Structural Analyses of Fixed Offshore Wind Turbine Jacket-Type Support Structure

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Abstract. This work aims to study a steel jacket supporting a 10 MW offshore wind turbine (OWT) in a 40 m water depth on the Northeastern Brazilian Coast. In order to do so, various structural analyses were carried out. First, the system's natural frequencies were evaluated, and stresses caused by local environmental loads of wind, waves, and currents were assessed. GeniE was responsible for calculating the utilization ratio of the jacket's elements under extreme loads. The jacket foundations, composed of piles on sandy soil, were also analyzed in GeniE, highlighting the representation of soil-foundation interaction and the soil load capacity according to API-RP-2A-WSD. SIMA-RIFLEX performed fatigue analysis through the Rainflow Counting method associated with an S-N curve to assess fatigue damage, which is pivotal for the project. Different wind turbulence intensities were investigated as this factor proved to influence the structure's lifetime greatly. A final adjustment was made to the jacket cross-section, after the analyses, in order to guarantee its structural integrity.

Keywords: Offshore Wind turbine, Jacket-Type Support Structure, Ultimate limit state, Fatigue limit state.

1 Introduction

The development of technologies associated with wind energy production has become more present to ensure diversity and energy supply while reducing the environmental impacts accentuated by fossil fuels. Currently, global wind energy represents about 50% of renewable energy generation, surpassing solar and other renewable sources [1]. In Brazil, most wind turbines are installed in the Northeast. This particular region suffers the most with critically low levels of water reservoirs and is well known for its great wind potential, which contributed to the success of its onshore wind farms. Amarante *et al*. [2] claim that the onshore wind source potential could reach 143.5 GW at a 50 m height. However, Silva *et al*. [3] state that the Brazilian offshore potential revolves around 1.3 TW in shallow waters (up to 50 m water depth). Even with a high offshore wind potential, Brazil still does not have offshore wind farms in operation. Several studies and projects are underway.

According to Wind Europe [4], monopiles remain the preferred choice of developers, with over two-thirds of all installations in 2020 (80.5% of the 356 newly installed foundations). As Nogueira *et al*. [5] depicted, even though the monopile foundation is a massive success in the market, this support structure has drawbacks in certain situations, such as refusal in hard soils. Driving a large diameter foundation in calcareous soils could be challenging, requiring the usage of more sophisticated methods [6]. It is also unsure how much skin friction, and consequently bearing capacity, is available through the grouted driven piles alternative [7] since the external diameters of these structures have been increasing with time.

In such cases, a better solution would be adopting jackets, especially at deeper water levels (over 30 m). The employment of slender elements for both the support structure and piles makes this foundation exceptional when addressing hydrodynamic loads and soil-structure interaction. Despite its higher manufacturing costs [8], the jacket tends to be several times lighter than a monopile at this water level range. Unsurprisingly, Moray East (United Kingdom) is the bottom-fixed project with the deepest waters (45 m) of 2020 and utilizes jackets [4].

Therefore, this paper aims to design a jacket-type foundation to support a high power-rating wind turbine developed by the Technical University of Denmark (DTU) [9] under Brazilian environmental loads in a 40 m water depth. The following section presents the considerations made for modeling the turbine and the environmental loads. Then, an Ultimate Limit State (ULS) and geotechnical capacity checks will be made following API RP 2A - WSD [10]. Finally, another verification is carried out for the Fatigue Limit State (FLS). The wind's turbulence intensity will be varied at the end of this last topic to perform a sensitivity study on the foundation's lifespan. The conclusion discusses the most critical aspects of all these analyses.

2 Wind turbine model

2.1 Turbine and foundation properties

Figure 1 shows the offshore wind turbine (OWT) modeled in SIMA-RIFLEX [11] and a detailed scheme of the jacket's cross-sections, while Fig. 2 shows the modeled jacket nodes' coordinates. The DTU's 10 MW wind turbine has a 178.3 m rotor diameter and a 119 m hub height. DTU's exact rotor-nacelle assembly was modeled in RIFLEX, and its complete description is available at Bak et al. [9]. This work preserved the outer diameter and thickness at the tower top and thickness at its base. However, the tower's length was shortened by 13.5 meters compared to DTU's report [9] because of the jacket's elevation above seawater. The steel's mechanical properties composing the tower and the jacket are also found in the report [9]. Stolpe et al.'s work [12] helped to create the foundation's dimensions. Even though his model is in a 50 m water depth, the cross-sections' diameter-thickness ratios offered a starting point for the development of the structure (Tab. 1). The "stiff" cross-section represents a generic element with infinite stiffness when compared to the other elements. This model also has a transition piece to connect the jacket to the tower, employing the same cross-section as the tower's base.

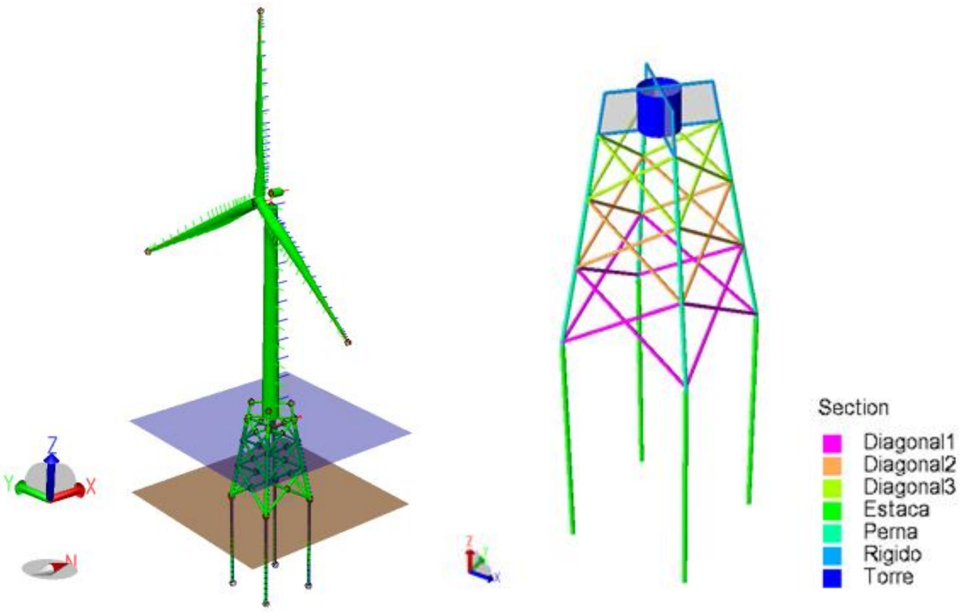

Figure 1. Left: Model in SIMA-RIFLEX. Right: Scheme detailing the jacket's cross-sections.

Table 1. Tower and Jacket's cross-section dimensions.

Section	Length [m]	Ext. diameter [m]	Thickness [mm]
Tower	102.13	5.5 (top) – 8.0 (base)	20 (top) – 38 (base)
Brace 1	30.7	0.762	19.05
Brace 2	25.9	0.660	19.05
Brace 3	22.0	0.559	19.05
Chord	13.8	0.965	28.58
Pile	50.0	1.016	30.96

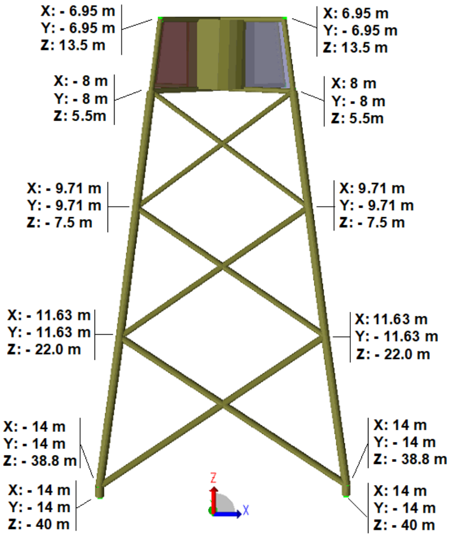

Figure 2. Modeled jacket nodes' coordinates.

2.2 Environmental loads representation

The Design Load Cases (DLCs) selected for this study are DLC 1.2 for FLS and DLC 1.3 for ULS checks, as defined in DNVGL-ST-0437 [13]. These two DLCs represent a significant portion of environments that a wind turbine will experience over its lifespan without simulating all of the possibilities presented in the standard. The Brazilian Navy [14] provided the necessary data (sea and wind conditions) for the composition of six fatigue load cases according to DLC 1.2 (Tab. 2). These are among the cases with the highest probability of occurrence along the Northeast Coast (wind from east direction). U_{10} represents the mean wind speed at a 10 m height. The significant wave height H_s and wave's peak period T_p were obtained as a function of the mean wind. The ULS check (DLC 1.3) adopted parameters from Case 3, as it caused the greatest thrust force in internal tests, and a sea current defined by a power-law profile with a 1/7 exponent and surface velocity of 0.114 m/s [14]. This current is not present in FLS analyses as defined by the standard [13]. Another difference can be seen in the wind condition: DLC 1.3 employs the Extreme Turbulence Model (ETM) instead of the Normal Turbulence Model (NTM) adopted by DLC 1.2. For analyses run in SIMA-RIFLEX (FLS), an irregular sea was created through the superposition of regular waves utilizing the Jonswap wave spectrum (peakedness parameter $\gamma = 3.3$). At the same time, TurbSim software [15] was used to export a realistic wind to RIFLEX.

A power-law profile with a 0.05 exponent represents the mean wind speed portion. At the same time, a 5.8% turbulence intensity (TI) is assumed in all FLS Cases to represent the wind's dynamic parcel with the Kaimal's spectrum. This intensity was varied for the fatigue behavior study in the last topic. The other two values adopted were 7.5% and 10%. A 39x39 grid (237 m x 237 m) is defined in TurbSim to envelop the rotor and the tower completely. The first 100 s of the complete analysis (1000 s) are discarded as they show a transient response. Morison's formulation calculated the hydrodynamic forces in all analyses (drag and inertia coefficients equal 0.65 and 1.60, respectively). The tower's aerodynamic drag coefficient is 0.6.

Table 2. FLS loading cases and their occurrences.

Case	U_{10} (m/s)	H_S (m)	T_P (s)	Occurrence (%)
1	7.5	1.375	5.5	5.07
2	8.5	1.375	5.5	16.89
3	9.5	1.625	5.5	29.71
4	9.5	1.875	6.5	16.11
5	10.5	1.875	6.5	20.24
6	11.5	1.875	6.5	11.98

GeniE [16] was responsible for the ULS checks as it can quickly provide the utilization ratios for the various elements of the jacket. In this software, only the support structure is modeled (jacket + piles). The internal loads obtained from RIFLEX at the tower-transition piece interface are imported into the model while GeniE applies the sea wave and current conditions.

2.3 Soil-foundation interaction and resonance check

API RP 2A - WSD [10] provides the equations necessary to compose springs representing the soil-foundation interaction. P-y curves represent the soil's horizontal stiffness while t-z and q-z curves constitute its vertical (soil-pile shear transfer and mobilized end bearing resistance, respectively). This work assumed a uniform layer of medium dense sand (β friction factor equal to 0.37 [17]). This sand has an angle of internal friction of 35º and 8.5 kN/m³ of submerged specific weight.

A designer of OWTs must be aware of the environmental loads and rotor operation frequencies. The soft-stiff range is the designer's desired region to steer clear of these frequencies and also avoid a costly project [5]. The DTU's 10 MW wind turbine soft-stiff region is 0.176 – 0.27 Hz. This area is defined by the rotor operational frequencies (6 to 9.6 rpm) and a ten percent margin [9]. The first natural frequencies of this OWT were 0.22 Hz with the present considerations. Therefore, the design is in the soft-stiff region, and resonant effects have been avoided successfully.

3 Ultimate Limit State and Geotechnical Capacity

Table 3 presents the loads obtained by SIMA-RIFLEX for DLC 1.3 at the tower-transition piece interface. As previously stated, these data were entered into GeniE for the ULS check and geotechnical verification. The software output (Fig. 3) showed that the highest utilization ratio was 0.33 and, therefore, all jacket's elements are avoiding any yielding risks. This also implies that the structure might need optimization.

Table 3. Internal loads at tower-transition piece interface.

Loadings	Value
Fx (kN)	2317.8
Fy (kN)	146.4
Fz (kN)	-700.3
Mx (kN.m)	-763.8
My (kN.m)	12339
Mz (kN.m)	-1.8

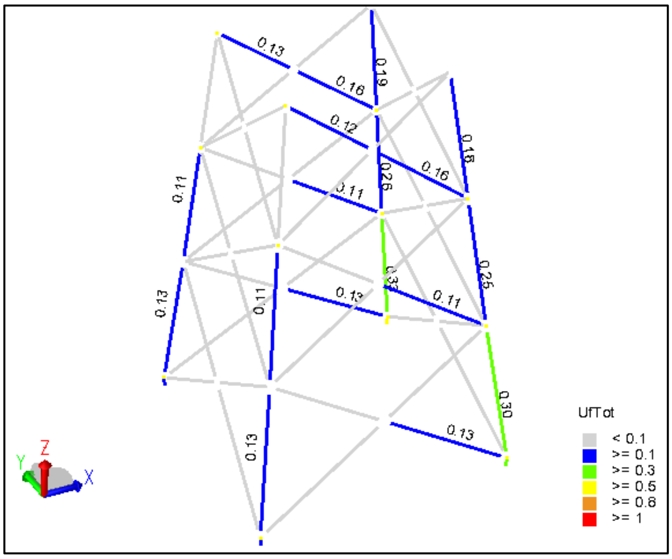

Figure 3. GeniE: Jacket's utilization ratios.

Pile capacity for axial bearing loads is also an essential aspect of the foundation design. In this regard, the ultimate bearing capacity of piles in the axial direction is given by eq. (1) [10]:

$$Q_d = \pi \cdot D \int_0^L f dl + q \cdot A_p, \tag{1}$$

where D is the pile's diameter (m); L is the pile's length (m); f is the unit skin friction capacity (81 kPa as recommended [10]); q is the unit end bearing capacity (5 MPa as recommended [10]), and A_p is the gross end area of the pile (m^2). These assumptions, the soil's characteristics, and Tab. 1 dimensions led to Q_d equal to 16981 kN (11320 kN considering a safety factor of 1.5 [10]).

Table 3 loads, sea waves, and current produced an extreme axial response at the most requested pile's head of 9123 kN, lower than the previously stated design capacity value. Therefore, the foundation is safe.

4 Fatigue Limit State

A wind turbine is subjected to a wide variety of cyclical loads during its lifespan. Consequently, fatigue analysis becomes a fundamental design criterion. Palmgren-Miner linear damage rule assesses fatigue damage:

$$D_f = \sum_{i=1}^{B} \left(\frac{n_i}{N_i}\right), \tag{2}$$

where n_i is the number of cycles sustained by the structure for each stress block i, N_i is the number of cycles until failure for a particular stress range, B is the total number of stress blocks, and D_f is the damage. This approach considers that failure will occur when $D_f = 1$. The structure's lifespan is given by $1/D_f$, where D_f is the damage for a year equivalent in loading cycles. The number of stress blocks (B), stress range on the elements, and n_i are determined by the Rainflow Counting method, while N_i is assessed by an S-N curve for steel (T curve in seawater with cathodic protection [18]).

Several connection points of the jacket were analyzed. They represent stress concentration points, making them more susceptible to the appearance of cracks (Fig. 4). Thus, the damage to the jacket connections was obtained considering the dynamic analysis results on the connected elements and the stress concentration factors (SCFs). These were calculated analytically considering the type of joint and methodology presented in API RP 2A -WSD [10]. SIMA-RIFLEX [11] generated the stress times series for each environmental condition derived within DLC 1.2 (Tab. 2) for these points of interest.

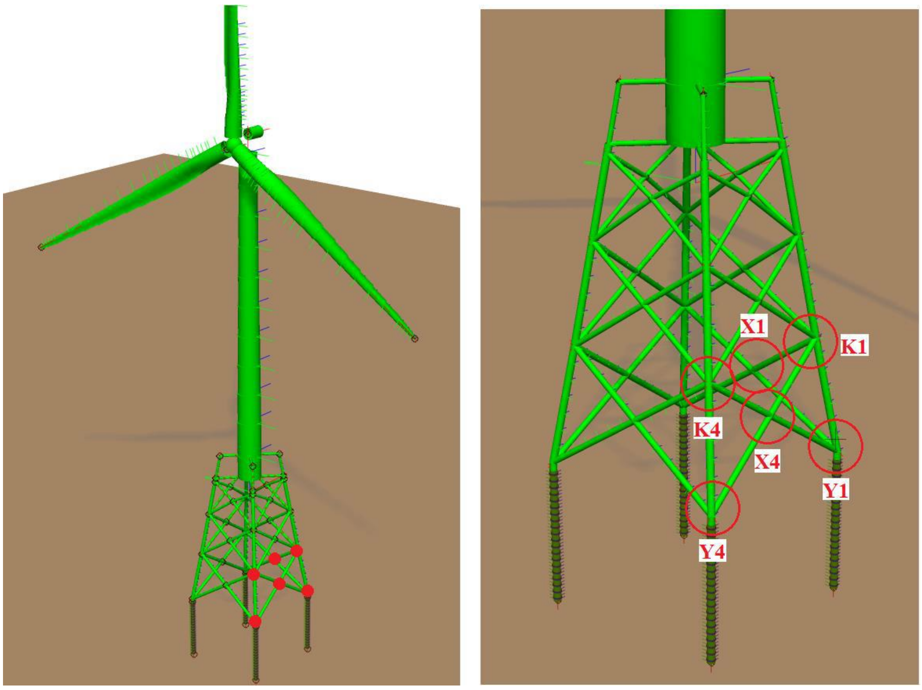

Figure 4. Representation of the analyzed tubular joints.

Table 4 presents the fatigue lifetime of these joints considering a safety factor of 3. For a 25-years service lifetime, only X1 and X4 joints are considered adequate at all analyzed levels of wind turbulence. According to the table, Y1 and Y4 joints suffered the most damage and are closely followed by K1 and K4 joints. It is also noted that the jacket's lifespan decreased above 200% for a 30% increase in turbulence intensity.

Observing that the crucial regions of the support structure were related to jacket chords' joints (Y and K), a second analysis was carried out. It considered a 40% thickness increase in the jacket's chords (40 mm) to reduce stress and assess the influence on fatigue damage. The jacket chords' diameter was also increased (1.016 m) to maintain the diameter-thickness ratio found in the literature. This change led to a 0.231 Hz first natural frequencies and a 0.25 utilization ratio. As before, although ULS checks suggest that the jacket structure needs optimization, the whole process made clear that the FLS analysis must base the final geometry.

Table 4. Joints' lifetime according to turbulence intensity.

Joints' lifetime [year]						
TI	Joint Y1	Joint Y4	Joint X1	Joint X4	Joint K1	Joint K4
5.80%	1.6	1.8	3212.6	4080.6	4.6	31.8
7.50%	0.6	0.7	815.1	1048.8	1.6	8.0
10.0%	0.3	0.3	213.2	254.5	0.6	2.6

Table 5 presents the fatigue lifetime of these joints considering the increase. It is possible to observe that this change increased service lifetime from 1.6 years to 37 years for the most critical point (Joint Y1). Since 5.8% turbulence intensity for the wind is the expected value for the Northeast region [19], the results can be considered adequate. However, the results for higher turbulences show how sensitive this type of foundation is to the wind. If these were expected for this project, the support structure would have to be resized.

Table 5. Joints' lifetime according to turbulence intensity after the increase in the jacket's chords.

Joints' lifetime [year]						
TI	Joint Y1	Joint Y4	Joint X1	Joint X4	Joint K1	Joint K4
5.80%	37.0	43.0	3204.4	4071.1	150.1	177.7
7.50%	9.3	10.6	552.8	1047.1	36.7	210.0
10.0%	3.7	4.2	457.6	337.0	12.4	75.2

5 Conclusions

This work designed a steel jacket to support a 10 MW wind turbine under environmental loads from the Brazilian Northeast Coast. In parallel, one of the objectives of this work was to evaluate the influence of the wind's turbulence intensity on the fatigue life of the foundation. This structure is expected to remain in operation for around 25 years. Thus, for the first geometry (based on Stolpe *et al*. [12]), the model met the ULS and geotechnical criteria but failed the FLS considering a safety factor 3. Although ULS checks suggest that the jacket structure needs optimization (0.33 utilization ratio), the whole designing process made clear that the FLS analysis must base the final geometry. Results showed that the jacket's lifespan decreased close to 200% for an increase of almost 30% in the turbulence intensity. Y and K joints were the most critical points of the support structure.

A second model was proposed considering an increase in the jacket's chords thickness and diameter. The new structure increased only 5% in natural frequency, remaining at the soft-stiff region. Observing that for the lowest turbulence intensity (5.8%, the most probable one [19]), the assessed lifetime exceeded the expected one, the results can be considered adequate. The accumulated damages obtained for the other two TIs (7.5% and 10%) resulted in a lower than desirable service life. As these TIs are very rare [19], this would not be a limiting factor for the project.

For future work, it is essential to consider different directions of incidence of environmental loads since the hypothesis of all DLC 1.2 loads originating from the east direction is conservative and leads to greater fatigue damage. Besides that, more attention needs to be destined to the calculation of SCFs. Two important guidelines raised by the review of works in the literature [20][21] suggest that approximation of diameters (and divergence of thickness) of chords and braces would lead to lower SCFs and, therefore, longer service lives.

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