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Linear performance assessment of offshore wind turbine jacket substructure with varying brace topology in the Indian Ocean scenario

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Offshore wind energy has become a rapidly growing industry; however, the harsh conditions of the ocean can pose a significant risk to the structural integrity of offshore wind turbine substructures. India's coastal and offshore regions have a high potential for wind energy due to steady winds and minimal obstructions, but the country's offshore wind potential remains largely unexplored. To address this, a study was conducted on a proposed fixed offshore platform in the Gulf of Mannar region of the Indian Ocean, supporting a 10 MW offshore wind turbine at a depth of 75 m. The study aimed to evaluate the platform's structural performance under various environmental conditions, focusing on wind energy development. The study analysed the impact of different bracing configurations, such as X, K, and V bracing systems, on the structural stability of the substructure using the finite element software, Structural Analysis Computer Software (SACS). The study also simulated pile-soil interaction to understand the platform's actual behaviour. Results indicated that the X-bracing configuration outperformed the K and V configurations in terms of overall structural stability. The study highlights the importance of considering environmental load orientations and topology characteristics in marine renewable offshore wind energy projects, as well as the significance of choosing an appropriate bracing configuration to maintain the safety, coastal sustainability and performance of offshore wind turbine substructures in the Indian Ocean.

[**Keywords**: Brace topology, Coastal sustainability, Gulf of Mannar, Marine renewable energy, Offshore wind farm]

Introduction

In recent years, offshore wind energy production has made significant progress. Based on recent statistics and analysis from the Global Wind Energy Council, 21.1 GW of offshore wind power was put into service in 2021, which is a threefold increase over the year prior[1]. This makes 2021 the most successful year in offshore wind energy production history, with a 22.5 % market share for new installations worldwide. With a total global wind energy generating capacity of 837 GW, the world can now avoid emitting 1.2 billion tonnes of CO_2 annually, which is equivalent to South America's yearly carbon emissions.

Conventional Offshore Wind Turbine (OWT) foundations such as monopile, multi-pile cap foundation, gravity foundation, and composite suction bucket foundation have limitations and can only be used in a water depth of up to 30 m. However, future offshore wind turbines require structures that can accommodate greater water depths, further distances from shore, and higher capacity turbines with larger rotor diameters and foundation requirements[2], as shown in Figure 1. To meet these requirements, the jacket platform has emerged as a viable alternative supporting structure for offshore wind turbines[3], particularly for depths greater than 50 m. Recently, the jacket platform has also been used as a production or oil-recovering platform, and researchers have explored the feasibility of converting existing gas extraction infrastructure into offshore platforms for wind turbine towers[4]. While monopile foundations remain the most commonly used support structure for offshore wind turbines, the growing use of jacket-type platforms highlights their potential as a reliable and cost-effective solution for supporting future offshore wind turbines in deeper waters.

The design of water-based steel jacket constructions is complex due to various factors[5], including hydrodynamic interaction and dynamic response, which are not present in land-based turbines. In contrast to onshore turbines, offshore turbines, including the rotor, nacelle, and tower, are affected by winds, while the supporting structure is affected by several environmental factors such as waves, water currents, ice, earthquakes, sea wave load, impact load due to ship movement, depth variation due to tidal and storm surges, and marine vegetation growth[6], as depicted in Figure 2. Compared to onshore wind farms, offshore wind farms have a significantly lower environmental impact. Offshore turbines have higher power capacities and larger rotors than onshore turbines, which increases capacity. The mass of offshore support systems increases nearly quadratically[7,8] as turbines scale up from the standard 5 MW to the 10 MW range.

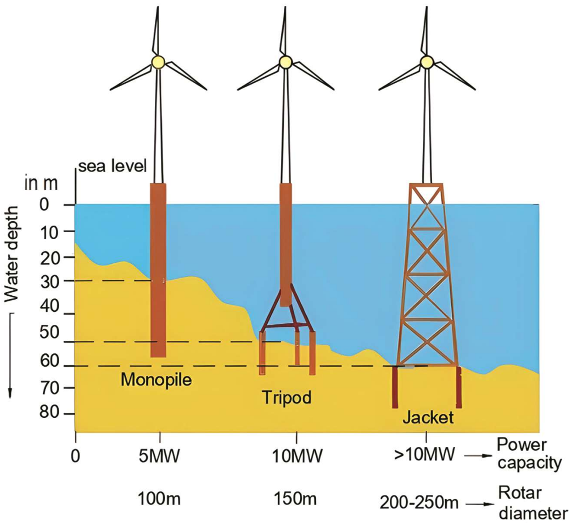


Fig. 1 — Trends of commonly used OWT platform substructure

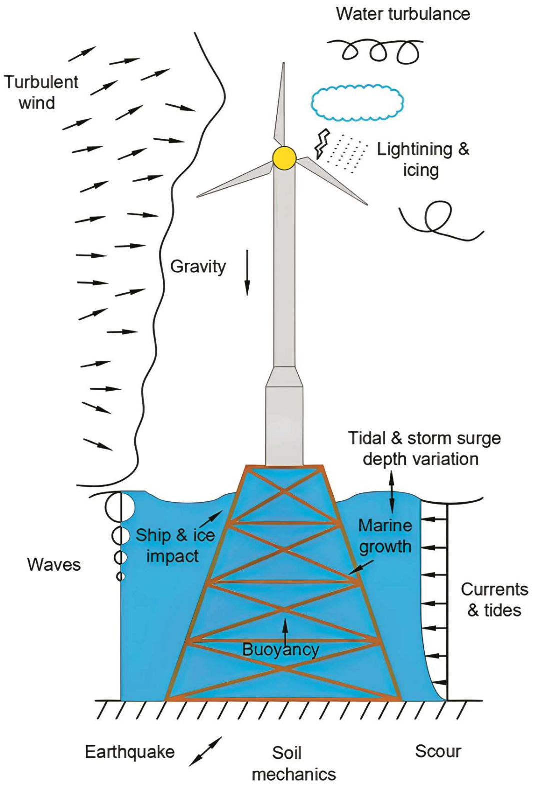


Fig. 2 — Different sources of loadings on Offshore Wind Turbine (OWT)

Recent researches such as Kallehave *et al.*[9] and Oest *et al*.[10] have offered a variety of approaches and models for structural optimisation of jacket support structures. The speed and scope of optimisation have significantly increased due to recent advances in topology optimisation technologies, particularly those related to continuum structure optimisation. Topology optimisation can be used to propose a finished new design at an extremely early stage of the product development process[11]. Size, shape and topology optimisation are the three main categories for structural optimisation and the process of optimisation steadily becomes more challenging[12]. Only the initial topology design could have produced the ideal structure due to sizing and form optimisation. In other words, if the initial topology design is not optimal, the structure from sizing and shape optimisation may not be the best actual structure[13]. Using ANSYS software, Tian *et al.*[14] created a calculation model for a marine platform with an eye on offshore engineering structures. They then optimised the platform's dynamic and static designs under various working conditions. The outcome is 8 % lower when using topological optimisation with volume as the objective function. An analytical gradient-based technique was presented by Chew *et al.*[15] to optimise the diameter and thickness of the offshore wind jacket substructure. Structural optimisation approaches aid in the design of a jacket in a 50 m depth of water. The jacket structure research has mainly focused on static and dynamic response and overall quality optimisation. However, research on optimising the specific topological structure and transmission mode is still lacking. This research addresses the untapped potential of offshore wind energy in India, particularly in the Gulf of Mannar region, Dhanushkodi, and Rameshwaram. It aims to overcome the critical challenge of designing pile foundation systems for fixed jacket platforms under axial and lateral loads. By investigating the impact of bracing topology on offshore structures response it offers more accurate and effective design solutions. The findings are expected to inform policymakers and industry stakeholders about the feasibility and economics of offshore wind projects, contributing to India's renewable energy expansion and its goal of 30 GW offshore wind farms by 2030(ref. 16).

Materials and Methods

Platform description and geometrical modelling

Structural Analysis Computer Software (SACS)

The SACS suite software was used to create a comprehensive 3D FE model of the platform, which includes a jacket, piles, and other appurtenances. The Work flow of SACS is presented in Figure S1. Every member was modelled as a set of rigidly connected 3D frame elements. Both static and dynamic structural analyses are included in the SACS system. The system is comprised of many compatible programme modules that are all properly interfaced. Physical experiments are time-consuming and expensive. Instead, design engineers can use numerical analyses to decrease the number of prototypes, which will save a lot of time and work. However, it is unlikely that the numerical analysis will yield 100 % accuracy, regardless of how well the simulation software works. Model validation and verification enable techniques for creating computational models that can be used to generate engineering predictions with quantified confidence[17]. In most cases, end customers don't need to check commercially available software. The programmers carry out the verification and ensure that their output is error-free mathematically and technically.

Moreover, several research projects that were published in reputable journals employed the SACS software. Based on pushover analysis, the SACS was used to examine the behaviour of existing offshore jacket platforms[18]. The composite non-tubular joint structure of an offshore jacket subjected to wave stresses was evaluated for fatigue using the SACS software for a global analysis of multidirectional wave loads for the jacket platform[19]. On the other hand, it is the end user's primary job to validate the numerical model by adopting appropriate boundary conditions, constitutive models, and components to produce a numerical model that accurately replicates the actual physical model. The parameters and constitutive models are verified. To obtain "best fit" with the test data, soil parameters are modified repeatedly. The validation of boundary conditions ensures that the specified boundaries have no impact on the analysis results. The results are identical when a finer mesh is analysed because the meshing and spatial discretisation are valid. The analytical outputs are validated for the complete numerical model after each model component has been independently validated. This is done by comparing the convergence of the numerical model with the reference results and by evaluating the convergence of the model results.

Geometrical modelling of the platform

The jacket (template), piles, and deck portion make up the bulk of a fixed platform. The jacket is a welded tubular structure in three dimensions. The jacket's legs create a square in plan view. The legs are inclined 1/12.5 degrees on each side. The bracings are thick enough to have a diameter-to-thickness ratio of 20 to 70 to prevent any tendency to buckle. The bracing system helps transmit horizontal loads to the foundation, maintains structural integrity during fabrication and installation, prevents the jacket pile system from wriggling, supports corrosion anodes and well conductors, and transfers wave forces produced by these components to the foundation, among other general functions.

The platform with four legs composed of tubular steel is considered in the study. The area's water depth is 75 meters. The platform is 90 m tall overall, and its cross-section is square in shape. 20 m × 20 m is the top measurement, while 32 m × 32 m is the base dimension on the seabed (-75.00 m). The working point elevation is +15.00 m. The jacket legs are battered at 1 to 12.5 in both broadside and end on framing. X-bracing subdivides the jacket into 3 bays, each measuring 25 meters. Steel jacket's material characteristics Young's Modulus, yield stress, ultimate stress, coefficient of thermal expansion and Poisson ratio are taken as 200 Gpa, 320 Mpa, 400 Mpa, 1.2 E^{-5}/°C and 0.3, respectively[20].

The jacket structures are created following the requirements outlined in international standards using the code-based modelling approach[21,22]. The jacket structure's design complies with all applicable codes and is durable enough to withstand normal operating conditions and adverse weather. Figure 3 shows a structural drawing of the proposed platform. For comparative study, another two models were developed, replacing the X-bracings with V-bracing and K-bracings while keeping other parameters the same. While other bracing configurations exist, X, V, and K-braces are popular due to their ease of fabrication, efficient use of materials, and effective performance in resisting lateral loads. Additionally, these brace configurations can be easily incorporated

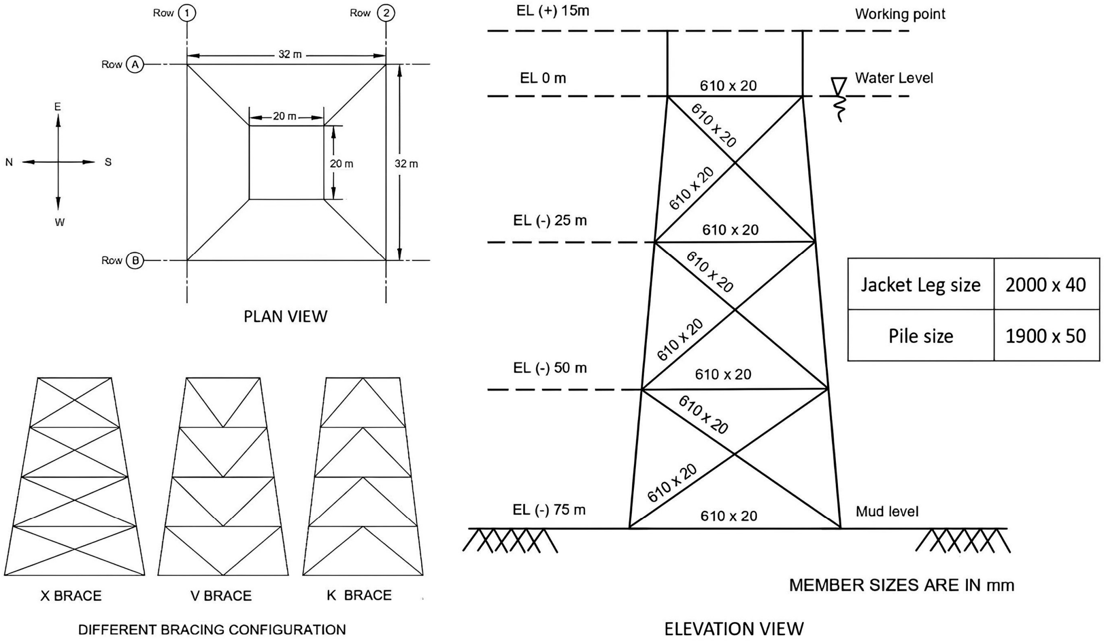


Fig. 3 — Plan and elevation view of the sub-structure platform

into steel structures of various sizes and shapes, making them versatile and widely applicable. The structural weight of the X, V, and K-brace systems is 24718 kN, 23250 kN, and 23410 kN, respectively.

Platform finite-element structural model

A 3D finite-element structural model has been created to depict the sub-structure's in-place conditions. Each frame member is accurately represented along with its cross-sectional characteristics, such as sectional variation, joint eccentricities, and connections. Using the SACS suite software, which comprises jacket, piles, stubs, and bracing systems, a comprehensive 3D model of the platform is managed[23]. Dummy members are restricted at the six DOFs at the jacket leg, and the two lateral DOFs at the pile end replicate shim plate centralisers inside the jacket leg at horizontal planes. The soil was defined by the nonlinear load-deflection curves such as P-Y, T-Z and Q-Z curves and their values are tabulated in Tables S1 – S3. Twenty-six layers of soil are defined up to a depth of 123 m below mud line data for plotting nonlinear load-deflection curves. However, these layers do not contribute to the overall rigidity of the structure. Figure 4 illustrates the finite element model of the platform with four legs as two sets of horizontal axes, 1 and 2 parallel to the y-axis and A and B parallel to the x-axis.

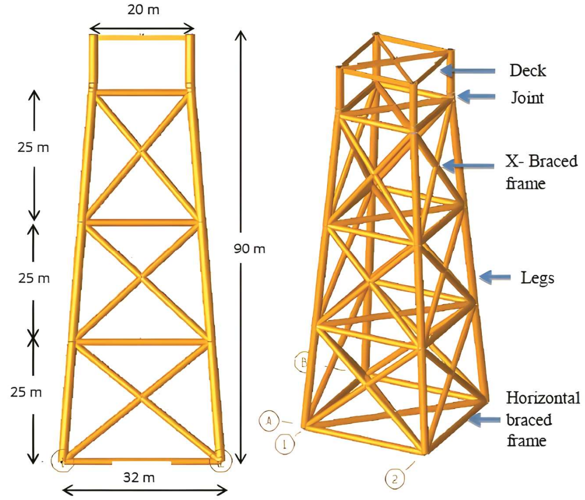


Fig. 4 — FE-3D model of the proposed platform

Hydrodynamic modelling of the platform

Structural design loads

Individual fundamental load situations considered in the study include the jacket's weight, buoyancy loads, wave and current loads, topside turbine loads, and wind loads. The entire 10 MW wind turbine top structure of 1000 tons was applied as concentrated loads on the four jacket piles. The SACS-SEASTATE software module uses member cross-sectional areas and densities to calculate the self-weight of each structural component of the jacket model. From the mudline to the MSL, the jacket legs and piles are regarded as inundated. The marine approach calculates the buoyancy forces in SACS for all design waves.

Hydrodynamic loadings

The study area of the platform selected eight locations and collected environmental data from the Global plotter, as shown in Figure 5. The data were averaged for eight different loading directions for the 1-year and 100-year return periods. For the operating case, the study considers the maximum environmental conditions for all eight directions.

The study applies both wave and current loads to the offshore jacket structure, with the current velocity varying by depth and affected by the presence of the platform. The current blockage factor is used to account for the decrease in current velocity caused by the structure, with typical values ranging from 0.70 to 0.90 for jacket structures. In this study, the current blockage factors of 0.80 and 0.85 are used for end-on and broadside wave loading, as well as diagonal wave loading[24].

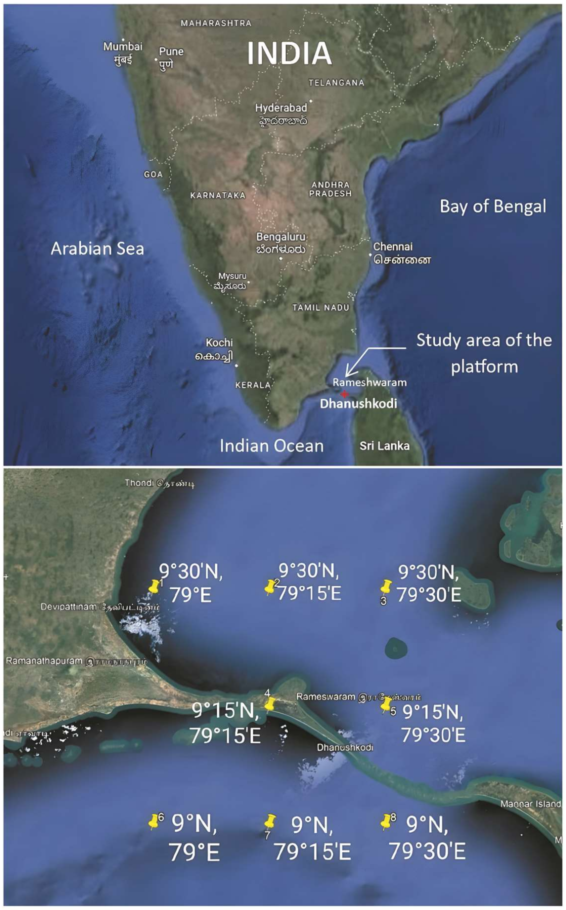


Fig. 5 — Data collection points of the proposed study area

The study considered wind, wave, and current acting simultaneously in the same direction, and their values in eight different directions are tabulated in Table 1 for operating and extreme load cases. The Doppler effect of the current on the wave was considered. The SEASTATE program was used to determine the apparent period and stream function order. It is assumed that the wave kinematics factor is 0.866. For end-on/broadside and diagonal orientations, the current obstruction factors are considered 0.80 and 0.85, respectively. The resulting particle velocities were determined using Morison's equation, which complies with API-RP-2A specifications. Dynamic amplification factor was used to account for the increase in forces on the structure caused by its dynamic response to environmental loading.

Marine growth and miscellaneous modelling

The thickness of marine growth is most significant in the splash zone and decreases with depth from the mean sea level. To accurately calculate the wave and current loads, the increased diameter of the member due to marine growth must be considered in the structural analysis. The study took into account a wild-type marine growth of 50 mm and 25 mm within the elevation range of -25 m to -50 m. The density of marine growth is considered to be 1300 kg/m^3 in the analysis[2]. The roughness of the marine growth affects the drag and inertia coefficients. For tubular members, the drag and inertia coefficients are 0.683 and 1.68 for smooth surfaces and 1.103 and 1.26 for rough surfaces. To simulate the actual in-place condition, shielded members and dummy members (wishbones) are applied in the model override.

The hydrodynamic and stiffness characteristics of jacket miscellaneous and ancillary structures in offshore structures are evaluated with the appropriate releases to accurately depict their behaviour under in-place loading circumstances. The drag and inertia coefficients are globally increased by 5 – 7 % to account for the environmental loading on anodes[25]. The presence of anodes affects hydrodynamic forces and coefficients of a tubular structural part, and there is minimal consensus on the exact numbers, with variations of up to 40 % observed when comparing different sources[26,27].

Results and Discussion

Response of structure under in place analysis

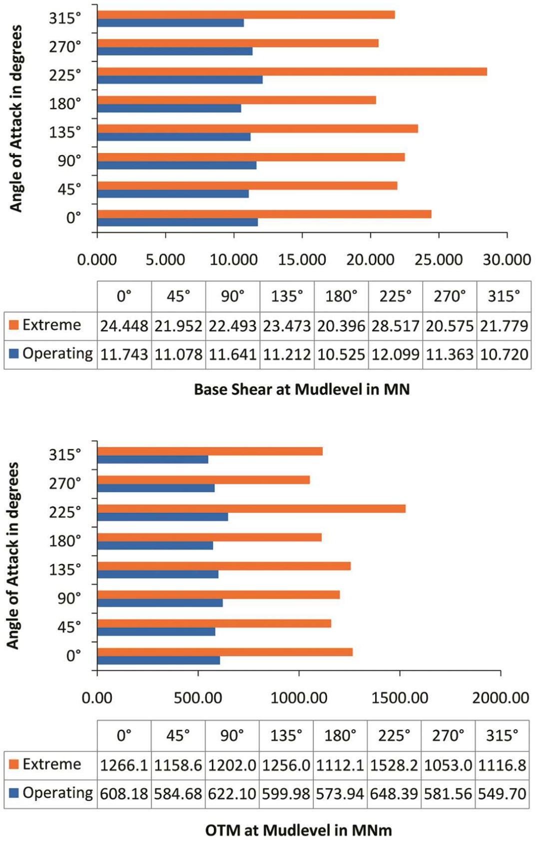
The direction of wave loading is one of the essential loading elements in platform design. Waves are incident on the platform from various directions to

Table 1 — Oceanographic data for different load cases

Direction	Wave height (m)	Wave period (sec)	Current speed (m/s) Elevation from mudline (m)					Wind speed (m/s)
			0 m	25 m	50 m	75 m	100 m	
Load case: Operating (1-year return period)								
All eight directions	12.74	12.3	0.5	0.85	1.01	1.21	1.38	30.97
Load case: Extreme (100-year return period)								
N – 0	16.6	14.6	0.561	1.067	1.309	1.54	1.804	46.78
N 45 W – 45	18.45	15.3	0.341	0.759	0.946	1.122	1.353	45.02
W – 90	18.78	15.6	0.231	0.671	0.825	0.99	1.199	44.36
S 45 W – 135	19.45	15.9	0.297	0.726	0.902	1.089	1.298	45.69
S – 180	14.59	13.2	0.407	0.891	1.122	1.331	1.595	47.89
S 45 E – 225	19.8	16.1	0.341	0.792	1.188	1.32	1.397	47.89
E – 270	17.6	15.5	0.275	0.715	0.913	1.045	1.276	47.89
N 45 E – 315	15.93	14	0.275	0.715	0.902	1.078	1.342	47.89

establish this study's essential loading direction condition. The in-place study is carried out for the OWT Jacket platform under various load combination situations split into two primary storm conditions: operating storm and extreme storm conditions, which are presented in Table S4. The procedure used to assess the design of an offshore platform complies with AISC-ASD and API-RP2A-WSD. The assumptions of the linear static analysis include linear structural behaviour, with neglect of material nonlinearity and large deformations. The ratio between the actual stress that affects the structural member and the allowable stress is termed Unity Checks (UC), which is used to evaluate the design and strength of structures. Using the maximum unity check ratios, the in-place analysis provides a preliminary evaluation and identification of the platform's significant elements and joints that may impact structural reliability. The platform’s components are analysed in both operational and severe storm circumstances. The relevant structural reaction of the structures is analysed using the operational and extreme storm environmental parameters. Both operating and extreme sea state conditions must meet the standard requirements for designing and reassessing fixed offshore structures[28].

The response results regarding base shear, overturning moment, and joint displacement are investigated. These results help assess the structure under in-place conditions due to the different combinations of the environmental storm conditions and gravity loads.



	0°	45°	90°	135°	180°	225°	270°	315°
🟧 Extreme	24.448	21.952	22.493	23.473	20.396	28.517	20.575	21.779
🟦 Operating	11.743	11.078	11.641	11.212	10.525	12.099	11.363	10.720

Base Shear at Mudlevel in MN

	0°	45°	90°	135°	180°	225°	270°	315°
🟧 Extreme	1266.1	1158.6	1202.0	1256.0	1112.1	1528.2	1053.0	1116.8
🟦 Operating	608.18	584.68	622.10	599.98	573.94	648.39	581.56	549.70

OTM at Mudlevel in MNm

Fig. 6 — Maximum BS & OTM for X-bracing system under storm conditions

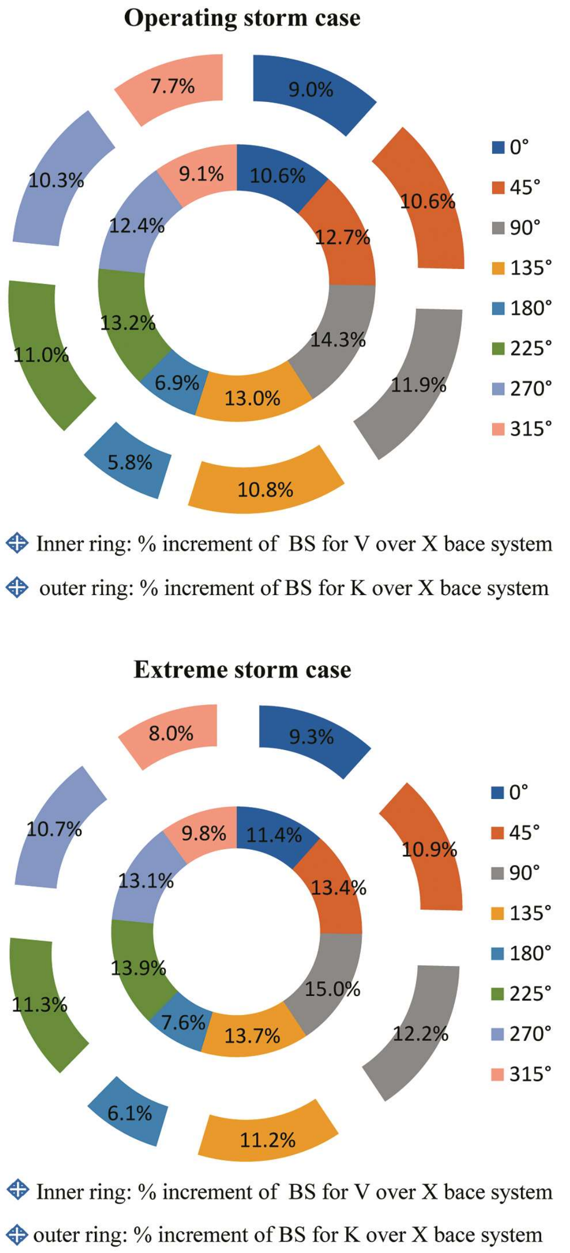
BS and OTM responses

The design requirements for offshore platforms include Base Shear (BS) and overturning moment (OTM) responses, which act on the platform as a cantilever supported on mudline elevation and extend it through the water to the intended height. The maximum BS and OTM at the mudline acting on the X-braced platform due to environmental loading cases under two storm conditions are presented in Figure 6. The OTM and BS at the mudline correspond to the entire environmental loading on the three jacket configuration structures analysed.

The results show that when the wave impact angle is 225°, the maximum BS and OTM occur, and the least value at 180°. Due to its highest wave height and most exposed jacket surface areas, the 225° wave direction draws the most wave and current loads of any wave direction. The average increment of BS and OTM value of extreme condition of that normal condition is about 81.06 to 135.69 %. This indicates that the offshore platform is susceptible to large variations in the loading conditions, and the design should be able to withstand these extreme conditions.

The average increment of base shear value for V brace over X brace is 11.51 % for operating and 12.25 % for extreme cases and that of OTM is 13.06 % for operating and 13.82 % for extreme cases. Similarly, for the K brace, the BS value increased by 9.62 % for operating and 9.97 % for extreme cases, and that of OTM is 12.14 % for operating and 12.57 % for extreme cases. This indicates that the choice of bracing topology has a significant impact on the response of the offshore platform. The V brace and K brace systems experience higher BS and OTM values compared to the X brace system. Table 2 compares maximum BS and OTM values on broadside diagonal directions. The diagonal side attracts 39.81 % more BS and 37.4 % more OTM than broadside loading (225°) in the X bracing system. Similarly, in the extreme case, diagonal side of V bracing and K bracing patterns attract about 48.1 % and 45.6 2 % more BS and OTM values, respectively. This indicates that the diagonal direction is the most critical direction for loading on the offshore platform.

Among the three systems analysed, the X-bracing configuration demonstrates the lowest BS and OTM values under the considered environmental loading conditions. These results are illustrated in Figure 7 for BS values and Figure 8 for OTM values. This is due to the fact that the X-bracing pattern is a more rigid



Inner ring: % increment of BS for V over X bace system

outer ring: % increment of BS for K over X bace system

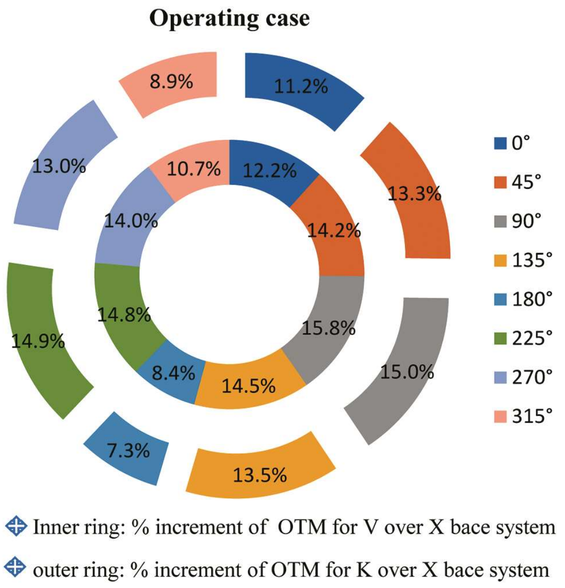
Inner ring: % increment of BS for V over X bace system

outer ring: % increment of BS for K over X bace system

Fig. 7 — Percentage increment of BS values of V and K braces over X bracing system

Table 2 — BS & OTM comparison on broad and diagonal directions of the platform

Load type	Maximum base shear (MN)					
	X brace		V brace		K brace	
	Broad side (180°)	Diagonal side (225°)	Broad side (180°)	Diagonal side (225°)	Broad side (180°)	Diagonal side (225°)
Operating case	10.525	12.099	11.251	13.692	11.169	13.593
Extreme case	20.396	28.517	21.947	32.488	21.726	32.161
	Maximum OTM (MNm)					
Operating case	573.94	648.38	621.90	744.57	615.88	744.81
Extreme case	1112.17	1528.22	1213.16	1766.64	1198.07	1762.29



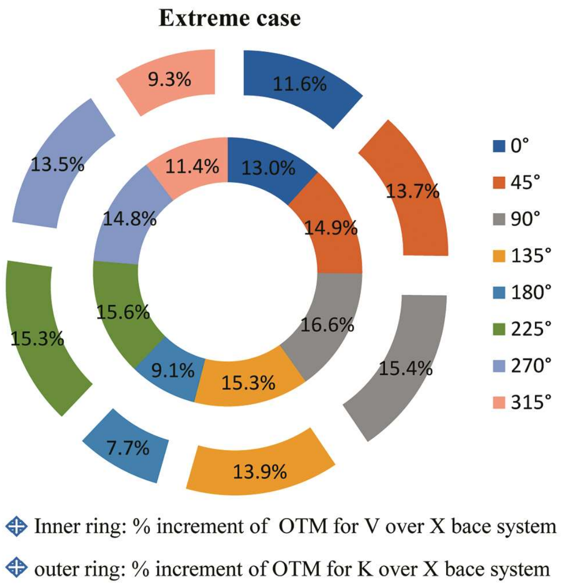


Fig. 8 — Percentage increment of OTM values of V and K braces over X bracing system

configuration, which is able to withstand lateral and longitudinal forces more efficiently compared to the V and K-bracing configurations. The V and K-bracing patterns, on the other hand, are more flexible and allow for more deformation, resulting in larger BS and OTM values.

Overall, the findings suggest that the X-bracing configuration is the most suitable choice for offshore wind turbine jacket substructures in the Indian Ocean scenario, as it provides the least BS and OTM values. However, the V and K-bracing configurations may be appropriate for certain conditions where flexibility is desired or where environmental conditions necessitate the use of a more flexible design.

The environmental load return periods and the bracing topology are the key variables that influence and govern the various storm situations. Directions 225° and 135° have the highest shear force and overturning moment, respectively, with maximum base shear and overturning moment observed on the diagonal side than the broadside. The least responses were observed in the northeast and southeast directions of the platform.

Horizontal displacement responses

The results of the study demonstrate that joint displacement values can have significant effects on the components connected to the platform. Exceeding permitted range values can lead to deformation and damage to the platform structure and all devices attached to it, posing a threat to the region as a whole. The drift values between the mudline and the topmost level of leg B-2 are summarised in Table 3.

As per API-RP2A-WSD, a drift allowance of 45 cm (height/200) is permitted for the platform[25]. This corresponds to a height of the level difference between the working point and mud level of 90 m, and the study found that the K and V bracing systems have 15.63 % and 7.28 % more drift values in the B-2 leg under extreme loading compared to the X bracing system. This highlights the effectiveness of the X bracing system, which provides good stiffness and stability in both horizontal and vertical directions, in reducing overall deformation of the substructure.

Figure 9 illustrates the absolute horizontal displacement responses for various environmental storm conditions at the highest and mudline levels of leg B-2 in the platform under study. The results show that, despite having different values, the platform legs exhibit similar tendencies for displacement reactions in all storm conditions. The maximum response values are reached at 225, 135, and 90 degrees of incidence with respect to the direction of environmental stresses.

The displacement responses reach maximum values in all environmental directions, except for 180°, 315°, and 0° environmental loading directions in all platform legs. The variation in storm conditions significantly affects the absolute horizontal displacements of the structure. The study found that the two storm conditions achieved for an incidence angle of 225° resulted in the absolute maximum

Table 3 — Jacket leg drifts values for extreme conditions

Leg	Levels	X brace		V brace		K brace	
		Max. absolute values (cm)	Relative values (drift) (cm)	Max. absolute values (cm)	Relative values (drift) (cm)	Max. absolute values (cm)	Relative values (drift) (cm)
B2	Mudline (-75 m)	11.91	23.87	14.01	28.06	12.78	25.6
	Working point (+15 m)	35.776		42.07		38.38	

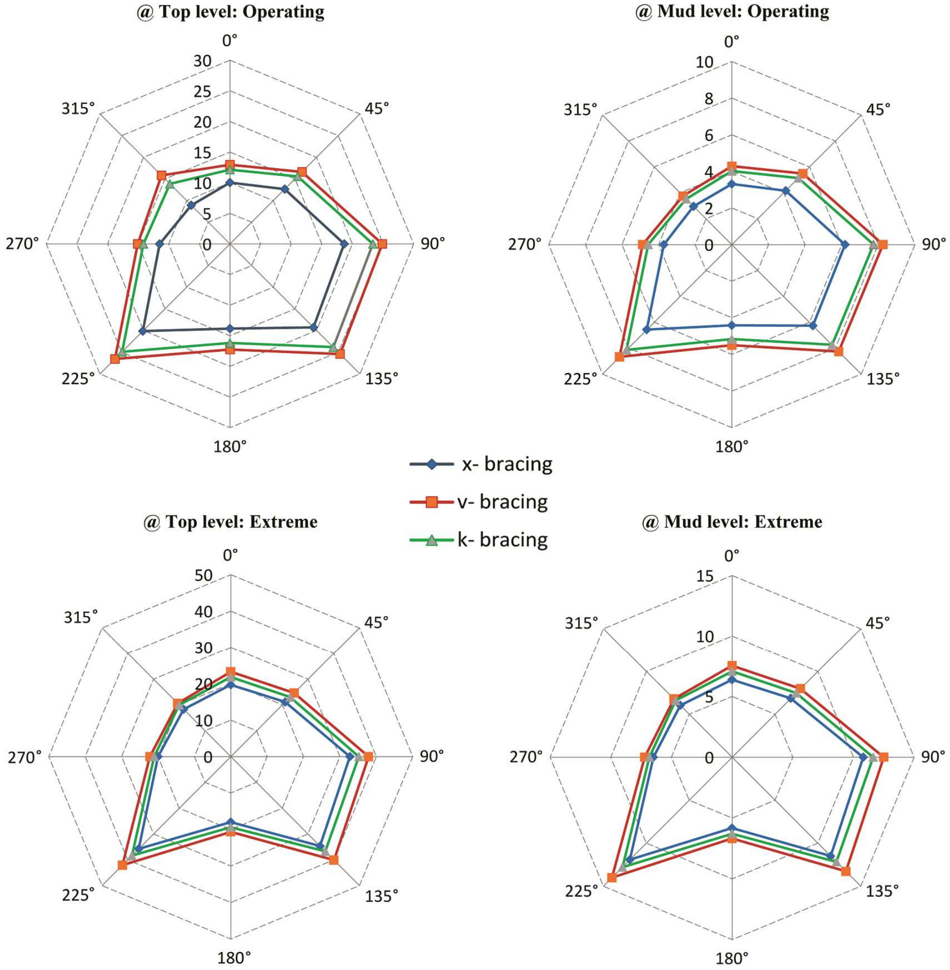
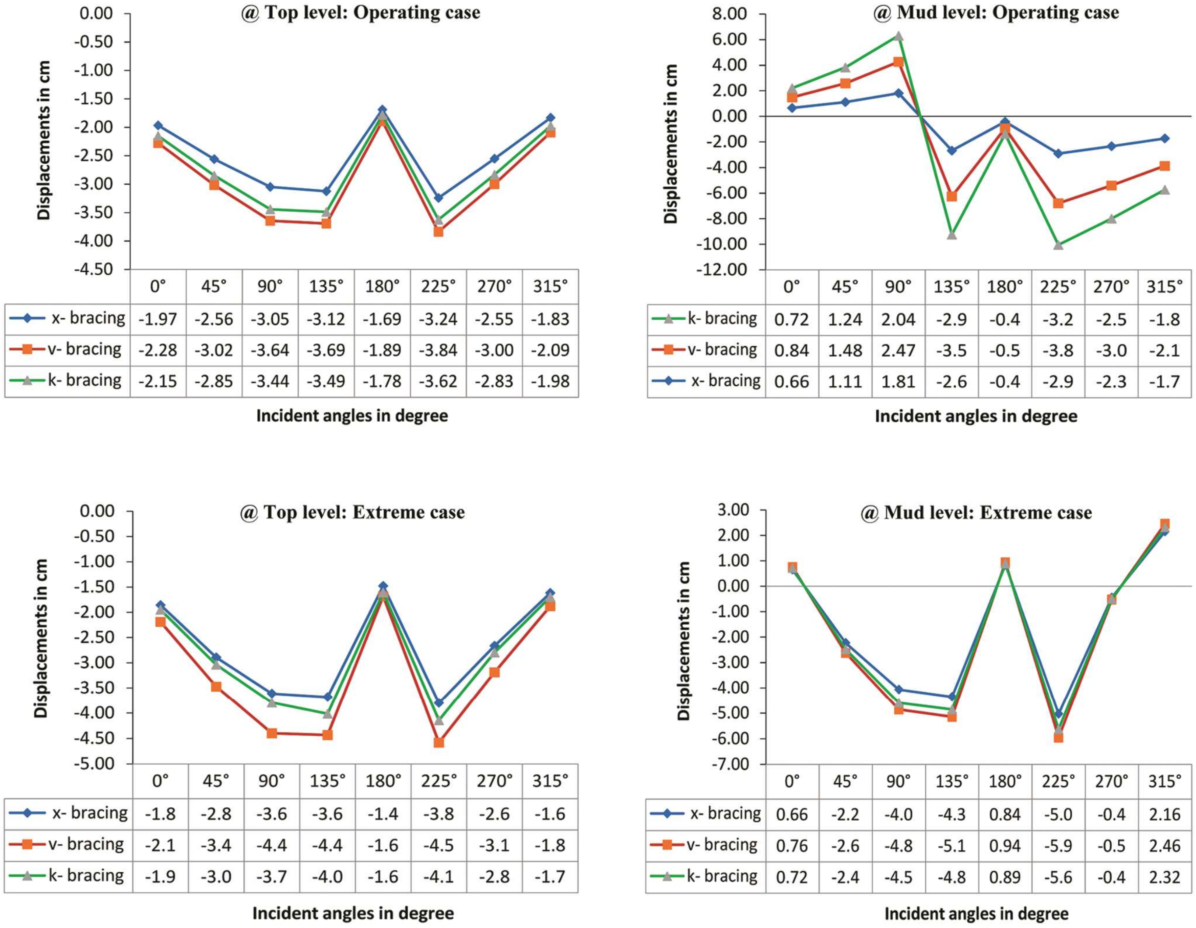


Fig. 9 — Horizontal displacement of leg B-2 at the top and mud level under storm cases

horizontal displacement responses at the mudline and uppermost platform levels in all platform legs. These findings emphasise the importance of considering joint displacement values and selecting an effective bracing system to reduce deformation and damage to the platform and its components, particularly during extreme loading events.

Vertical displacement responses

The Figure 10 indicates that the vertical displacement response for the top level of leg B-2 is highly sensitive to the incidence angle of the environmental loads. The maximum value is observed at an incidence angle of 225°, while the response declines suddenly at 180°. The higher values of vertical displacement at the top level for K and V bracing configurations as compared to the X brace configuration may be attributed to their lower stiffness and flexibility. The negative vertical displacement observed at the top level of all legs under every load scenario indicates the compression experienced by the structure due to the environmental



@ Top level: Operating case

	0°	45°	90°	135°	180°	225°	270°	315°
x- bracing	-1.97	-2.56	-3.05	-3.12	-1.69	-3.24	-2.55	-1.83
v- bracing	-2.28	-3.02	-3.64	-3.69	-1.89	-3.84	-3.00	-2.09
k- bracing	-2.15	-2.85	-3.44	-3.49	-1.78	-3.62	-2.83	-1.98

@ Mud level: Operating case

	0°	45°	90°	135°	180°	225°	270°	315°
k- bracing	0.72	1.24	2.04	-2.9	-0.4	-3.2	-2.5	-1.8
v- bracing	0.84	1.48	2.47	-3.5	-0.5	-3.8	-3.0	-2.1
x- bracing	0.66	1.11	1.81	-2.6	-0.4	-2.9	-2.3	-1.7

@ Top level: Extreme case

	0°	45°	90°	135°	180°	225°	270°	315°
x- bracing	-1.8	-2.8	-3.6	-3.6	-1.4	-3.8	-2.6	-1.6
v- bracing	-2.1	-3.4	-4.4	-4.4	-1.6	-4.5	-3.1	-1.8
k- bracing	-1.9	-3.0	-3.7	-4.0	-1.6	-4.1	-2.8	-1.7

@ Mud level: Extreme case

	0°	45°	90°	135°	180°	225°	270°	315°
x- bracing	0.66	-2.2	-4.0	-4.3	0.84	-5.0	-0.4	2.16
v- bracing	0.76	-2.6	-4.8	-5.1	0.94	-5.9	-0.5	2.46
k- bracing	0.72	-2.4	-4.5	-4.8	0.89	-5.6	-0.4	2.32

Fig. 10 — Vertical displacement of leg B-2 at the top and mud level under storm cases

loads. The difference in the patterns of vertical displacements at the mudline level for each leg may be attributed to the differences in the geometric and mechanical properties of the individual legs. For instance, Leg B-2 experiences a transition from positive to negative vertical displacements at mud level with the maximum positive value occurring at an environmental direction load of 90° and the maximum negative value occurring at 135° and 225°. The two lowest values appear perpendicular to the broad directions of the jacket (0° and 180°).

Similarly, Leg B-1 also exhibits a similar pattern of vertical displacement at the mudline level, with the maximum positive value occurring at an environmental direction load of 225° and changing to negative at an angle of 135°, eventually changing back to negative in the direction of the environmental load. The observed patterns of vertical displacement and the differences in the values among the legs highlight the significance of selecting an appropriate bracing configuration that provides sufficient stiffness and stability to the offshore platform structure. Moreover, the results emphasise the need to consider the environmental load incidence angle and its potential impact on the structural behaviour of the offshore platform.

Members and joints stress checks

Structural member checks are crucial for ensuring the safety of offshore jacket structures. These checks involve subjecting each member to various failure modes and utilising an equation for punching-shear interaction to yield an utilisation factor. The Unity Check (UC) factor is then used to indicate the member's use for each failure scenario. In this study, the requirements of ISO 19902 were validated against each member, and a tabulated summary revealed that none of the platform members had any failures. Maximum joint UC values were observed in the top levels, as presented in Table 4. The member unity check ratios also incorporated hydrostatic collapse checks.

Table 4 — Unity Check (UC) factors

Jacket configuration	Maximum joint unity check		Maximum leg member unity check		Maximum brace member unity check	
	Location	UC	Location	UC	Location	UC
X-brace	Horizontal brace – Horizontal brace at elevation (+)15.00	0.328	Jacket leg B1	0.59	Horizontal brace at elevation (-)75.00	0.78
V-brace	Horizontal brace – Horizontal brace at elevation (+)15.00	0.336	Jacket leg B1	0.62	Horizontal brace at elevation (-)75.00	0.85
K-brace	Vertical brace – leg A1 at elevation (+)0.00	0.344	Jacket leg A1	0.71	Horizontal brace at elevation (+)0.00	0.69

The JOINTCAN module was used to compare the punching shear for the joints against the criteria of ISO 19902, and it was determined to be sufficient. The joint was then categorised based on the load path for each loading condition (as an X, T, K, Y joint, or a mix of these). The majority of the members were found to achieve the maximum UC ratio for V bracing and for the top portion of the jacket in the K bracing system. The study revealed that the V-bracing arrangement is suitable for the sub-structure's lower portion, which primarily carries vertical loads. In contrast, the K-bracing system is more effective for the upper part of the sub-structure, which mainly carries horizontal loads. The X-bracing system is frequently employed in the sub-structure's middle section, which carries both horizontal and vertical loads.

In comparison to the other two bracing configurations, the X-bracing has the least overturning moment and joint displacement. This suggests that the X-bracing configuration is better suited for the given operating and extreme environmental conditions in the Indian Ocean. This result is consistent with past studies of Zhang *et al.*[29] and Tabeshpour *et al.*[30] on optimum design in offshore structures, which also demonstrated that the X-bracing layout is more successful at reducing the effects of environmental loads. The research indicates that choosing an appropriate bracing configuration is vital for maintaining the offshore jacket structures' safe and efficient operations.

Conclusion

This study assessed offshore wind turbine jacket substructures in the Indian Ocean, focusing on environmental conditions and bracing configurations. The key findings are: Upper-level members, particularly horizontal and side braces, experience notable displacement but remain within the safety limits; environmental load return periods and bracing topology are critical factors affecting responses; and X-bracing outperforms other configurations, aligning with prior offshore structure studies.

In summary, this research enhances understanding of offshore jacket behaviour in the Indian Ocean and informs bracing choices to maintain safety, coastal sustainability and efficiency in marine renewable energy projects. Future work could explore dynamic analysis on various hybrid brace topologies.

Supplementary Data

Supplementary data associated with this article is available in the electronic form at https://nopr.niscpr.res.in/jinfo/ijms/IJMS_52(12)559-570_SupplData.pdf

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Statement

This article does not contain any experimental studies with animals performed by any of the Authors.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Some data, models, or codes generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions.

Author Contributions

PA: Conceptualization, methodology, investigation and writing - original draft; and CM: Review and editing.

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