility. In the preliminary mesh generation, the global element size is controlled at approximately 1000 mm, considering the balance between computational efficiency and numerical accuracy. The beam elements are modeled using two-node elements. The complete finite element model of the 1500 t-class WTIV is shown in Figure 2.

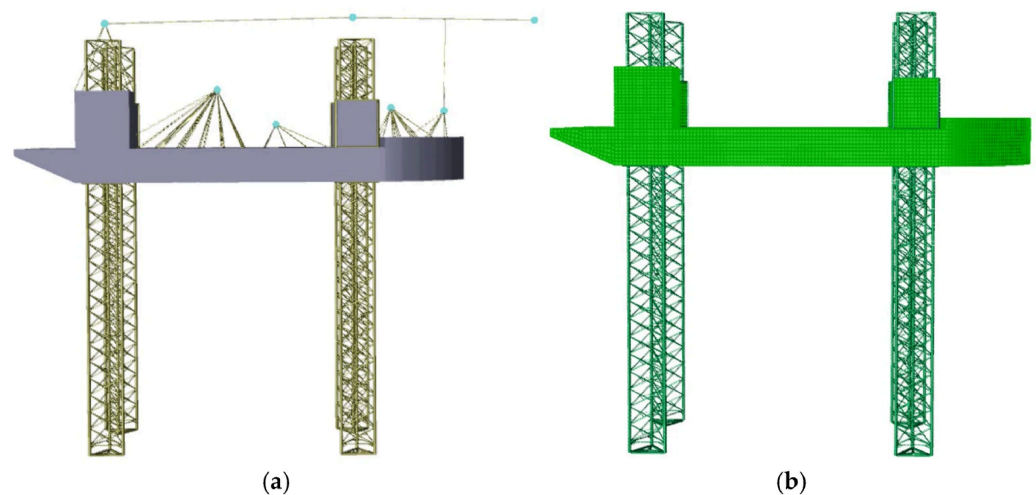


Figure 2. Finite Element Model of the 1500 t-class WTIV: (a) global finite element model; (b) finite element mesh.

3.2. Mesh Convergence Study

To evaluate the numerical accuracy and mesh sensitivity of the finite element model, three different mesh densities were investigated. In this case, the wind-wave-current loads under LC1 conditions are applied to the jack-up legs in the form of point loads. The resulting maximum displacement and maximum stress of the leg structure are listed in Table 3.

Table 3. Meshing parameters and calculated maximum displacement and stress.

ID	Element Size (mm)	Max Displacement (mm)	Error (%)	Max Stress (MPa)	Error (%)
Mesh1	1500	86.9797	0.57	159.579	0.17
Mesh2	1000	87.1975	0.32	159.712	0.09
Mesh3	500	87.4753	-	159.858	-

As shown in Table 3, both the maximum displacement and stress gradually converge with mesh refinement. Compared with the finest mesh model (Mesh3), the relative differences in the medium mesh model (Mesh2) are only 0.32% for displacement and 0.09% for stress, respectively. Even for the coarsest mesh model (Mesh1), the corresponding deviations remain below 1%. Therefore, considering both computational efficiency and solution accuracy, the mesh parameters for Mesh2 are deemed appropriate and thus chosen in this study.

3.3. Boundary Conditions

The legs of the WTIV are connected to the main hull through rack-and-pinion systems and locking devices. During operation, the upper and lower guides, together with the locking mechanisms, provide constraints and load transfer to the legs. Owing to the complexity of the jacking system, it is challenging to establish a fully detailed finite element representation. Therefore, simplified boundary conditions are adopted in this study.

At the leg–hull connection, the pin connection is modeled by considering only vertical stiffness, while the guiding system provides constraints in the horizontal directions. Both are assumed to have infinite stiffness [32]. At approximately 3 m below the seabed, hinged boundary conditions are applied to the legs, restraining translational degrees of freedom in all directions to simulate the support effect of the spudcan embedded in the soil. The

rotational stiffness of the spudcan–soil interaction is neglected, and all rotational degrees of freedom are assumed to be free [11,33,34].

3.4. Environmental Conditions and Load Application

In this study, the influence of crane slewing angle on the structural response of the leg system is first investigated. Subsequently, strength assessments of the legs are carried out under four representative operating conditions, namely preloading, non-operating, operating, and survival conditions. For the operating condition, the crane slewing angle corresponding to the maximum structural response is selected for the strength assessment. The detailed parameters for each operating condition are summarized in Table 4, while the corresponding environmental parameters are listed in Table 5.

Table 4. Detailed parameters of different operating conditions.

No.	Operating Condition	Condition Description	Applied Loads
LC1	Preload Condition	Leg penetration: 81 m; Air gap: 8 m; Embedment: 3 m	Self-weight, variable loads, environmental loads (Preload condition)
LC2	Elevated Condition (Crane not working)	Leg penetration: 83 m; Air gap: 10 m; Embedment: 3 m	Self-weight, variable loads, environmental loads (operating condition)
LC3	Crane Slewing Angle: 0°	Leg penetration: 83 m; Air gap: 10 m; Embedment: 3 m	Self-weight, variable loads, environmental loads (operating condition)
LC4	Crane Slewing Angle: 45°		
LC5	Crane Slewing Angle: 90°		
LC6	Crane Slewing Angle: 135°		
LC7	Crane Slewing Angle: 180°		
LC8	Crane Slewing Angle: 225°		
LC9	Crane Slewing Angle: 270°		
LC10	Crane Slewing Angle: 315°		
LC11	Survival Condition	Leg penetration: 63 m; Air gap: 15 m; Embedment: 3 m	Self-weight, variable loads, environmental loads (survival condition)

Table 5. Environmental parameters.

Environmental Parameter	Water Depth (m)	Wave Period (s)	Wave Height (m)	Wind Speed (m/s)	Current Velocity (m/s)	Wave Theory
LC1	70	4.6	7.5	13.8	1.03	Stokes 5th
LC2	70	9.3	8.8	36.0	1.03	Stokes 5th
LC3–LC10	70	6.5	8.3	15.8	1.03	Stokes 5th
LC11	45	18.6	11.5	51.5	1.54	Stokes 5th

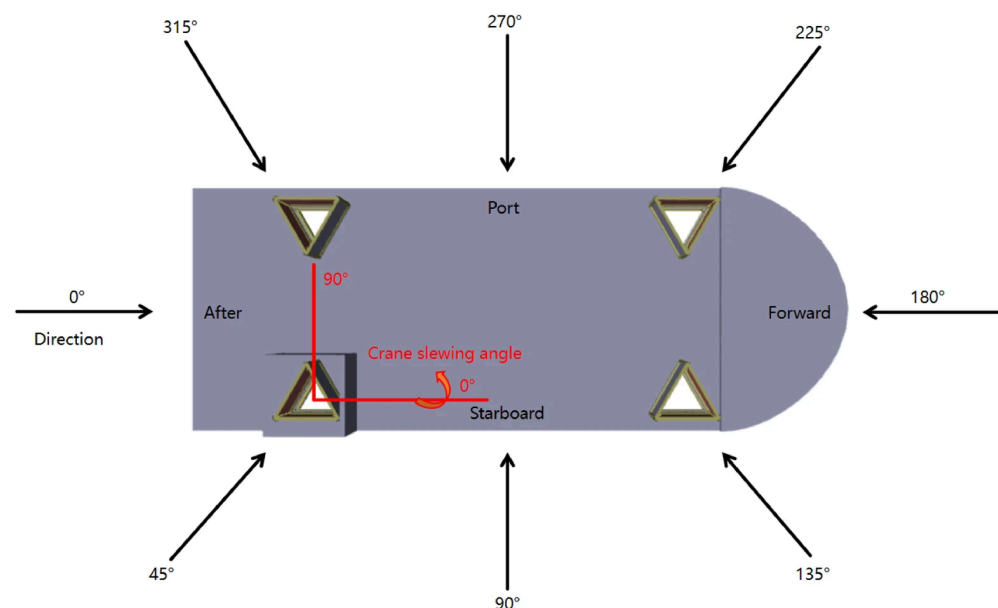
To evaluate the mechanical response of the leg structure under complex environmental and operational conditions, multiple types of loads are comprehensively considered in the finite element model, including weight loads, environmental loads, inertia loads, and P-Δ effect loads. In terms of weight loads, these primarily consist of the structural self-weight, living quarters (LQ), lifting equipment, compartment loads, and deck operational loads. The self-weight of key load-bearing components, such as the legs and jacking system, is automatically applied based on material density. Major concentrated masses, including the LQ, crane system, wind turbine components, and compartment loads, are equivalently represented by lumped mass elements. Their total mass and center of gravity are defined in accordance with the weight estimation report. Detailed weight load information is provided in Table 6.

Table 6. Summary of detailed weight loads (t).

Weight Loads	LC1	LC2	LC3-LC11	LC12
Living Quarter			880	
Main Crane Boom Rest			300	
Main Crane Jacking House			1260	
Other Jacking House			2550	
Main Crane Hook			102	
Main Crane Boom			560	
Main Crane Rotator			1738	
Steel Hull			9686	
Tank Load	976	976	976	785
Deck Load	6545	6545	5045	1000
Lifting Load (Includes Factor 1.1)	/	/	1650	/
Miscellaneous	5340	5340	5340	5073

Notes: The slash (/) means no lifting load under non-operating crane conditions.

During the calculation and application of wind, wave, and current loads, all environmental loads are assumed to act in the same direction to ensure conservative loading conditions for each case. Eight loading directions are considered, namely 0° , 45° , 90° , 135° , 180° , 225° , 270° , and 315° . The load direction is defined such that 0° corresponds to the stern along the longitudinal axis of the vessel, 180° to the bow, and 90° to the port side along the transverse direction. The directions of crane operational loads and environmental loads are illustrated in Figure 3.

**Figure 3.** Directions of crane operational loads and environmental loads.

In addition, during crane operations, the slewing angle of the crane varies within a full $0\text{--}360^\circ$ range relative to the vessel's longitudinal axis. Accordingly, the operational load directions are also discretized into eight angles: 0° , 45° , 90° , 135° , 180° , 225° , 270° , and 315° . The four legs are designated as F.P. (Forward Port), F.S. (Forward Starboard), A.P. (After Port), and A.S. (After Starboard), respectively. Furthermore, inertia loads and P- Δ effect loads are incorporated in all loading conditions to improve the accuracy of structural response prediction. In the finite element implementation, wind loads, inertia loads, and P- Δ effect loads are applied in the form of concentrated nodal forces, with their magnitudes determined based on the formulations described above. For conservatism, the

maximum load magnitude is adopted for all loading directions in the strength assessment. The summary of loads under different load cases is presented in Table 7.

Table 7. Summary of loads under different operating conditions.

Operating Condition	Wind Load (kN)	Inertial Load (kN)
LC1	1324	854
LC2	8816	976
LC3-LC10	1775	823
LC11	11,307	3311

4. Results and Discussion

4.1. Structural Response of Truss-Type Legs

4.1.1. Structural Response of Truss-Type Legs Under Different Crane Angles

Figure 4 shows the displacement response of the leg structure under different crane slewing angles. As shown in Figure 4a, the maximum displacement exhibits strong directional dependence on the slewing angle, with higher values observed at 90° and 270° . This indicates that transverse crane operations induce larger global deformations. Figure 4b presents the maximum total displacement and its directional components at different slewing angles. The minimum displacement occurs at 45° , with a value of approximately 118 mm, while the maximum appears at 270° , reaching about 178 mm, representing a 33% increase. This confirms that the crane slewing angle significantly affects the leg's deformation.

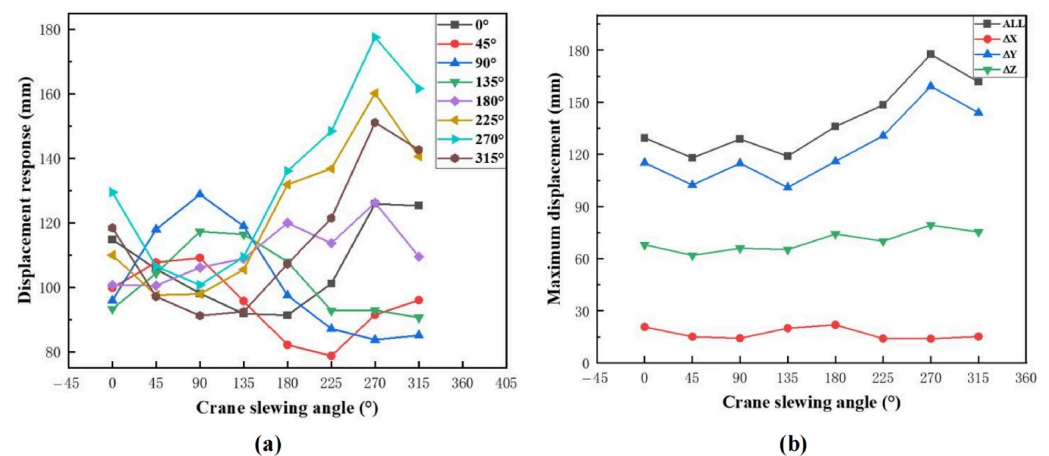


Figure 4. Variation in the maximum displacement of the leg structure under different crane slewing angles: (a) total displacement response; (b) maximum displacement components.

In terms of displacement components, the ΔY component dominates across all cases and follows the same trend as the total displacement, indicating that it governs the structural response. The ΔZ component is secondary, whereas the ΔX component remains small and shows little variation with the slewing angle. This behavior reflects the inherent stiffness anisotropy of the truss leg, where differences in bending stiffness along different directions lead to amplified lateral deformations under specific crane orientations.

Figure 5 presents the stress responses of the leg structure under various crane slewing angles. As shown in Figure 5a, the overall stress varies smoothly with the slewing angle and exhibits a clear bimodal distribution, indicating two distinct unfavorable angular intervals. This behavior reflects directional differences in load transfer paths and structural stiffness distribution, leading to pronounced directional dependence of the stress response. As illustrated in Figure 5b, the stress contribution differs significantly among member types.

The chord members carry substantially higher stresses than braces and span breakers, acting as the dominant load-bearing components that control the structural strength. The maximum stress of approximately 210 MPa occurs at a slewing angle of 270° , which is 18% higher than the value at 45° . Notably, the peak stress coincides with the peak displacement at the same angle, confirming 270° as the most critical loading orientation. In contrast, the stresses in the diagonal and bracing members remain relatively stable and show lower sensitivity to changes in the slewing angle, thereby mainly contributing to load transfer and overall structural stability.

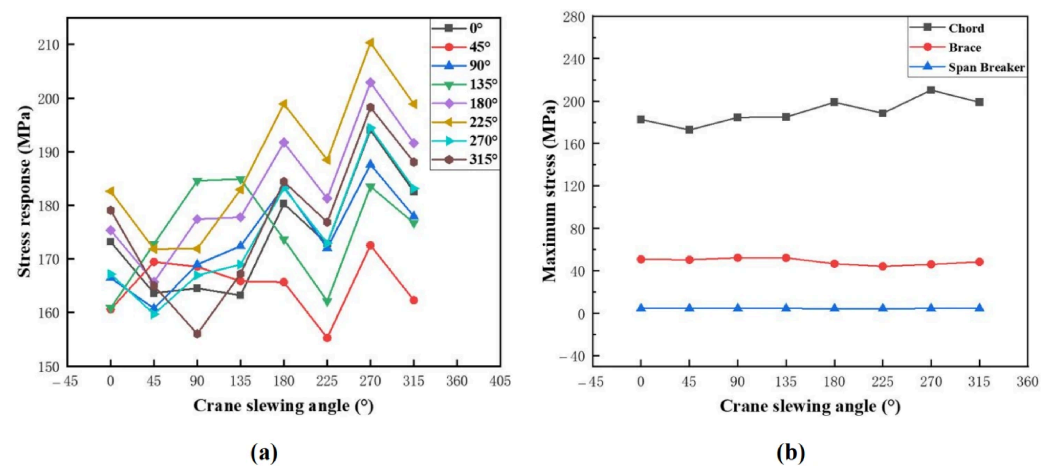


Figure 5. Variation in the maximum stress of the leg structure under different crane slewing angles: (a) maximum axial stress; (b) maximum stress of each member.

Figure 6 illustrates the variations in initial lateral displacement and the corresponding P- Δ effect-induced load with crane slewing angle. Both quantities exhibit strong directional dependence and reach their maxima at a slewing angle of 270° .

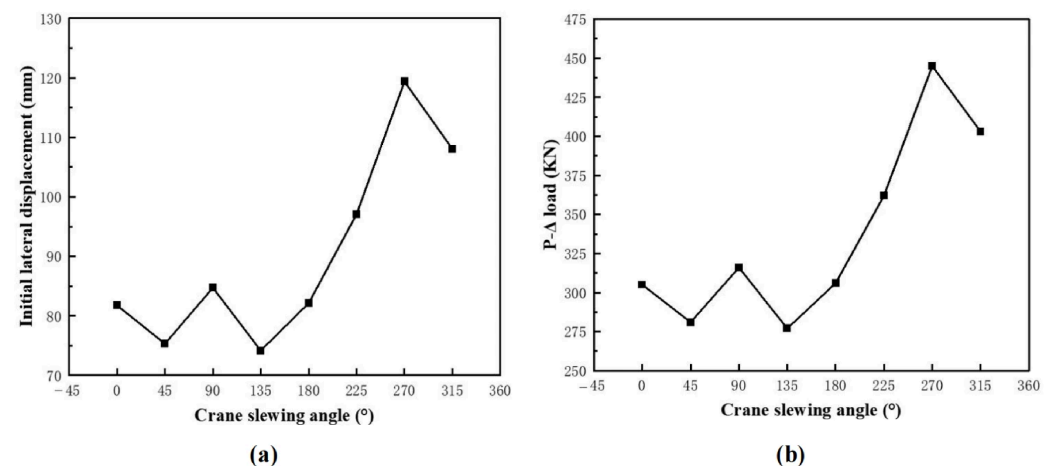


Figure 6. Variation in initial lateral displacement and P- Δ effect load with crane slewing angle: (a) initial lateral displacement; (b) P- Δ load.

Mechanistically, variations in crane slewing angle alter the spatial distribution of the lifted load and the corresponding overturning moment applied to the platform. At 270° , the horizontal projection distance between the lifted load and the platform center is maximized, leading to the largest effective eccentricity. This generates the maximum overturning moment and significantly amplifies the initial lateral displacement of the leg structure. The enlarged lateral displacement further intensifies the P- Δ effect, where the coupling between

axial force and lateral deformation introduces additional bending moments. This forms a nonlinear amplification mechanism characterized by mutual enhancement of displacement and internal forces, leading to a substantial increase in the overall structural response.

From the viewpoint of structural stiffness, the loading direction at 270° is closely aligned with the principal flexible direction of the truss leg, where the lateral bending stiffness is relatively low. Under this condition, the structural resistance to lateral loading is weakened, making displacement and internal forces more prone to amplification. For other slewing angles, the eccentricity effect is weaker, or the loading direction does not coincide with the structural weak axis, resulting in lower response levels.

In summary, the crane slewing angle significantly affects the displacement and stress responses of the leg structure by changing the load eccentricity and its alignment with the principal stiffness directions of the legs. The 270° condition represents the most unfavorable scenario, owing to the combined effects of the maximum overturning moment, alignment with the structural weak axis, and the P- Δ amplification effect. Therefore, this condition is regarded as critical for subsequent strength evaluation and operational safety control.

4.1.2. Structural Response of Truss-Type Legs Under Different Crane Angles and Wave Loads

Figure 7a presents the contour map of the maximum displacement response under combined crane slewing angles and wave directions. The maximum displacement occurs when both the slewing angle and wave direction are 270° , indicating a pronounced high-response region under this combination. This suggests that the structural stiffness in the transverse 270° direction is relatively weak. Therefore, alignment between the crane slewing angle and wave direction within this critical sector should be avoided during offshore operations. In contrast, the displacement response is significantly reduced under combinations of slewing angles from 180° to 225° and wave directions from 0° to 90° , representing a relatively favorable operating window.

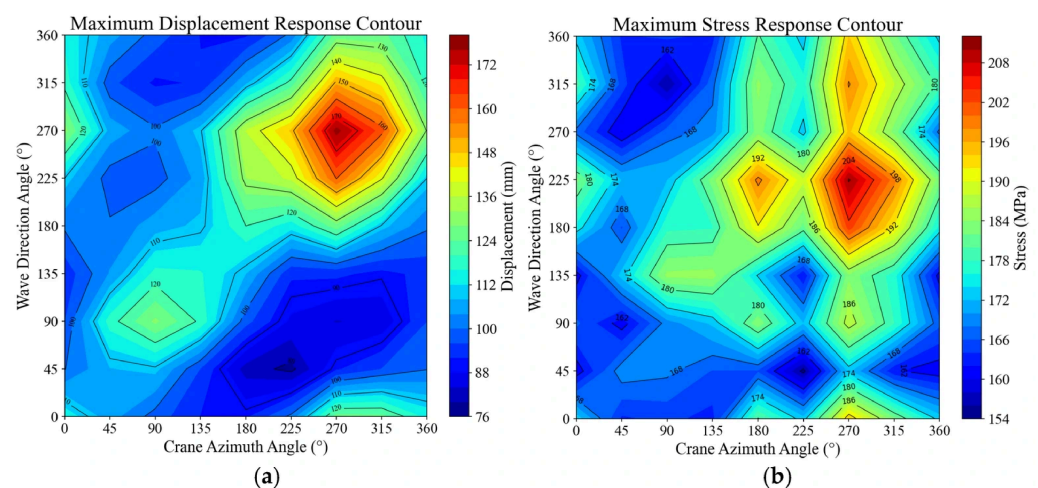


Figure 7. Contour plots of maximum structural responses under crane slewing angles and wave directions: (a) maximum displacement (mm); (b) maximum stress (MPa).

Figure 7b shows the contour distribution of the maximum stress response under the same combined conditions. Stress levels are generally higher when the slewing angles are near 180° and 270° , with wave directions ranging from 180° to 270° . The peak stress appears at a slewing angle of 270° and a wave direction of approximately 225° . Conversely, stress levels remain relatively low when slewing angles range from 180° to 270° , and wave directions lie between 0° and 90° .

Compared with single-variable analysis, the contour maps further demonstrate that the leg structural response is governed not only by the crane slewing angle but also significantly by the environmental load direction, with a clear coupling effect between the two. The structural response is notably amplified when both the slewing angle and wave direction fall within the range of 180–270°. In contrast, combinations of slewing angles from 180° to 225° and wave directions from 0° to 90° yield relatively low stress and displacement, representing a favorable operating range. This behavior is closely related to the platform layout and load application direction. Since the crane is installed near the aft starboard side, a slewing angle of 270° generates a large overturning moment, leading to increased axial forces and bending moments in the corresponding legs, resulting in peak stress and displacement. When operational and environmental loads are aligned, their components are superimposed, significantly increasing horizontal forces and overturning moments and amplifying the structural response. Conversely, a non-aligned orientation distributes loads across multiple directions and reduces localized response concentration.

Therefore, in practical operations, the combination of a crane slewing angle near 270° and a wave direction within 225–270° should be avoided to reduce adverse load effects and improve structural safety. In addition, load direction variation redistributes internal force paths, causing different legs and key members to carry distinct axial forces and bending moments. This load-coupling-driven internal force redistribution is the primary reason for the localized high-response regions observed in the contours.

In summary, the leg structure exhibits strong directional characteristics and significant multi-load coupling effects. The most unfavorable condition is jointly determined by the crane slewing angle and environmental load direction. Thus, in structural design and operational assessment, it is essential to identify critical adverse load combinations using multi-parameter coupled analysis to enhance structural safety and evaluation reliability.

4.2. Strength Evaluation and Discussion

To evaluate the structural performance of the truss-type leg under different operating conditions, four representative load cases are considered, including the preloading condition (LC1), non-operational crane condition (LC2), operational crane condition (LC9), and survival condition (LC11). For the crane operating case, the most unfavorable slewing configuration identified in Section 4.1 is adopted.

In the strength assessment, combined static, operational, and environmental loads are applied simultaneously. For each load case, the maximum stresses of chord members, braces, and span breakers are summarized in Table 8, and the corresponding maximum displacements are presented in Table 9.

Table 8. Maximum stress results under different load cases.

Operating Condition	LC1	LC2	LC9	LC11
Chord (MPa)	−166.77	−264.31	−210.33	−289.66
Brace (MPa)	−38.85	−119.06	−46.22	−244.02
Span breaker (MPa)	−4.27	5.97	−4.62	−24.14
Load direction (°)	45	45	225	135
Check result	OK	OK	OK	OK

Notes: “OK” indicates that the structural strength check satisfies the allowable design requirement.

Figure 8 shows the stress distributions of the leg structure under different Operating conditions. Overall, the stress distribution patterns remain consistent across all cases, where the chord members act as the primary load-carrying components and exhibit significantly higher stresses than braces and span breakers. For LC1, LC2, and LC11, the maximum stress is mainly concentrated at the connection between the fore port-side leg and the hull,

while relatively high stress is also observed near the leg–spudcan interface. This stress distribution pattern is consistent with previously reported results for jack-up WTIV structures, where the leg–hull connection was identified as a critical structural region [11,16,35]. This is attributed to the combined effect of load concentration and transfer characteristics in the non-operational configuration, where the crane is stowed near the fore port-side region. In addition, auxiliary concentrated loads, including LQ and the wind turbine tower, further intensify the local vertical loading in this area, resulting in increased axial force accumulation along the corresponding leg. The stress concentration at the leg–spudcan connection is further amplified by boundary restraint effects at the support, which enhance local bending responses. In contrast, under LC9, the load path is redistributed due to crane operation. The crane boom, hook, and lifted payload are transferred to the aft starboard side through the crane pedestal, leading to a shift in the maximum stress region to the corresponding leg–hull connection.

Table 9. Maximum displacement results under different load cases.

Operating Condition	LC1	LC2	LC9	LC11
Maximum value (mm)	97.61	309.86	177.57	338.60
X component (mm)	−56.46	11.25	−69.21	15.44
Y component (mm)	50.87	301.99	−129.63	334.62
Z component (mm)	−61.91	−77.98	−79.28	−57.54
Load direction (°)	90	90	270	90

Among all load cases, the maximum structural stress is observed under the LC11 condition, with a peak value of 289.66 MPa in the main chord members. This indicates that LC11 represents the most unfavorable condition. The higher stress level is primarily driven by extreme environmental loading, which increases both axial and bending responses in the primary load-carrying members. In addition, the results under different wave directions show that oblique wave conditions consistently lead to higher stress levels across all load cases. This is because oblique wave incidence induces combined longitudinal and transverse loading components, resulting in enhanced global bending effects of the leg structure. From a structural performance perspective, these results highlight the strong directional sensitivity of the truss-type leg system under combined operational and environmental loading conditions. The findings suggest that wave heading should be carefully considered in operational planning, particularly under severe sea states, to mitigate unfavorable loading effects and improve structural safety.

Figure 9 shows the displacement contour distributions of the leg structure under different Operating conditions. Although deformation patterns vary with loading conditions, the maximum displacement consistently occurs at the top of the legs, indicating that the global response is governed by overall bending deformation. Similar deformation characteristics have also been reported in previous studies on jack-up WTIV structures, where the local concentration of operational loads significantly influenced the global bending response of the leg system [16,35].

Under LC11 at a wave direction of 90°, the maximum displacement reaches 338.60 mm, representing the most unfavorable deformation condition among all cases. For LC1, LC2, and LC11, the peak displacement occurs at the fore port-side leg, which is consistent with the load concentration induced by the stowed crane and associated equipment. In contrast, under the LC9 condition, the load transfer path is redistributed to the aft starboard side, resulting in a shift in the maximum displacement location to the corresponding leg. In addition, it is observed that the maximum displacement under all load cases occurs in the transverse wave directions (90° and 270°), confirming that lateral environmental loading plays a dominant role in the global deformation response. This is primarily due to the fact

that transverse wave excitation induces significant lateral bending of the overall structure, thereby amplifying the global displacement response.

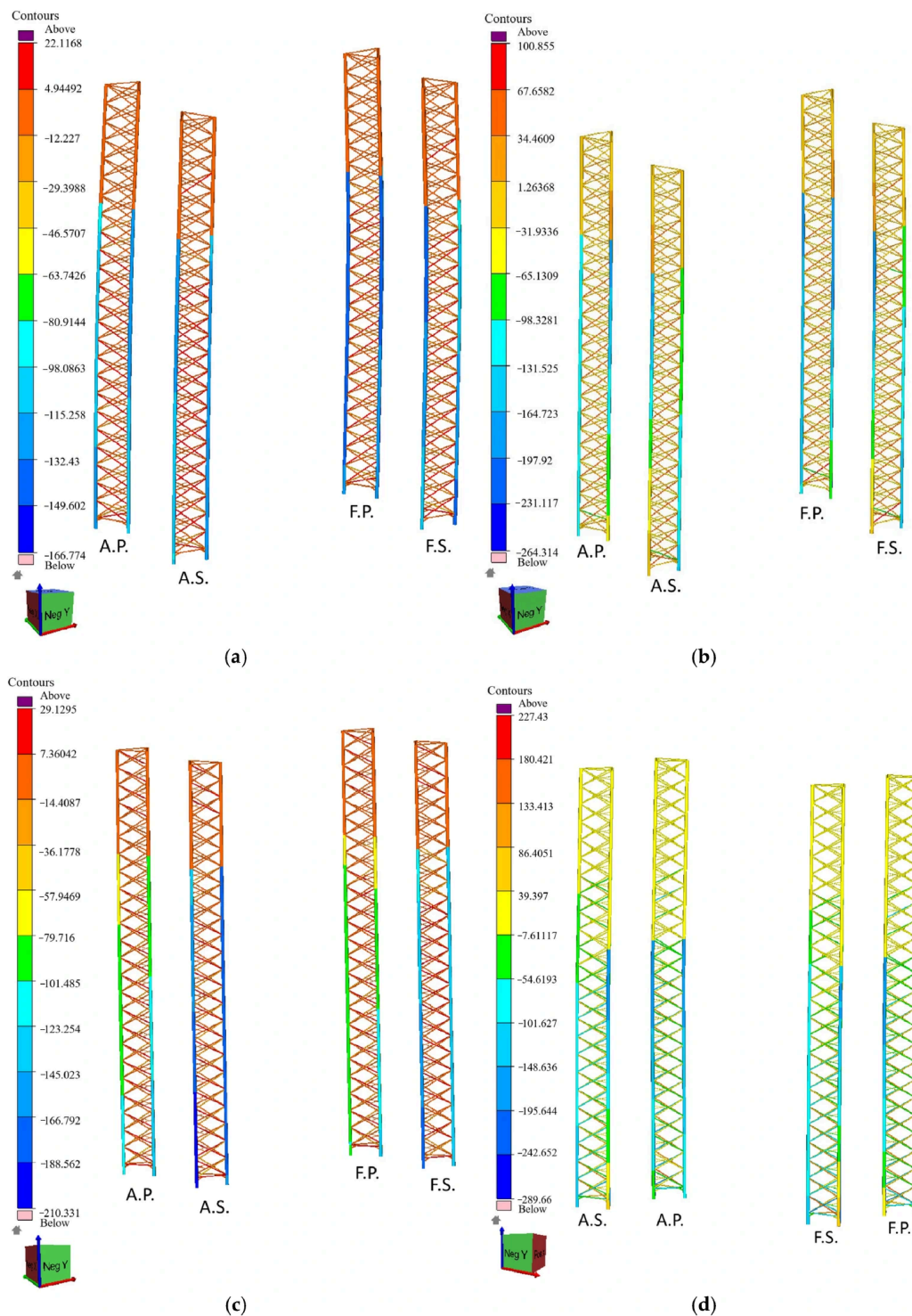


Figure 8. Contours of maximum stress under different load cases (MPa): (a) LC1; (b) LC2; (c) LC9; (d) LC11.

In summary, the maximum displacement of the leg structure under all load cases is 338.6 mm, which is acceptable relative to the overall dimensions of the vessel and indicates a globally stiffness-dominated response. The maximum stress is 289.66 MPa, remaining below the allowable material strength. Overall, these results suggest that the truss-type

leg exhibits sufficient global strength and stiffness to withstand the combined effects of operational and environmental loading under the investigated conditions.

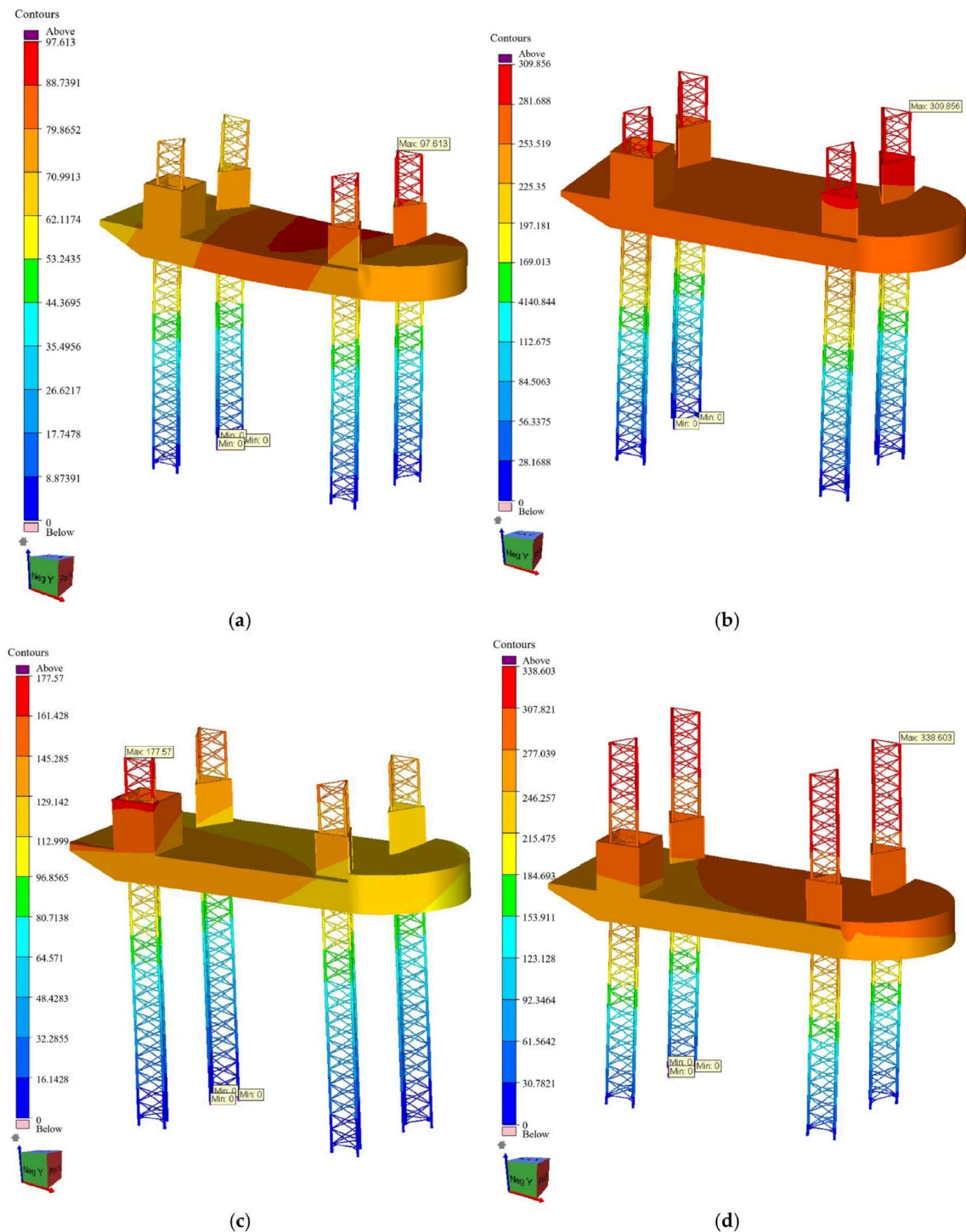


Figure 9. Contours of maximum displacement under different load cases (mm): (a) LC1; (b) LC2; (c) LC9; (d) LC11.

4.3. Results Validation

To evaluate the reliability of the numerical model, the calculated results are compared with published benchmark data for a similar 1600 t jack-up wind turbine installation vessel. Although full-scale experimental measurements are not available in this study, validation is conducted through comparison with results reported in the literature.

Chai et al. [16] performed systematic strength and fatigue analyses on truss-type legs and spudcan connections of a jack-up WTIV under typical operating conditions, including preloading and storm survival. Both vessels belong to the 1500–1600 t-class offshore wind installation platform, with highly consistent truss-type leg configurations, service sea areas, and design specifications, providing a solid foundation for comparative verification. The selected preload and storm survival cases are widely recognized as the most critical loading scenarios in practical offshore engineering, and their boundary conditions are sufficiently comparable for structural response verification.

As shown in Table 10, under the preloading condition, the present result is 166.77 MPa, compared with 184.6 MPa reported by Chai et al. [16]. For the storm survival condition, the corresponding values are 289.66 MPa and 308.2 MPa, respectively. The relative differences are 9.6% and 6.0%, which are within an acceptable range for global structural response analysis of offshore platforms.

Table 10. Comparison of maximum leg stress under typical load cases.

Load Case	This Study (MPa)	Chai et al. [16] (MPa)	Relative Difference (%)
Preload Condition	166.77	184.6	9.66
Survival Condition	289.66	308.2	6.02

The discrepancies can be attributed to differences in structural idealization, environmental loading representation, and modeling assumptions. Considering the complexity of large-scale offshore structures, the overall agreement indicates that the proposed numerical model provides a reasonable and reliable prediction of global structural responses for strength and directional sensitivity analyses.

5. Conclusions and Limitations

This study systematically investigates the directional structural responses and global strength performance of truss-type legs for a 1500 t jack-up wind turbine installation vessel, focusing on the coupled effects of crane slewing angles and wave directions under typical operational and survival conditions. A refined finite element model was established using SESAM and verified through mesh convergence and comparison with the literature. The main conclusions are summarized as follows:

- (1) The leg structure exhibits pronounced directional dependence. Both displacement and stress reach their maxima at 270°, with the maximum displacement approximately 33% higher than the minimum value. The response is dominated by the ΔY lateral component, which is attributed to stiffness anisotropy of the truss system and load eccentricity induced by crane operations. The overall deformation is governed by bending, with the maximum displacement consistently occurring at the leg top.
- (2) A significant coupling amplification effect exists between crane operational loads and environmental loads. The most adverse responses occur when the crane slewing angle and wave direction are aligned within 225–270°, where load superposition markedly increases overturning moments and bending effects. Oblique and transverse waves generate combined longitudinal and transverse load components, leading to the highest stress and deformation among all scenarios.
- (3) The stress distribution further indicates that the main chord members serve as the dominant load-carrying components, while critical stress concentration regions are primarily located at the leg–hull and leg–spudcan connections. The location of the critical stress region varies with crane operating state due to load-path redistribution associated with crane slewing and payload transfer.

- (4) These findings provide quantitative guidance for offshore engineering practice:
- (1) Operations should avoid crane-wave alignment within the critical sector of 225–270° to mitigate coupled load amplification;
 - (2) Oblique and transverse wave directions should be avoided during both operation and storm survival;
 - (3) Local reinforcement should be enhanced at leg–hull and leg–spudcan connections to improve resistance against stress concentrations.

Overall, the present study demonstrates that the structural response of jack-up WTIV legs cannot be adequately characterized using simplified single-direction loading assumptions. Instead, the coupled interaction between crane operation and environmental loading introduces significant direction-dependent response amplification, which should be explicitly considered in global structural assessment frameworks.

Nevertheless, several limitations remain in the present work. The hydrodynamic analysis is based on a Morison equation framework with constant hydrodynamic coefficients, while wake effects and detailed member-to-member hydrodynamic interactions are not explicitly resolved. In addition, regular design waves are adopted instead of stochastic irregular sea states, and the dynamic response is considered through an equivalent quasi-static approach combined with the DAF rather than full-time-domain dynamic simulations. Furthermore, fatigue behavior and soil-structure interaction effects are beyond the current scope. Future work will therefore focus on incorporating irregular wave spectra, fully coupled time-domain dynamic analysis, fatigue assessment, and soil-structure interaction to further improve the prediction accuracy and applicability of the proposed framework.

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