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STRUCTURAL OPTIMISATION OF TENSION LEG PLATFORM FOR AN OFFSHORE WIND TURBINE

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Abstract. *Wind power is a proven sustainable energy source, with Offshore Wind Turbines (OWTs) offering higher efficiency by exploiting strong offshore winds. Advances in technology now allow Floating Offshore Wind Turbines (FOWTs) to operate in deep waters beyond fixed foundations. This study focuses on the structural optimisation of Tension Leg Platform (TLP)-type FOWTs using Finite Element Methods (FEM). The analysis includes hydrostatic pressure, aerodynamic thrust, turbine weight, and mooring loads, simulated with OpenFAST. A single-objective optimisation algorithm minimises platform mass under stress and buckling constraints. Results show that optimised stiffener placement significantly reduces mass while maintaining structural integrity, offering valuable guidance for future FOWT design and cost reduction.*

Keywords: *Finite element analysis, structural mechanics, floating offshore wind turbines, structural optimisation.*

INTRODUCTION

Wind energy has emerged as one of the most significant renewable energy sources in the global transition toward sustainable power generation. The depletion of fossil fuel reserves and the adverse environmental effects of their combustion have accelerated efforts to develop alternative energy technologies. Among these, wind power has demonstrated great potential due to its abundance and scalability. With advances in technology and growing governmental support, the deployment of wind farms has expanded rapidly, both onshore and offshore.

Compared to onshore systems, Offshore Wind Turbines (OWTs) benefit from stronger, more consistent winds and reduced visual and acoustic impacts on populated areas. Although offshore installations involve higher capital, installation, and maintenance costs, they offer superior energy yield and long-term sustainability. In particular, Floating Offshore Wind Turbines (FOWTs) enable energy production in deeper waters where fixed-bottom structures are not feasible, significantly increasing potential deployment areas.

This study focuses on the structural optimisation of a Tension Leg Platform (TLP)-type FOWT using Finite Element Analysis (FEA). The model integrates hydrostatic pressure, aerodynamic thrust, turbine weight, and mooring loads, with dynamic behaviour simulated via OpenFAST. A single-objective optimisation

algorithm is employed to minimise platform mass under mechanical stress and buckling constraints with the help of Ansys Mechanical 2024R1. The focus of this optimisation lies in varying critical design elements: the placement of internal reinforcements and the thicknesses of cylindrical shell, pontoon and stiffeners. Results highlight the crucial influence of internal stiffener configuration on reducing structural mass while ensuring stability and reliability.

This research considered the NREL IA15 MW upwind 3-bladed Reference Turbine [1]. Table 1 describes main parameters of the reference turbine.

Cut-in wind speed	3 m/s
Rated wind speed	11.4 m/s
Cut-out wind speed	25 m/s
Rotor diameter	240 m
Hub height	150 m
Tower height	129.386 m
Tower mass	1466.7 tons
Blade length	117 m
Blade mass	6850.8 tons
Rotor nacelle assembly mass	1017 tons
Electrical generator efficiency	0.9658
Cut-in rotor speed	5 rpm
Cut-out rotor speed	7.56 rpm

Table 1: Turbine properties

The platform material is steel, namely S355 steel. This material has a Young modulus of 210 Pa and a shear modulus of 80.8 GPa. Steel’s density is 7 850 kg/m3. The S355 steel yield strength is considered to be 355 MPa [2]. For the analyses, the density of water was considered as 1025 kg/m3 [3].

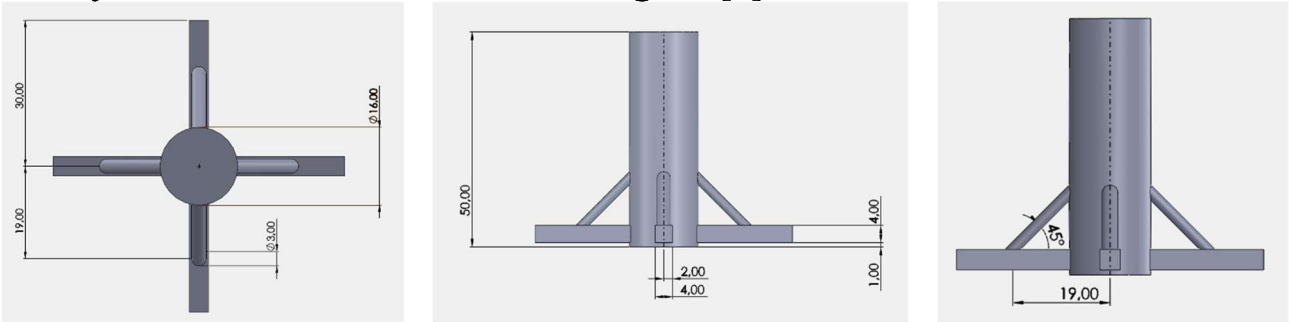


Figure 1: 3D model of the Tension Leg Platform

The platform's geometric design is carried out using Salome 9.9.0 (“Salome 9.9.0” 2024), an open-source software for 3D CAD modelling. The design consists of shell elements, which are subsequently imported into Ansys.

LITERATURE REVIEW

Floating Offshore Wind Turbines (FOWTs) have attracted significant research attention due to their potential to harness high wind energy resources in deep-water

regions where fixed-bottom structures are impractical. Early works such as Robertson et al. (2014) and the IEA Wind (2020) reference turbine have provided essential benchmarks for floating platform configurations and load modeling. Recent studies have focused on optimizing substructure design to balance structural integrity, mass reduction, and cost efficiency. Sirigu et al. (2020) introduced novel optimization methods for static structural finite element analysis (FEA) of floating foundations, emphasizing the interaction of hydrodynamic and aerodynamic loads. Similarly, Park and Choung (2023) examined dominant load parameters influencing the substructure design of large-scale (10 MW) FOWTs, underscoring the importance of load coupling effects. Vasconcelos (2020) conducted a structural analysis under service conditions, highlighting the relevance of stress distribution and buckling constraints in offshore environments. These studies collectively demonstrate the progression from conceptual modeling to advanced numerical optimization of FOWT substructures. The current research builds upon this foundation by applying finite element optimization techniques to a Tension Leg Platform (TLP) type FOWT, emphasizing the critical role of internal stiffener configurations in reducing steel mass while maintaining safety and stability under combined static and hydrodynamic loads.

METHODOLOGY.

Static Structural implementation: The analysis includes a variety of static loads that the structure must bear.

1. Hydrostatic pressure from sea water.
2. Forces and moments resulting from static aerodynamic thrust and the weight of the turbine.
3. Loads from mooring lines.
4. Hydrostatic pressure from internal ballast.

The loads transferred between the tower and mooring lines are computed in OpenFAST time-domain simulations ("OpenFAST" 2024), an open-source software developed for the dynamic analysis of floating wind turbines.

The water ballast is required to maintain required draft from design. The structural steel mass is obtained by setting the thicknesses for each group of shell elements. The calculation of ballast is demonstrated in equation 1 where $V_{submerged}$ is the volume of submerged platform, M_{steel} is the structural steel mass, $M_{waterballast}$ is the fixed ballast inside the pontoons and $M_{turbine}$ is the mass of the turbine.

$$M_{ballast} = \rho V_{submerged} - M_{steel} - M_{waterballast} - M_{turbine} \quad (1)$$

The centre of mass of the platform is then evaluated by summing the centre of mass (CoM) of steel, the centre of mass of water ballast in the pontoons, additional ballast inside the main column and dividing the result by total mass. It is assumed that the ballast density is 1025 kg/m^3 (generic water).

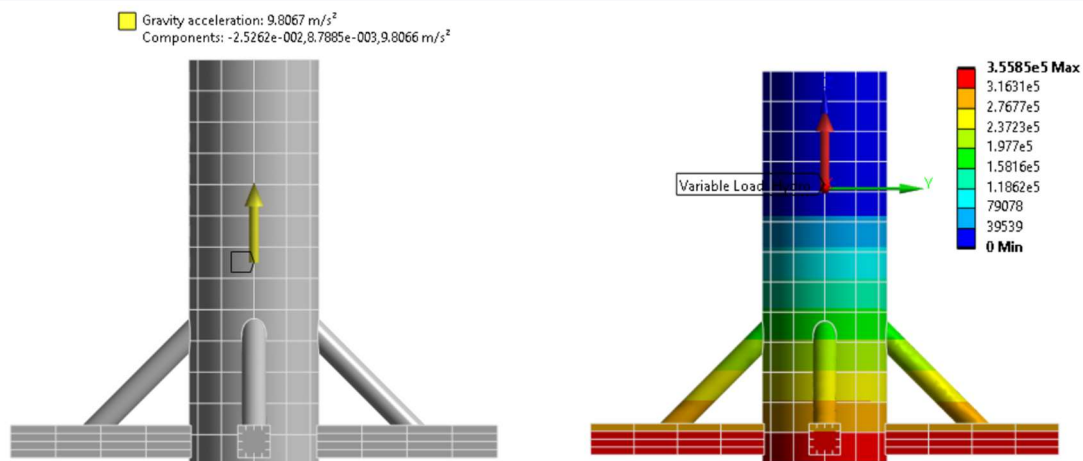


Figure 2: Implementation of gravity acceleration (left) and hydrostatic pressure (right)

The ballast is represented as an internal hydrostatic pressure. This internal pressure is advantageous for the structural integrity of the platform because it counteracts the external hydrostatic pressure exerted by seawater [4]. The level of this internal pressure corresponds to the height of the ballast. Additionally, the model includes the gravitational force resulting from the mass of the steel.

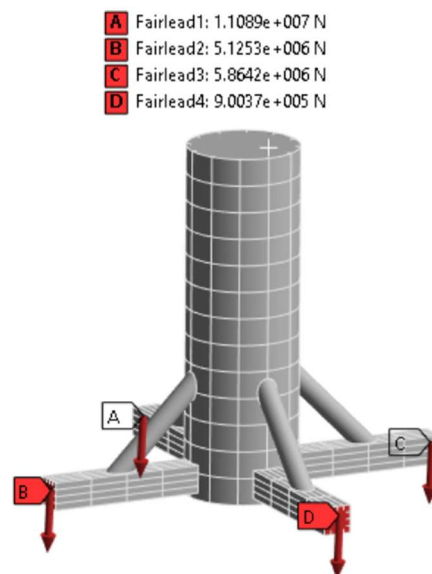


Figure 3: Forces applied on the fairleads

To factor in the aerodynamic thrust forces and moments, as well as the self-weight of the wind turbine, the platform's orientation is adjusted relative to the sea water level (SWL) [4]. These specific values are derived from time-domain simulations conducted in OpenFAST. The distribution of hydrostatic pressure, influenced by the pitch, roll angles, and heave, primarily governs the tower's reaction forces. These forces are essential as they bear the weight of the turbine and counteract the pitching and rolling moments generated by the turbine's thrust. The pontoons in the design do not experience hydrostatic pressure due to the presence of water ballast within them. It is

assumed that there is a balance between the internal and external pressures [4].

To prevent rigid body motion, two constraint methods were considered: inertial relief and a fixed constraint at the interface between the tower and the platform. Inertial relief applies acceleration forces on the mass elements to balance unbalanced forces so that small resultant force which could cause movement does not occur. Imperfections in force application would, of course, cause some unwanted acceleration, and the key is that this must be as little as possible [4]. Simply, due to these aspects inertial relief is usually the way to go for modeling floater constraints without over-constraining the model. However, the pre-stress distribution that can be generated by inertial relief in ANSYS Mechanical cannot be used as part of an eigenvalue buckling analysis [4]. Thus, a constrained was imposed around the perimeter of the base of the tower-platform interface. Though such an approach can keep the stability of the structure, it can also cause deviation in stress distribution since the tower base acting as rigid and result into fictitious stress concentrations within this area [4]. This approach should be cautionary to not introduce unrealistic results. The fairleads have a square surface attached corresponding to the cross-sectional area of each arm moored on either side of the platform, and mooring loads are applied as forces distributed across this mooring bent as shown in figure 3 while figure 2 describes the implementation of hydrostatic pressure and gravity acceleration in ANSYS.

OpenFAST Model: The OpenFAST model assesses the heave, pitch, and roll angles essential for simulating hydrostatic pressure distribution and the mooring forces exerted on the fairleads [4]. Furthermore, it analyzes the forces and moments at the base of the tower to facilitate comparative analysis [4]. The simulation is carried out for 100 seconds with integration time step of 0.1 seconds and additional linear damping, aiming to achieve steady-state values. These simulations take place under still water conditions and a constant wind speed corresponding to the rated wind speed of 10.56 m/s. Integration time step is to be chosen with care since the smaller is the time step, the longer is the computation time. Afterwards, the analysis involves running multiple simulations with varying center of mass (CoM) values for the platform. The results of these simulations are analyzed through linear interpolation, as the relationships between the variables and the platform's CoM are mostly linear, with minor non-linearity introduced by the mooring system. Four CoM values, ranging from -13 to -16 meters below sea water level, are used for this analysis. The interpolation equations for these key values are provided for reference in equations from 2 to 5. Subsequently, the mooring forces are rotated from the global reference system of the SWL to the platform's local reference system.

$$\begin{cases} Heave = -0.000016 COM - 0.3798 \\ Roll = 0.000192 COM + 0.055 \\ Pitch = 0.000103COM + 0.149 \end{cases} \quad (2)$$

$$\begin{cases} F_{x,1} = 98.67 COM - 58537.34 \\ F_{x,2} = 105.28 COM - 462960.97 \\ F_{x,3} = -257.91 COM - 1006576.64 \\ F_{x,4} = 65.48 COM - 503 \end{cases} \quad (3)$$

$$\begin{cases} F_{y,1} = -8.007 COM - 3138.632 \\ F_{y,2} = -39.266 COM - 9673.368 \\ F_{y,3} = 30.834 COM + 10728.752 \\ F_{y,4} = -47.732 COM - 11062.651 \end{cases} \quad (4) \quad \begin{cases} F_{z,1} = 1025.689 COM - 875841.685 \\ F_{z,2} = 1680.427 COM - 5067305.709 \\ F_{z,3} = -2763.894 COM - 11103949.714 \\ F_{z,4} = 29.688 COM - 5841754.630 \end{cases} \quad (5)$$

The optimisation process utilized in this study employs the "scipy.optimize.fmin" function from the SciPy library ("Fmin Function" 2024). This function implements the Nelder-Mead algorithm, which is a gradient-based optimizer designed to locate the local minimum of a given function.

The function is utilized in the optimization process to adjust the thicknesses of various structural components, including the main column, braces, and internal stiffeners. To streamline the process, the positions of the internal stiffeners are kept fixed during optimization. This decision serves two main purposes: first, it reduces the number of input variables, which in this study ranges from 4 to 10; second, it ensures a consistent geometry and mesh throughout all iterations, thereby simplifying the workflow.

The optimization process aims to minimize the total mass of structural steel while incorporating constraints related to yield stress and buckling strength. Yield stress constraints are evaluated by comparing the Von Mises stress to the steel's yield stress, typically 355 MPa, a standard value for offshore wind platforms [5], [6]. A safety factor of 1.5 is applied, resulting in a stress limit of 235 MPa.

Buckling constraints are examined via eigenvalue buckling analysis, which entails resolving an eigenvalue problem that arises from the equilibrium equations of the structure. Here, the eigenvalue—often referred to as the load multiplier—indicates how much a given load must be adjusted in order to induce a loss of stiffness and stability within the structure. This type of analysis is especially vital for floating wind platforms, where shell elements predominantly experience compressive stresses, rendering them susceptible to buckling instabilities. To ensure safety during this evaluation, a factor of 1.5 is incorporated into the load multiplier associated with the initial buckling mode.

The objective function incorporates these constraints as penalties, alongside the assessment of steel mass. These penalties are formulated as parabolic functions based on the specific constraint. The objective function is defined in equations 6, 7 and 8 where σ represents the Von Mises stress and LM is the load multiplier of the first buckling mode [4].

$$OBJ = M_{steel} + OBJ_{YIELD} + OBJ_{BUCKLING} \quad (6)$$

$$\begin{cases} OBJ_{YIELD} = 0.4 \sigma^2 112\sigma + 9000 & \text{if } \sigma > 235 \\ OBJ_{YIELD} = 0 & \text{if } \sigma < 235 \end{cases} \quad (7)$$

$$\begin{cases} OBJ_{BUCKLING} = 16032 LM^2 - 48080 LM + 36048 & \text{if } LM < 1.5 \\ OBJ_{BUCKLING} = 0 & \text{if } LM > 1.5 \end{cases} \quad (8)$$

ANALYSIS AND RESULTS

FIRST ATTEMPT: The optimization process begins with focusing on the external geometry of the structure, which consists of shell elements. Internally, the only components considered are the walls that separate the cylinders from the pontoons and braces. The thicknesses of shell elements are categorized in three groups such as main column, pontoons, and braces. The mesh size is selected to be 0.5 meters, which generates around 30875 nodes. The initial thickness of each group is set to 4 centimeters. One of the most important consideration in the initial optimization is that the platform is not reinforced with internal stiffeners. The results of this optimization allow to demonstrate the critical importance of reinforcements in the structural performance of the platform.

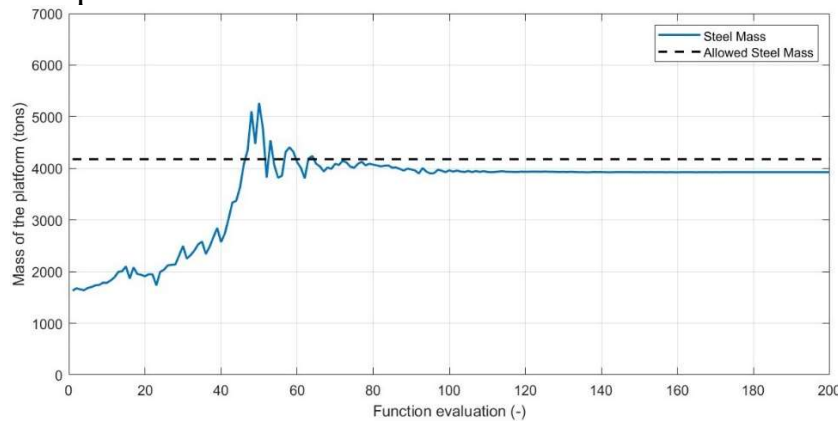


Figure 4: First optimization results of structural steel mass.

Figure 4 presents a graphical representation of how the steel mass evolves during the optimisation process whereas figure 5 depicts the evolution of Von Mises stress and Load multiplier. As it can be seen from figures, the optimisation algorithm reached a point of convergence after approximately 100 iterations. Although the results indicate that the steel mass amounts to be slightly lower than allowed steel mass, the steel mass accounts to be significantly high.

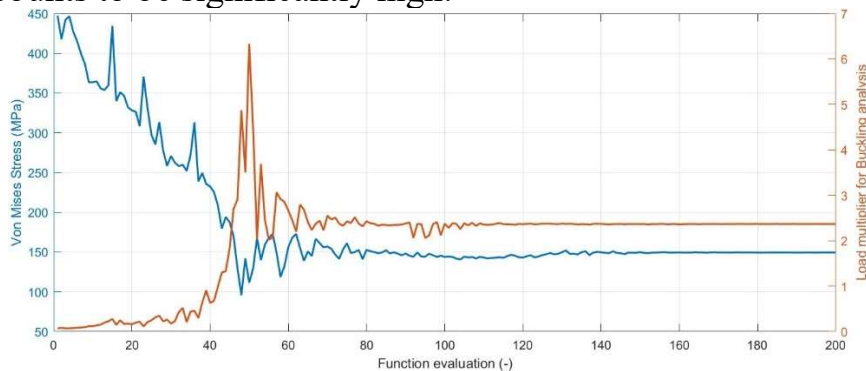


Figure 5: Optimization results of Von Mises stress and Load Multiplier.

Furthermore, the final values for thickness of each group is demonstrated in the figure 6, where the main column thickness amounts 14 centimeters.

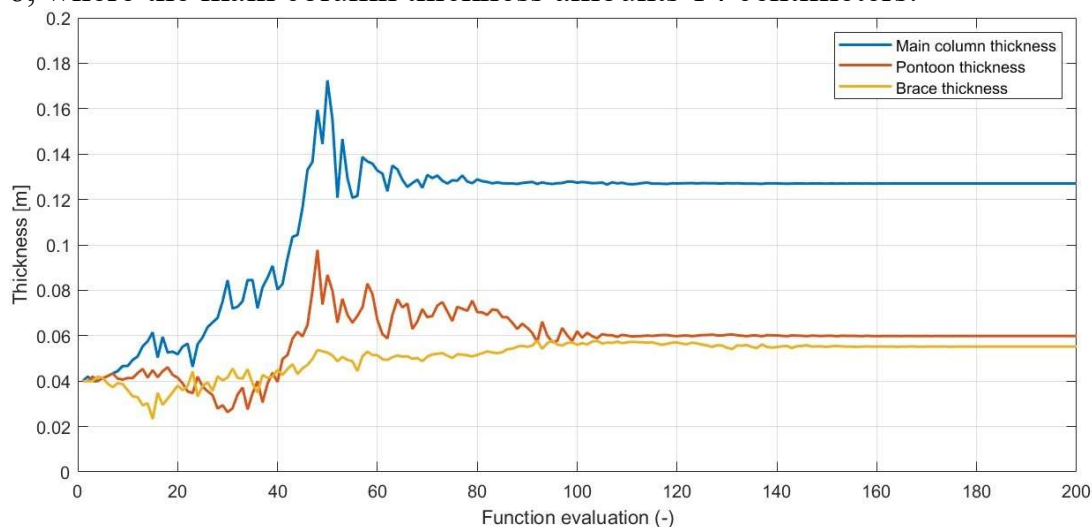


Figure 6: First optimization results of thicknesses of surface groups.

Figure 7 shows the distribution of stress on the optimised platform. This stress map highlights that the bottoms of the cylindrical columns and arms are critical areas in terms of design and therefore require reinforcements. These areas require a substantial increase in material thickness to withstand deformation — specifically, 14 cm for main columns and 6 cm for the pontoons.

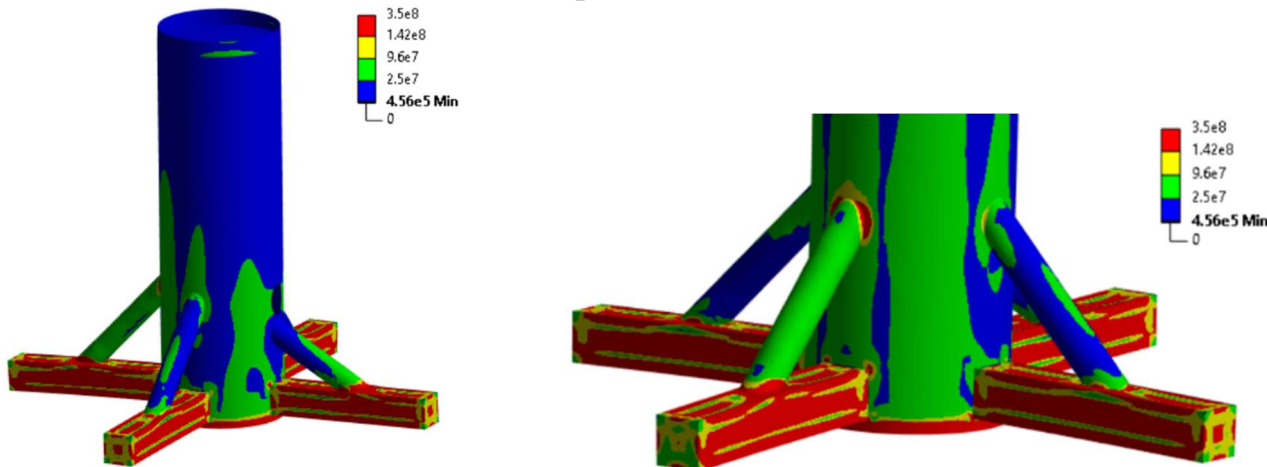


Figure 7: Final stress distribution evaluated at the end of the optimization.

SECOND ATTEMPT: In response to these insights, a second iteration of design optimisation is undertaken. This iteration involves adding reinforcements and adjusting the thicknesses of various structural elements to address the identified weaknesses. The platform is then re-optimised based on these new specifications. In the second optimisation attempt, additional stiffeners are introduced to the main and external columns of the structure.

These stiffeners are specifically designed to counteract the hydrostatic pressure

at the bottom of the columns, as described in figure 8. To facilitate the optimization, the thicknesses of reinforcements are considered in the groups where they have been placed. Longitudinal stiffeners are spaced at every 1 meter transversally while radial rings are spaced at 3.6 meters vertically.

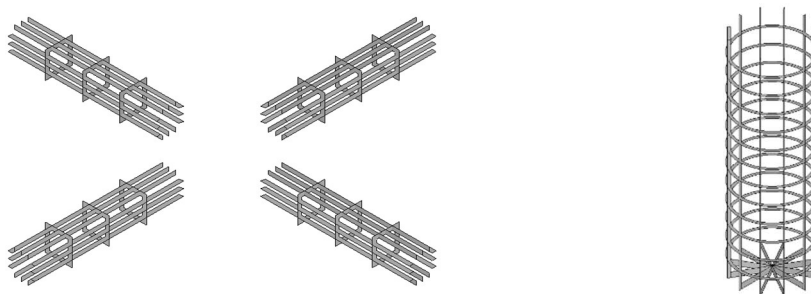


Figure 8: Main column stiffeners (left) and Pontoon stiffeners (right)

The progress of this optimisation is charted in Figure 9. The addition of these new stiffeners significantly reduced the thickness required for the columns. This led to a substantial reduction in the overall mass of the platform, bringing it down from 3961 tons to 2870 tons. Moreover, it can be demonstrated from the graphs that the algorithm converged after around 100 iterations.

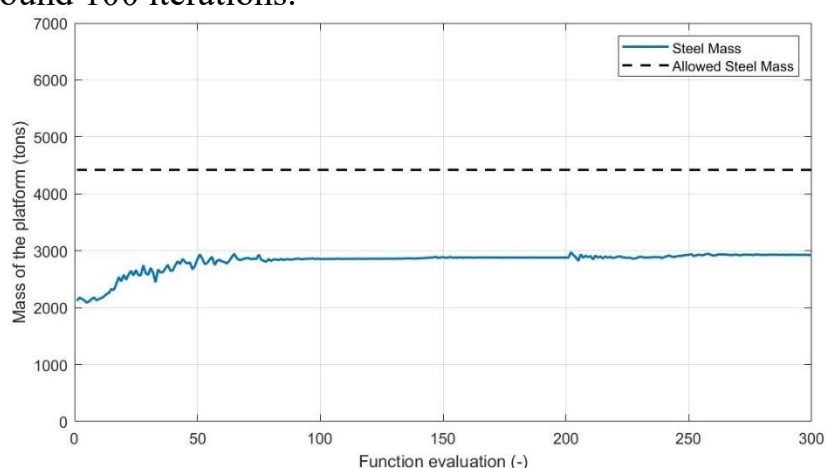


Figure 9: Second optimization results of structural steel mass.

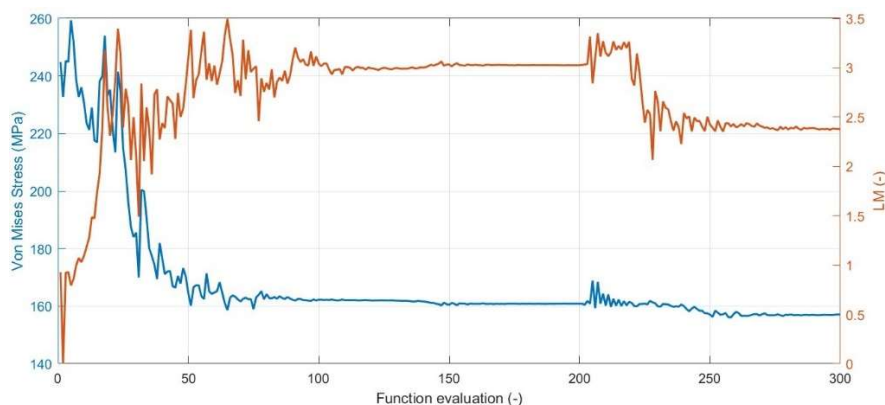


Figure 10: Second optimization results of structural Von Mises stress and Load multiplier.

This situation highlights a common issue with the gradient-based algorithm, namely its difficulty in consistently converging to a global minimum [61]. It can be clearly illustrated in figure 10 where Load multiplier initially converges at about 3.1 and finally reaches to 2.5 after perturbation.

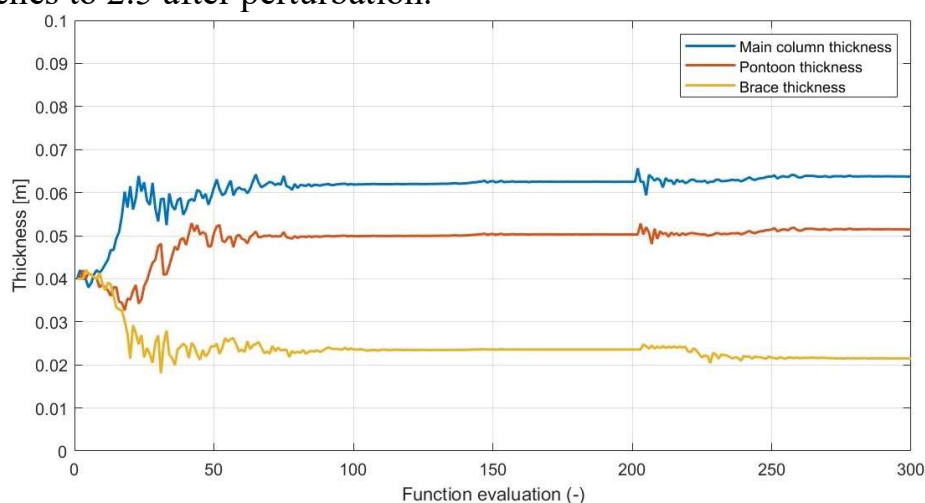


Figure 11: Second optimization results of thicknesses of surface elements.

As clearly illustrated in Figures 10 and 11, the integration of these elements has successfully led to a feasible design. The final thickness of main column group is evaluated to be around 6.4 centimeters, which corresponds to a significant decrease with respect to the previous value.

Table 3 illustrates the values of important parameters in initial and final optimisations, which further justifies the importance of reinforcements to the structural performance of the platform. The stress distributions of final optimized structure are displayed in figure 12. The stress is now primarily concentrated in the braces and at the junctions where the braces connect to the main column and the pontoons. The pontoon thickness is now 5 cm. Given these observations, there is potential for further optimisation of the pontoons, possibly by adding new stiffeners to these components.

	Initial optimisation	Final optimisation
Steel mass	3925,4 tons	2927.19 tons
Equivalent Von Mises stress	149.47 MPa	157.03 MPa
Load multiplier	2.37	2.38
Main column thickness	12.7 cm	6.38 cm
Pontoon thickness	5.99 cm	5.15 cm
Brace thickness	5.52 cm	2.15 cm

Table 3: Comparison of optimisation results.

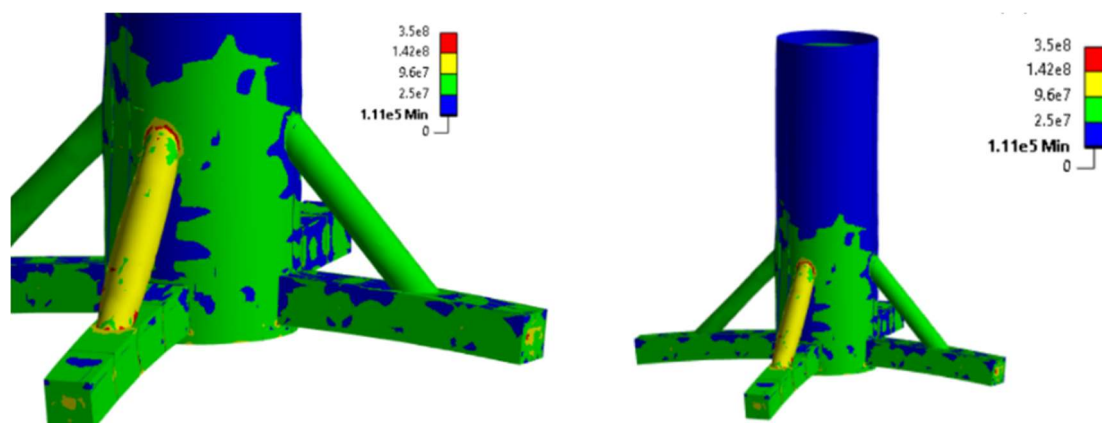


Figure 12: Final stress distribution at the end of the optimisation.

CONCLUSION

This paper presented a structural optimisation of a Tension Leg Platform designed for offshore wind turbines. Key points of the study are summarised as follows:

1. **Optimisation process:** The optimisation was carried out in multiple stages. First, the weak areas of the substructure were identified. Then, extra stiffeners were added to these critical regions, and the thicknesses of selected structural components were adjusted to enhance their strength and stability.
2. **Achievements:** The optimised platform achieved a steel mass comparable to the reference design while satisfying key structural constraints, including a maximum permissible stress of 235 MPa and a buckling safety factor of 1.5.
3. **Importance of stiffeners:** The study emphasizes that the positioning and sizing of internal stiffeners play a vital role in reducing the overall structural mass, especially in the lower sections of the columns.
4. **Optimisation algorithm:** It is recommended to substitute the gradient-based optimisation algorithm with a more robust approach as the number of variables increases, in order to prevent the process from converging to local minima.
5. **Limitations:** The analysis in this study was limited to static loading conditions. Future work should include time-domain simulations based on standard design load cases to account for transient effects and wave-induced loads.
6. **Future works:** Future research could investigate alternative shapes and configurations of internal stiffeners to further reduce steel mass while enhancing safety factors for yield stress and buckling resistance. Additionally, future studies should account for manufacturing costs, particularly the influence of stiffener placement and quantity on fabrication expenses such as welding.

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