An Investigation of Different Offshore Wind Turbine Jacket Support Foundation Models Designed for Central Mediterranean Deep Waters

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ABSTRACT
The trend for improving the cost effectiveness of offshore wind turbines is to maximise wind turbine size while minimising support structure costs. Minimising the support structure costs in deeper waters is undoubtedly more challenging. Studies have shown that the type of foundation model used at the base of the support structure has a significant influence on the overall design result. Two foundation models are studied independently: the pinned foundation and the rigid foundation. The effect of the foundation type on the modeled overall support structure characteristics, are investigated. The objective of this study is to produce an optimised jacket design for a 70 metre water depth in the central Mediterranean region. The study shows that different foundation types influence the internal loads of the individual jacket members and consequently affect the structure's natural frequencies. The final result shows that the jacket structure with a rigid foundation design was 5.4 tonnes lighter than its pinned counterpart.

1. INTRODUCTION
Current offshore wind energy is significantly more expensive than onshore wind energy [1]. A main contributing factor to the expense of offshore wind is the requirement of relatively expensive support structures and their foundations. This requirement is a necessity due to the harsher weather conditions at sea and the larger and more expensive infrastructure required for installation and maintenance.

Regardless of these challenges, offshore wind technology as a whole is advancing at an accelerating rate due to the large energy potential available in this environment. Research efforts and continuous advancements in offshore technology are increasingly being made.

The main technology driver today is to increase the cost effectiveness of offshore wind energy by increasing turbine size and reducing substructure costs. This will enable project developers to exploit offshore areas in deeper waters located more distant from the coast where consenting is less difficult.

Malta, an island in the central Mediterranean region, is almost totally dependent on imported fossil fuels. A secure and more sustainable energy system will require diversification of the energy supply, with a greater share met by alternative technologies. Under the new energy package for Europe, Malta is bound to supply 10 % of its final energy consumption from renewable energy sources by 2020 and at the same time reduce the green house gas emissions by 20 % of the 1990 levels [1]. Wind energy may contribute a significant proportion to the country's renewable energy mix.

Given Malta's geographical land restriction (a total of 300 km^2 including built up areas), there is increased interest to develop wind farms at sea. Given the availability of large territorial waters, Malta's theoretical offshore wind potential is enormous. To date most offshore support structures for wind turbines have been commissioned for shallower waters in the North Sea, the deepest being the Beatrice project [2] at an installation water depth of 45 m. The more benign conditions of the Mediterranean Sea require a tailor made design and analysis for the Maltese region. A considerable large area with transitional depth range (50-70 m) is available in the South East Offshore Zone (SEOZ) of the Maltese Islands. This area includes Hurd Bank. No doubt that the depth limit of 70m requires a challenging design solution in terms of costs and installation requirements. On the other hand, when compared to those in the North Sea, the "milder" climatic include factors around Malta are expected to reduce the load bearing demand on the support structure and facilitate the installation and maintenance work.

This study proposes an optimisation design process of a jacket structure in which 2 different foundation types at the base of the structure were modeled independently. The ultimate objective of this work was to investigate an optimal modeling design process to improve the feasibility of jacket structures in central Mediterranean deep waters. It must be kept in mind that in reality the pre-piling method intended for this design will establish neither a 100% rigid nor a 100% pinned foundation. Therefore, by modelling the two foundation types the upper and lower limits of the effect the foundation has on the stress levels and on the total weight of the structure will be established. The extreme event analysis procedure was therefore repeated for both foundation types.

2. BACKGROUND ON OFFSHORE WIND TURBINE SUPPORT STRUCTURE DESIGN

An offshore wind turbine structure is subject to a large range of complex and non-linear environmental conditions. Design of an offshore support structure is carried out in compliance with international offshore standards of design. Offshore standards provide principles, technical requirements and guidance for design, construction and in-service inspection of offshore wind turbine structures. The support structure design within this study is in compliance with the DNV-OS-J101 [3] and the IEC 61400-1 [4] standards.

The design process of an offshore support structure starts with the assessment of all potential sites and support structure concepts. This first step includes establishing the conceptual design including the foundation (piled, gravity based or grouted), the sub structure (monopile, tripod, jacket or floating), the materials required and the optimal manufacturing and installation processes. In the initial stages of the design process, information about the turbine to be supported as well as site data (metocean data, geophysical and geotechnical data) is collected to be able to define the minimum overall height and the base width of the substructure. Following this, the design load cases acting on the support structure are established. A natural frequency analysis is undertaken to identify the critical frequencies of the entire system that will lead to resonance during the operation of the rotor. This analysis is followed by an ultimate load analysis and a fatigue analysis.

3. DESIGN BASIS

For this project the substructure design was carried out on the basis of the available data for the SEOZ site. A report [5] which described the evaluation of the bathymetric, wind, wave and geological conditions of the South East Offshore Zone (SEOZ) was compiled for this study. Figure

1 shows the Maltese islands including the indicated SEOZ site. The SEOZ is located between 5 and 14 km from the nearest shoreline and covers an area of approximately 55 km^2. This site has the potential to generate 770 Gigawatt hours per annum, equivalent to 16% of the predicated energy consumption for Malta in 2020.

Figure 1: The South East Offshore Zone (SEOZ) outlined for the area having a maximum sea depth of 70m (Map source: Google Earth©)

On the basis of this site evaluation report [5], the parameters given in Table 1 were established. Since the maximum sea depth at the SEOZ site is 70m, it was decided to design the substructure for this water depth. [6]. The various design parameters were established in accordance with the DNV and IEC standards [3, 4].

Table 1: Site condition design parameters [5]

Turbine	NREL	5 MW
Wind	Annual average wind speed	7.5 m/s
	IEC wind turbine class	III
	Turbulence intensity class	B
	50 year extreme wind speed	37.5 m/s
Wave	Significant wave height	6.8 m
Bathymetry	Water depth	70 m
Water Levels	Maximum still water level	+1 m
	Minimum still water level	-1 m
Sea Bed	Geology	Hard limestone (Globegerina/Upper Coralline Limestone)[12]

The design was based on the NREL 5MW reference wind turbine model. Table 2 displays the main parameters of the NREL turbine as specified in [6]

Table 2: Turbine Parameters [6]

Turbine parameter	Value	Unit
Rated Power	5.0	MW
Rotor Diameter	126	m
Mass of rotor and nacelle	350	tonne
Cut- in wind speed	3	m/s
Rated Wind speed	11.4	m/s
Cut- out wind speed	25	m/s
Nominal rotor speed	12.1	rpm
Lower bound rotor speed	6.9	rpm
Upper bound rotor speed	12.1	rpm

4. DESIGN METHODOLOGY

The design methodology adopted in this study consisted of two design phases; the preliminary design phase and the detailed design phase. Figure 2 illustrates a simple flow chart of the two-phase approach and the processes involved in each phase.

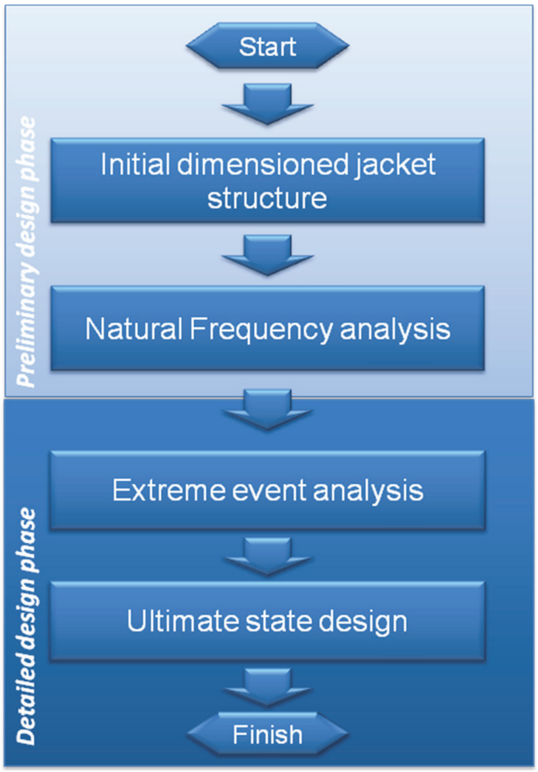

Figure 2 : Two phase design methodology flowchart

In the preliminary design phase, the initial configuration of the overall jacket structure was defined following the guidelines of the DNV standard [3]. This involved the determination of the transition piece elevation, the top and base widths, as well as the number of x-bracings. The base width of the jacket structure was determined by performing a natural frequency analysis exercise, which is the second process in the preliminary design phase.

The detailed design phase involved the extreme event analysis and the ultimate state design. In the extreme event analysis load cases were simulated on the modeled structure to evaluate the extreme loading on the structure. The load cases were set up in accordance with the DNV standard [3]. The simulation of the individual load cases was performed using GH Bladed [7] which is an industry standard tool for the integrated design of wind turbines. The tool models the combined static and dynamic loads acting on the entire wind energy converter resulting from the wind, waves, gravity and inertia.

Ultimate state design, being the final design process, involved the optimisation of the jacket structure. Optimisation of each member was carried out using the NORSOK [8] standard. This design process was repeated for the two different foundation types, i.e. the rigid and pinned foundation types. The results are shown in section 5 of this paper. Sections 4.1 - 4.4 in turn describe in further detail each design process illustrated in figure 2.

4.1 Initial dimensions for the jacket structure

In this first design process the main concept was to utilize a four legged offshore jacket structure for a 70 m water depth up to 15.1 m above mean sea level (MSL). Therefore the jacket structure required to be 85.1m in height. This required the definition of the number of X-bracings and diameter-to-thickness ratios (D/t) for every member in the structure. D and t represent the diameter and thickness of a tubular structural member respectively.

The NORSOK standard [8] sets some geometric restrictions. Figure 3 illustrates a typical Jacket K-joint detail with associated components labeled in red. According to the NORSOK standard [8] the angles between the brace and the leg must exceed 30°, the gap for a simple K-joint should be larger than 50mm and that the D/t ratio should be less than 120 for any tubular member used in the design.

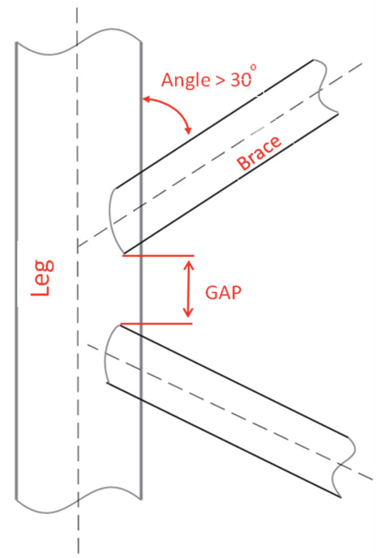

Figure 3: K-joint detail adapted from NORSOK Standard [8]

Preliminary drawings were prepared to determine the number of X-bracing levels that the jacket tower would have. The objective was to satisfy the NORSOK [8] standard while using the minimum number of X-bracings. Based on the Upwind reference Model[9], four levels of X-bracing were chosen. Similarly the Upwind reference model[9] is the result of a tailor made design process developed for a 50 m water depth subject to the Dutch North Sea climate. The angle between the leg and bracing was then incrementally increased from 30° upwards in steps of 1°, until the structure satisfied the design requirements set by the same NORSOK standard [8].The outcome was a four legged jacket structure with four levels of X-bracing that have a 35° angle between the leg and the bracing.

With the initial dimensions defined, a parametric geometric model was set up in the finite element software ANSYS [10] and the base width varied in order to obtain the x,y,z co-ordinates of the key points that define the jacket structure geometry for different sized models. The parametric study gave an indication of the position of the members and joints that were ultimately modeled in GH Bladed [7]. Figure 4 displays three complete jacket structure models with different base widths of 20m, 16m and 12m. The geometry configurations of these three jacket structures satisfy the geometric constraints of the NORSOK standard [8].

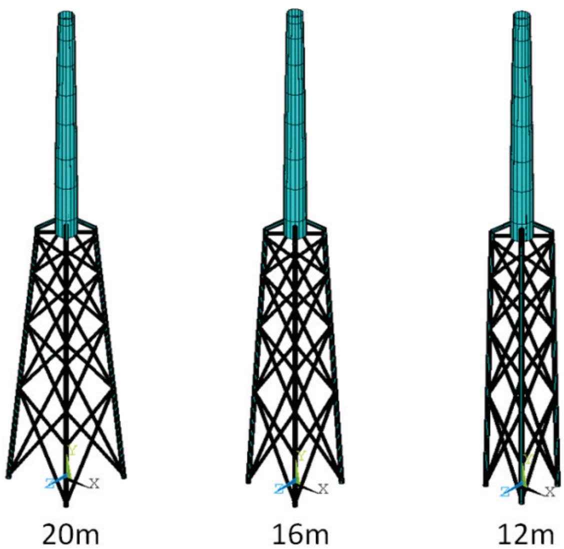

Figure 4: Three complete structure models with different base widths generated in ANSYS [10]

4.2 Natural frequency Analysis

This design process consisted of a parametric study in which the 1st natural frequency of multiple models was found as a function of varying jacket base widths. This process was carried out through the use of GH Bladed [7]. The base width of a jacket structure has a significant effect on the total mass and stiffness of the structure that ultimately influences the natural frequency of the structure. The aim of this process was to optimise weight while ensuring that the natural frequency does not coincide with that of the turbine rotor. The fundamental natural frequencies necessary to be avoided in wind turbine support structure design, are the rotor rotational frequency (1P) and the blade passing frequency which is equal to 3P in the case of a three bladed rotor. The frequency ranges of the reference NREL 5 MW wind turbine [6] were evaluated to be equal to 0.115 - 0.202 Hz and 0.345 - 0.606 Hz respectively. The design aim was to achieve a soft-stiff design. Therefore, the range considered was between the upper limit of the 1P frequency range and the lower limit of the

3P frequency range. A 10% safety margin was added to these limits to account for any discrepancy in calculations and any future optimisation of the member dimensions that will affect the overall 1st natural frequency of the structure. Therefore, a workable envelope of frequency range was determined to be between 0.222 and 0.31 Hz. Figure 5 indicates the workable frequency envelope in blue and the 10% safety margins in orange. The 1P and 3P frequency bands that must be avoided are indicated in pink in Figure 5. As a result, the target frequency band for the support structure was defined to be between 0.286 and 0.294 Hz, indicated by the red line in Figure 5. This was chosen closer to the upper limit of the workability envelope for the reason that when the 1st natural frequency of the structure lies closer to the 1P frequency range, higher fatigue damage is likely to be induced. This has been noted by Wybres De Vires in the final report of the UpWind work package 4.2 [11].

The base width of the jacket design was incrementally increased in steps of 1m from 12m to 20m. All other dimensions were kept constant. A modal analysis was carried out in GH Bladed [7] on each complete support structure model including the rotor nacelle assembly, the wind turbine tower and the jacket substructure. In this way the 1st natural frequencies of the analysed models were extracted. Table 3 shows the model support structures that satisfy the workable envelope shown in Figure 5. In addition to this, Table 3 also shows the predicted mass of each model based on assumed member diameters of 0.8m and 1.2m, as well as wall thicknesses of 20mm and 50mm for the X-braces and main legs respectively [9]. The predicted model masses were computed through the use of GH Bladed [7].

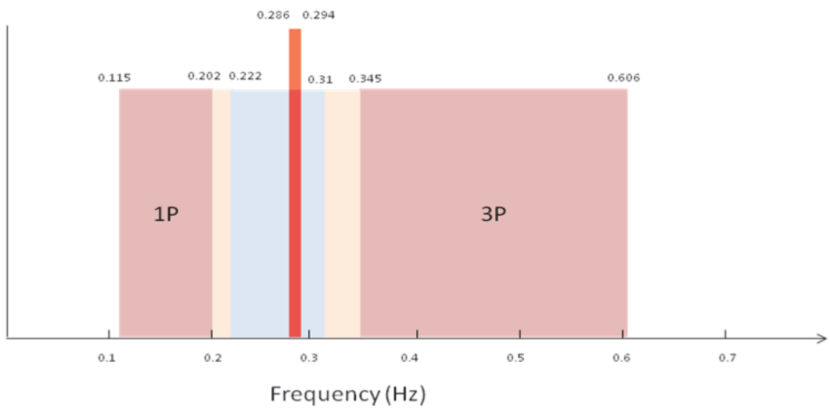

Figure 5: Workable natural frequency envelope

Table 3: Model base widths with corresponding 1st support structure natural frequency and mass

Base width [m]	1st natural frequency [Hz]	Jacket mass [Kg]
12	0.264	512710
13	0.271	514518
14	0.277	516326
15	0.283	518134
16	0.288	520245
17	0.292	522253
18	0.296	524534
19	0.3	526642
20	0.304	529001

Figure 6 shows how the 1st natural frequency and mass of the jacket structure varies with the increasing base width for the selected models. The quasi-linear relationship displayed by the curves in Figure 6 was found to be similar to those presented in the Upwind report [11]. Therefore, on the basis of selecting the optimal design weight while satisfying the target frequency band, a 16 m base width was selected for the jacket structure design.

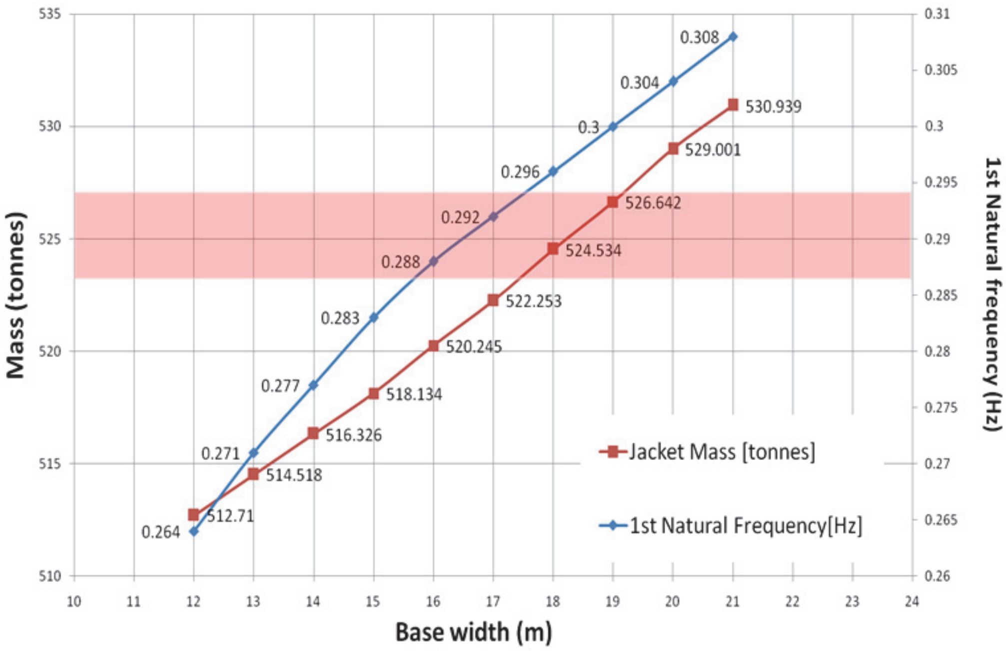

Figure 6: Total Mass and 1st natural frequency plotted against base width with a rigid foundation

4.3 Extreme event analysis

The aim of the extreme event analysis was to evaluate the extreme loading on the support structure through simulation of a number of design driving load cases. This process was carried out separately for jacket structures with rigid and pinned foundations. A design load case group was set up consisting of three main design driving load cases. These design load cases (DLC's) are known to produce the worst loading scenario (extreme loading) on the support structure [11]. The set up of the environmental and wind turbine parameters of the DLC's were done according to the DNV standard [3]. Simulations included both aerodynamic and hydrodynamic analysis. The following load cases [11] were included for the analyses:

a. DLC 1.3 - power production with extreme turbulence model (ETM)
b. DLC 1.4 - power production with extreme coherent gust with change of direction (ECD)
c. DLC 6.2a - parked rotor with loss of electrical network connection with extreme wind model (EWM)

Simulations in GH Bladed [7] of the above load cases were carried out on the jacket support structure model taking the base width equal to 16m as determined during the natural frequency analysis process. The maximum and minimum values for the six components of the load vectors (Fx, Fy, Fz, Mx, My and Mz) acting at the rotor hub centre (90m MSL) were derived (see Figure 7).

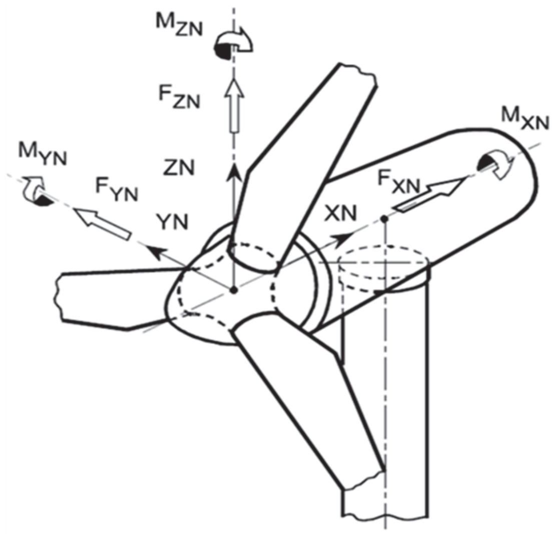

Figure 7: Six component vectors evaluated at the hub height through GH Bladed [7]

The evaluation of the extreme loading on the tower was carried out by evaluating the maximum tower member load vectors Fy at the base. The Fy load vectors in this case represent the local shear force at the base of each member.

The global loading imparted solely by the hydrodynamic environment on the submerged jacket structure members could not be directly computed using Bladed. Bladed was used to evaluate the water particle kinematics, i.e. the water particle velocity (u) and acceleration ($\mathring{u}$) at each node of the submerged jacket structure. The global wave load vector was computed at each node in the submerged structure using the Morison equation.

When modeling the rigid foundation, all degrees of freedom at the four foundation nodes at the base of support structure were fully fixed. For the pinned foundation the three rotational degrees of freedom (θx, θy, θz) at the four foundation nodes of the modeled structure were free to rotate while Δx, Δy, Δz were fixed.

4.4 Ultimate State Design

The objective of the ultimate state design process was to optimise the members of the jacket structure to withstand the extreme loading evaluated in extreme event analysis. Ultimate state design was achieved through dimensioning the jacket members to satisfy structural integrity checks according to the NORSOK design standard [8]. Member stability check equations included the combination of tension, compression, bending, shear and hoop stresses.

Optimisation of the jacket structure was achieved by carrying out a member optimisation design cycle (MODC). The procedure MODC was carried out through the use of the finite element software ANSYS [10]. Figure 8 illustrates the operational sequence of the MODC procedure.

The MODC procedure was initiated with the element support structure having the initial dimensions established in the preliminary design phase. BEAM 188 was used for modeling of the support structure in ANSYS. The model included the jacket structure, the transition piece and the wind turbine tower. A mesh convergence study was carried out which showed that 20 mesh divisions per element gave rise to sufficient accuracy and convergence while reducing the computational time for stress analysis to be carried out. The buoyant force was accounted for by determining an apparent density and applying it to the submerged part of the structure. The boundary conditions at the foundation nodes of the jacket model were then applied. The MODC procedure was repeated for both a fixed foundation and for a pinned foundation. The extreme loading evaluated in the extreme event analysis was then applied at the corresponding points of occurrence around the support structure. Following the applied extreme loading combinations at the hub centre, a stress analysis was carried out. A combination of axial, compression bending, shear and torsion stresses were evaluated for each member within the jacket structure.

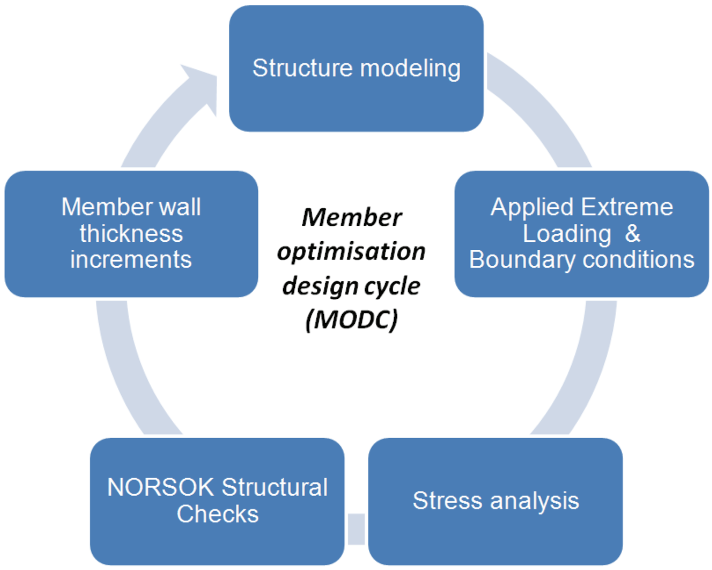

Figure 8: Member Optimisation Design Cycle (MODC)

Structural checks according to the NORSOK design standard [8] for each member were then carried out. Checks per member were carried out against the stresses computed from the ANSYS simulations. If a selected member failed to satisfy all checks then the member is deemed to have failed compliance with the NORSOK standard [8]. Members that fail to comply had their wall thickness increased by increments of 0.5mm. The cycle then repeated itself with the re-modeling of the support structure incorporating the changes in the newly dimensioned members.

The optimised cycle was repeated until all members satisfied all the required equations. The final result was an optimised jacket structure design for a 70 metre water depth that satisfied the structural integrity checks of the NORSOK design Standard [8].

5. FOUNDATION MODELLING DESIGN RESULTS

The following results describe comparatively the final optimised jacket designs as a result of the adopted design methodology.

Table 4 compares the resulting jacket member design dimensions for the two different modeled foundations. Figure 9 illustrates a side view of the jacket design with labeled sections that have tabulated results in table 4.

Table 4: Jacket design with rigid and pinned foundations - wall thicknesses and weightings

		Rigid	Pinned
X-bracing (mm) Wall thickness (mm)	Level 1	15	15
	Level 2	8	9
	Level 3	15	15
	Level 4	15	15
Main leg (mm) Wall thickness (mm)	Top section	50	50
	Middle section	36	36
	Lower section	38	39
Natural frequency (Hertz)	Support structure	0.300	0.301
Masses (tonnes)	Corrosion allowance	2.03	2.03
	Jacket	485.7	491.1
	Transition piece	72.1	72.1
	Tower	229.9	229.9
	Total	789.73	795.13

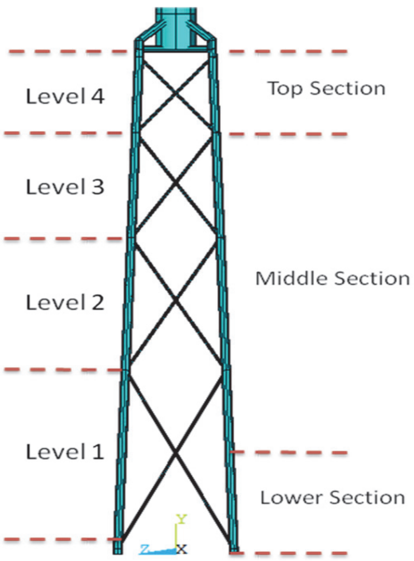

Figure 9: Jacket design Layout

It was seen that modelling of the jacket design with a rigid foundation resulted in a jacket design weight of 485.7 tonnes. This is 5.4 tonnes lighter than the jacket design modelled with a pinned foundation. Results from the modal analysis carried out in Bladed [7] on the final jacket designs show 0.001 Hz difference in the 1^{st} natural frequency. This small difference was a result of the 5.4 tonne weight difference between the two jacket designs.

Both designs have a natural frequency that satisfies the target workable frequency range. Similar to the final design seen in the UpWind project [11], thicker wall thicknesses were seen for the X-bracing and main legs at both the foundation and transition piece intersection. This result was expected at the foundation because essentially the structure is a cantilever model with the large stress values near the foundation. The significant increased thickness nearer to the transition piece intersection may be due to the geometric discontinuity of the jacket and transition piece intersection.

6. CONCLUSIONS

A tailor made design methodology for an optimised jacket design suited for a 70 m water depth was described. An investigation comparing jacket structures with rigid and pinned foundations was carried out.

The following main conclusions could be drawn from this study:

- The weight of the jacket structure design with pinned foundations was found to be 5.4 tonnes heavier than that with rigid foundations 491.1 instead of 485.7.
- The modeled rigid and pinned foundation designs had a support structure 1st natural frequency of 0.300 Hz and 0.301 Hz respectively. Both values satisfy the established natural frequency envelope in order to avoid resonance at 1P and 3P excitation frequencies.

7. FURTHER WORK

The effects of fatigue on the joints of a jacket structure are significantly dependent on the support structures natural frequency. This necessitates further work to study the effects of different foundation modeling types on a complete fatigue assessment of the support structure. Fatigue state design according to the DNV standard [3] will be used to ensure that the structure will have sufficient resistance against fatigue failure.

Following the fatigue assessment, further study on the installation procedure is necessary to conclude on the overall feasibility of the rigid or pinned foundation design.

8. ACKNOWLEDGMENTS

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