NAFEMS World Congress 2025 – Fatigue Analysis and Structural Optimization of Floating Offshore Wind Foundations Under DNV RP-C203 2024

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Abstract

Floating offshore wind turbines and their foundations are continuously exposed to complex environmental loading conditions due to wind, waves, and operational factors. These cyclic loads impose significant fatigue risks, particularly at welded joints, which act as primary stress concentration points. Ensuring structural integrity and compliance with offshore standards such as DNV RP-C203 requires a robust fatigue assessment methodology that integrates environmental conditions modelling, finite element analysis, and advanced data processing techniques.

This study presents a structured approach to fatigue life assessment and design optimization for floating offshore wind turbine foundations, focusing on five key areas: data acquisition and systematization, finite element modelling, large-scale data processing, interpretation of DNV RP-C203 fatigue calculations, and results documentation for certification. The objective is to extend the operational lifespan of offshore wind turbines while maintaining safe and continuous operations. It is achieved by developing a highly automated workflow that is ensuring that welded connections of the floating foundations meet fatigue resistance requirements. This workflow utilizes statistical data, measurements, finite element analysis, and design check automation tools to achieve time-effective and precise compliance with DNV Recommended Practice. Most recent version of DNV RP-C203 of 2024 is followed, this version takes into account the feedback from the industry experts and scientists and introduces adjustments to S-N curves that ensures maximum precision for the analysis results.

1. Data Acquisition and Systematization

The accuracy of fatigue assessment depends on the quality and comprehensiveness of environmental and operational loading data. Collecting this data requires a multi-source approach to ensure completeness and reliability. This section explores methods for gathering and systematizing wave, wind, and current data from various sources, including sensor arrays, remote sensing technologies, and historical datasets from oceanographic research institutions.

In most applications this data comes from 6 DOF motion sensors in a database that includes translational and rotational accelerations for the following motions: Sway, Heave, Surge, Pitch, Yaw, and Roll over a time domain. As there is no standard output format for sensor measurements, it has to be converted into a database that will be further filtered and used as an input for verification.

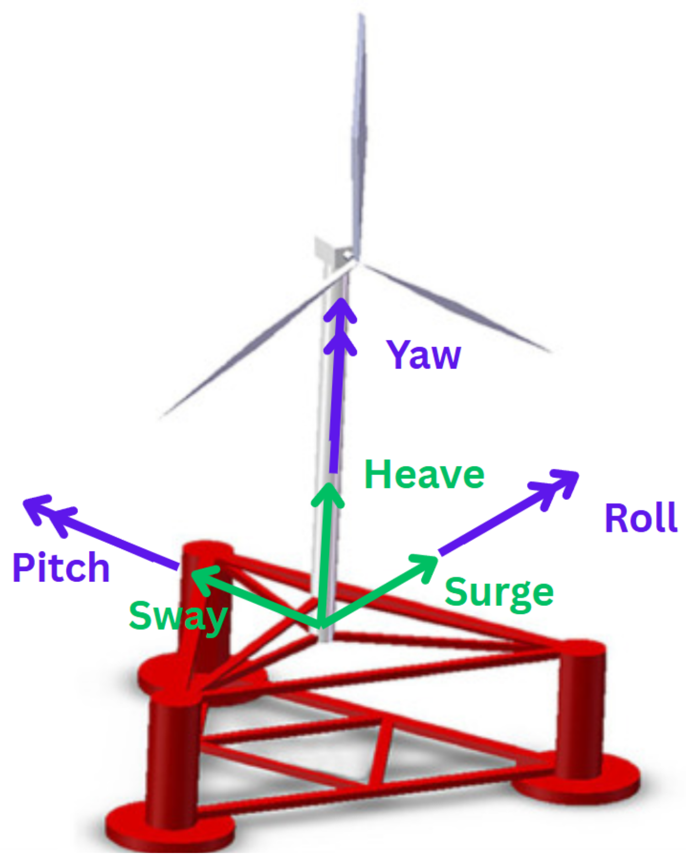

Figure 1: Floating offshore wind turbine (FOWT) motions diagram.

Data pre-processing involves filtering out anomalies and filling gaps in time-series data. Different methods and algorithms can be employed to ensure accurate representation of the environmental conditions. These methods are described in the Section 3 of this paper. Load condition spectra are developed based on the collected data, allowing for a more precise understanding of fatigue-critical responses in floating wind foundations.

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dlc1.2aa-1.txt - Notepad
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Tower Mx  [kNm] Tower My  [kNm] Tower Mz  [kNm] Tower Fx  [kN]  Tower Fy  [kN]  Tower Fz  [kN]
312320.0        11949.3 750863.0        4695.78 -3254750.0      -2274.0
321056.0        -57532.0        1033010.0       14241.5 -3253690.0      -2568.28
329140.0        -70269.8        1383770.0       23604.4 -3252450.0      -3574.96
331471.0        -16551.8        1760870.0       28381.3 -3251350.0      -3744.95
325203.0        32212.1 2139400.0       32488.1 -3250850.0      -2822.23
319505.0        24696.6 2556230.0       40020.8 -3251190.0      -2284.5
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Figure 2: Example of input data from 6 DOF motion sensor.

Furthermore, consideration is given to operational conditions, including turbine operations, which directly affect the structural response of the foundation. Floating offshore wind turbine operational conditions include power production mode – rotor thrust and potential vibrations, start-up/shutdown – transient loads during cut-in and cut-out wind speeds, emergency stop – high dynamic loads from rapid deceleration and braking, and fault – asymmetric loads due to failures. By systematically organizing this data, it is possible to create realistic load models for subsequent analysis.

As motion data includes six base cases in various combinations, it's possible to organize it by applying the unit forces to the FEA model for all translational and rotational accelerations. These unit forces are later multiplied by a factor to represent the actual values. Operational, test, and failure conditions must be taken into account as an Ultimate states, but usually are not included in the Fatigue analysis because of it’s rare occurrence.

The resulting dataset for the analysis includes 1,200 load cases, each comprising approximately 864,000 time steps, resulting in a massive data volume that demands precise, automated cycle counting and stress range identification techniques.

2. Finite Element Modelling and Identification of Critical Components

Once environmental and operational loading parameters are defined, a high-fidelity finite element model of the FOWT foundation is, with a special focus on welded connections, is built to simulate the six-degree-of-freedom (6-DOF) motion of the floating structure. These motions, include surge, sway, heave, roll, pitch, and yaw, all of which induce multi-axial stress states.

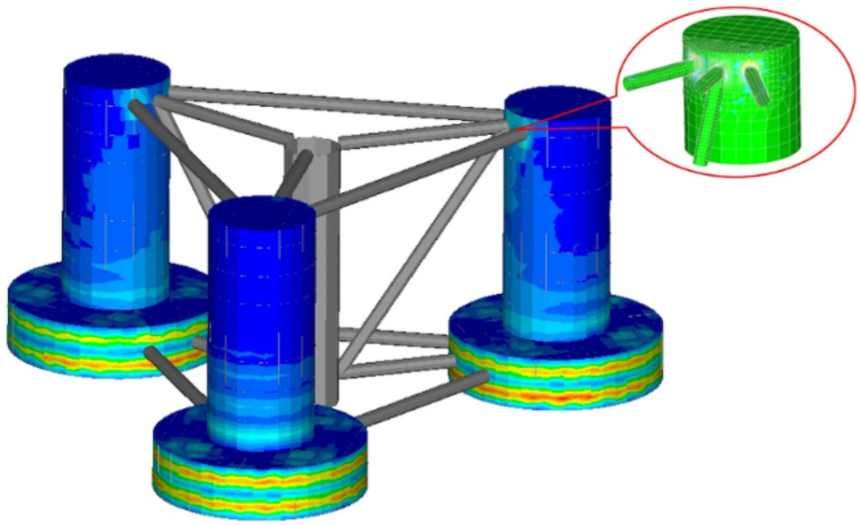


Figure 3: Floating offshore wind turbine foundation FEA model example.

Material property assignment step is important to define material characteristics for each component: Young's modulus, density, yield stress, and tensile strength values to replicate those of the materials used in real life, ensuring that the structural behavior of the foundation is accurately replicated in simulations.

The finite element model of the foundation is built with 2D "shell" elements and developed using advanced meshing techniques to accurately represent the geometric complexity of the structure, particularly at welded joints, which are prone to fatigue failure. Special attention is given to adequate mesh sizing that allows to assess the critical welded joints for the cases when hot spot stress method is used.

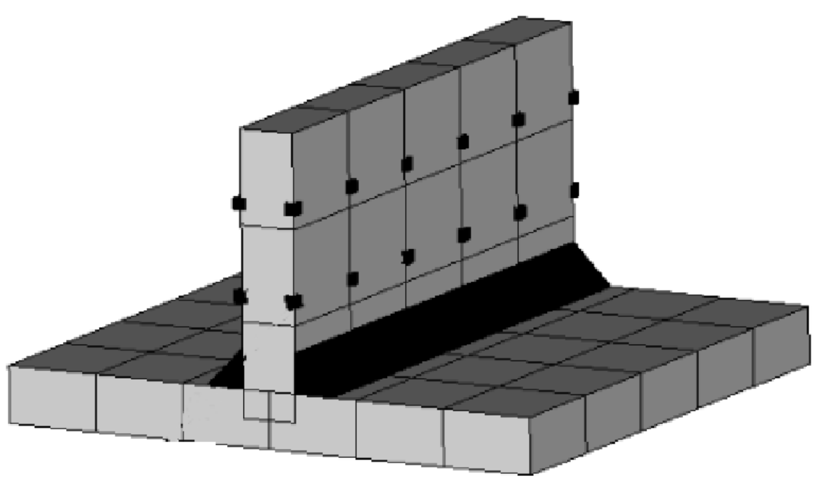
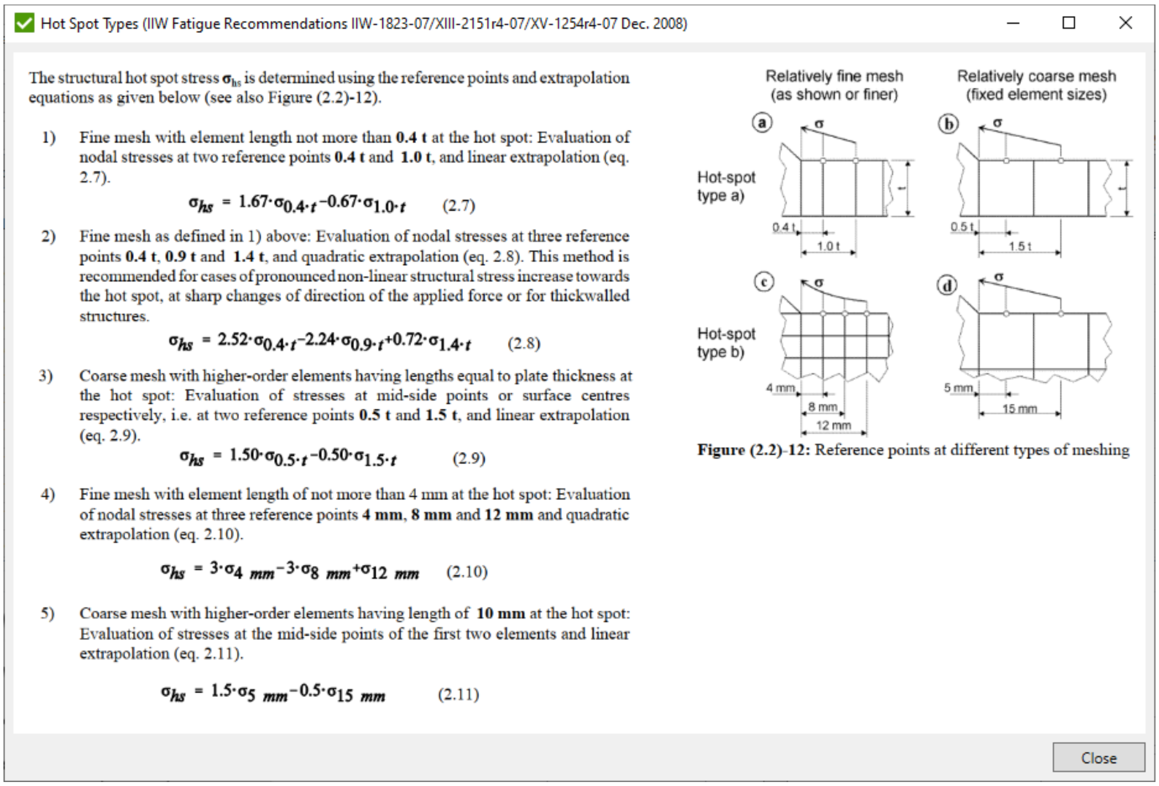


Figure 4: Fine mesh sizing that allows correct Hot Spot Stress definition

The structural hot spot stresses are determined for critical weld details using the reference points and extrapolation equations according to IIW Fatigue Recommendations (IIW-1823-07/XIII-2151r4-07/XV-1254r4-07 Dec.2008), and hot-spot stress analysis is conducted in the areas with elevated fatigue risk. Proper mesh sizing allows to ensure that stresses are extracted from the different finite elements at reference distance from the weld root.



The structural hot spot stress σ_{hs} is determined using the reference points and extrapolation equations as given below (see also Figure (2.2)-12).

1) Fine mesh with element length not more than **0.4 t** at the hot spot: Evaluation of nodal stresses at two reference points **0.4 t** and **1.0 t**, and linear extrapolation (eq. 2.7).

$$\sigma_{hs} = 1.67 \cdot \sigma_{0.4 \cdot t} - 0.67 \cdot \sigma_{1.0 \cdot t} \qquad (2.7)$$

2) Fine mesh as defined in 1) above: Evaluation of nodal stresses at three reference points **0.4 t**, **0.9 t** and **1.4 t**, and quadratic extrapolation (eq. 2.8). This method is recommended for cases of pronounced non-linear structural stress increase towards the hot spot, at sharp changes of direction of the applied force or for thickwalled structures.

$$\sigma_{hs} = 2.52 \cdot \sigma_{0.4 \cdot t} - 2.24 \cdot \sigma_{0.9 \cdot t} + 0.72 \cdot \sigma_{1.4 \cdot t} \qquad (2.8)$$

3) Coarse mesh with higher-order elements having lengths equal to plate thickness at the hot spot: Evaluation of stresses at mid-side points or surface centres respectively, i.e. at two reference points **0.5 t** and **1.5 t**, and linear extrapolation (eq. 2.9).

$$\sigma_{hs} = 1.50 \cdot \sigma_{0.5 \cdot t} - 0.50 \cdot \sigma_{1.5 \cdot t} \qquad (2.9)$$

4) Fine mesh with element length of not more than 4 mm at the hot spot: Evaluation of nodal stresses at three reference points **4 mm**, **8 mm** and **12 mm** and quadratic extrapolation (eq. 2.10).

$$\sigma_{hs} = 3 \cdot \sigma_{4\ mm} - 3 \cdot \sigma_{8\ mm} + \sigma_{12\ mm} \qquad (2.10)$$

5) Coarse mesh with higher-order elements having length of **10 mm** at the hot spot: Evaluation of stresses at the mid-side points of the first two elements and linear extrapolation (eq. 2.11).

$$\sigma_{hs} = 1.5 \cdot \sigma_{5\ mm} - 0.5 \cdot \sigma_{15\ mm} \qquad (2.11)$$

Figure (2.2)-12: Reference points at different types of meshing

Figure 5: Reference points and extrapolation equations according to IIW Fatigue Recommendations

By accurately reflecting the foundation's design and operational conditions in the model, the groundwork is set for robust fatigue evaluation. Good quality modelling allows to achieve precise results with optimal solution time and usage of computational resources, keeping the database compact and iterative design possible.

3. Large-Scale Data Processing for Fatigue Evaluation

Given the vast number of load cases — often in the range of thousands — an efficient data processing strategy is essential. This study employs advanced filtering techniques, and rainflow cycle counting, to reduce computational effort while maintaining result accuracy.

Rainflow cycle counting is used to identify and quantify stress cycles from complex load histories. The combination of these techniques allows for a comprehensive evaluation of fatigue damage while optimizing solution time and storage requirements.

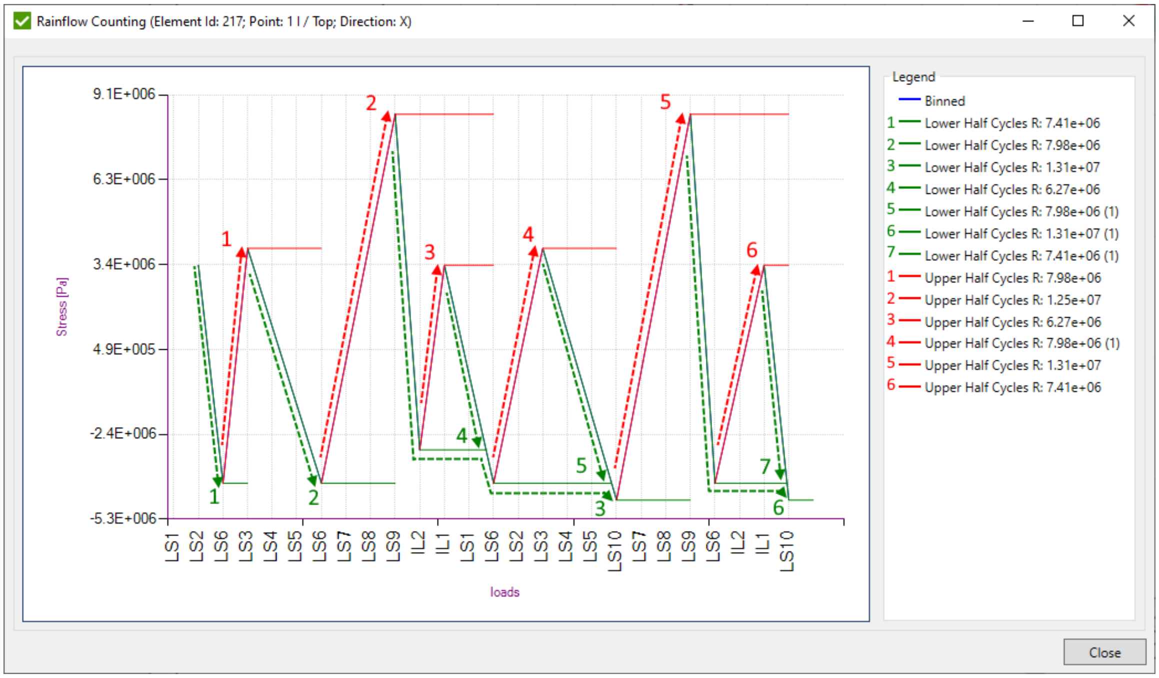


Figure 6: Rainflow counting method applied to stress cycles in floating offshore wind platform fatigue analysis.

Rainflow Counting method is used to determine the number of fatigue cycles that is based on a load-time history. It is used in the analysis of fatigue data in order to reduce a spectrum of varying stresses into a set of simple stress reversals. This simplification allows the number of cycles until failure of a component to be determined for each rainflow cycle using either Miner's rule to calculate the fatigue damage.

This automation ensures consistent and repeatable fatigue assessments, which are critical for certification and design optimization.

4. Interpretation of DNV RP-C203 for Fatigue Assessment

Compliance with DNV RP-C203 requires a detailed understanding of fatigue calculation methodologies, including S-N curves, stress range classifications, and damage accumulation rules. This section explores the selection of proven calculation methods for floating structures, considering their unique loading characteristics.

The appropriate S-N curves are selected based on material properties and weld classifications. Stress ranges are determined for every loading case by finite element analysis. Damage accumulation is assessed using Miner’s rule, with adjustments for different stress directions and variable loading.

The S-N curves are specified by the standard and take into account the type of the material, the connection type, the stress direction and the surrounding environment. As an example, see the S-N curves for the air environment from DNV-RP-C203 (2024):

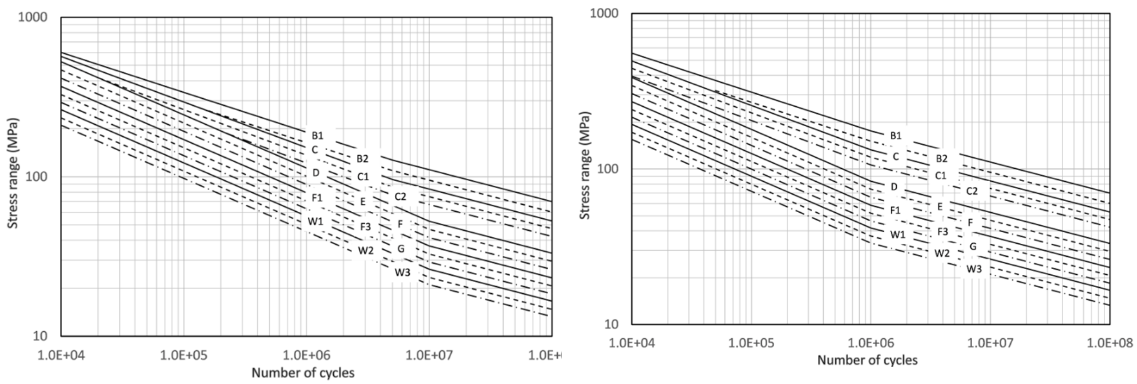


Figure 7: S-N curves in air and seawater with cathodic protection for different structural categories, illustrating fatigue resistance across varying conditions. Left figure: S-N curve for air, right figure: S-N curve for seawater

S-N category depends on the type of constructional detail (non-welded, welded) and stress direction (parallel to the weld, perpendicular to the weld and shear). In the finite element model, the required information is missing and as a result, the task of setting a classification can be time-consuming. Advanced FEA automation tool Weld Finder that works as a simultaneous extension to the popular finite element analysis interfaces is utilized to determine the welds, orient the stresses into the weld directions, and define a proper classification according to DNV-RP-C203: weld lines are detected by analyzing mesh connectivity and treating every material change, property change, thickness change, contacts, or specified angle between neighboring elements. The two nearest elements to the weld line are then treated as “weld” (with a possibility to add connected when the mesh is extra fine) and stresses in these elements are reoriented into the weld direction. This allows the assignment of the proper S-N curve not only to each and every element that is representing the weld, but also taking into account the direction of stresses.

The interpretation of results involves comparing calculated fatigue life with design requirements specified in DNV RP-C203. Outputs of the finite element analysis and parameters of the model are used as variables for the calculation core that interprets the formulas of the standard and automates the evaluation process for every loading case and structural part of the finite element model. This approach allows to evaluate not only the selected parts or cases, but complete design model under significant amount of loads in an automated way. Governing load analyses are then conducted to identify the most influential conditions affecting fatigue life, providing insights for design improvements.

5. Result Documentation and Collaboration to Achieve Certification

The final stage of the analysis focuses on structuring the results into a comprehensive documentation framework. This includes fatigue damage reports, sensitivity analyses, and optimization recommendations. Clear and detailed documentation is essential for certification and for communicating findings to stakeholders.

Reports are structured to provide a transparent and traceable record of the fatigue assessment process. They include detailed descriptions of the modelling approach, data processing techniques, and key findings. Sensitivity analyses highlight areas for potential design improvements, while optimization recommendations focus on enhancing the structural integrity and fatigue performance of the foundation. Optimization recommendations are defined by mapping the variables of the calculation core that allows to study multiple input scenarios in the single workflow without the need to run the finite element solver multiple times. Optimal design decisions are selected by achieving the degree of utilization that is lower than the threshold for every single welded joint separately.

Key findings of the fatigue assessment are displayed in a visual form of colored criteria plots and tabular data that is convenient for reporting or further postprocessing. Main outputs of the study are Fatigue Damage and Amount of Cycles. But intermediate results, like Stress Range, can also be included in the report. This makes the calculation results transparent, allows the surveyor to evaluate every detail in the process.

Collaboration is emphasized to ensure a successful and timely certification process. This involves sharing data and reports back and forward with certification bodies, design teams, and other stakeholders. Digital collaboration platform can be utilized to facilitate real-time communication and data sharing. This is a part of the study that will be further developed (alongside with AI methods) to align all parties involved in the process and deliver effective instruments for the engineers to not only present the results but receive an instant feedback during the design, manufacturing and operations.

6. Conclusion

By integrating environmental data acquisition, finite element modelling and analysis, and advanced fatigue check techniques, this study provides a structured methodology for assessing and improving the structural integrity and fatigue performance of floating offshore wind turbines and foundations. The proposed approach not only ensures compliance with DNV RP-C203 but also contributes to the development of more resilient and sustainable offshore wind energy infrastructure.

The insights gained from this study have broader implications for the design and maintenance of floating offshore structures, offering a pathway to enhanced operational efficiency and reduced lifecycle costs.

Future work will explore the integration of real-time monitoring data and machine learning techniques to further refine fatigue assessments and optimize structural designs. It will also be focused on predictive maintenance and inspections that will allow more effective operations and management of the offshore assets, which will be applicable but not limited to the floating wind turbine foundations. And finally, further studies and development will empower all stakeholders of the process with tools for effective digital collaboration.

7. References

[1]"DNV-RP-C203 Fatigue design of offshore steel structures," *DNV*, 2024. https://www.dnv.com/energy/standards-guidelines/dnv-rp-c203-fatigue-design-of-offshore-steel-structures/