C2Wind

White Paper

The Fully Restrained Monopile for Offshore Wind

Concept review

REPORT

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Section	Summary of Changes (latest revision only)

Disclaimer

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List of Abbreviations

Abbreviations and variables	
Abbreviation	**Meaning**
ALS	Accidental Limit State
CfD	Contracts for Difference
DLC	Design Load Case
FE	Finite Element
FEED	Front End Engineering Design
FLS	Fatigue Limit State
FRP	Fully-Restrained Platform
ibid.	From Latin ibidem (“in the same place”), it is used to save space in textual references to a quoted work which has been mentioned in a previous reference.
ILA	Integrated Load Analysis (i.e. the IEC Project Certification module, or the activities in this module – particularly load calculations).
LAT	Lowest Astronomical Tide
MAF	Modified Apparent Fixity
MBL	Minimum Breaking Load
MP	Monopile
RNA	Rotor-Nacelle-Assembly
SLS	Serviceability Limit State
TP	Transition Piece
ULS	Ultimate Limit State
WTG	Wind Turbine Generator (taken to be the RNA and its support structure in unison)

Executive Summary

The build-out of offshore wind in development zones with mid- to deep waters (60 to 100 meters) is challenged by the practical- and cost-efficient limitations of the current support structure technologies. Thus, harnessing the wind resources at mid- to deep-water sites in today's market is costly, and project profitability is challenged. Therefore, development zones in the mid- to deep water range represent a gap in today's offshore wind market.

The Fully-Restrained Platform (FRP) is a hybrid substructure & foundation concept targeting application in these mid- to deep-water sites, competing directly with floating foundation solutions. The FRP concept consists of a cylindrical centre-pile supported by a symmetrical mooring line arrangement anchored using piles driven into the seabed. The mooring line arrangement adds restoring forces and additional stiffness to the centre-pile, extending the application of the well-known Monopile (MP) support structure concept for deeper waters - harvesting benefits typically reserved for multi-legged support structures.

The present Concept Review document compiles the investigations and findings resulting from C2Wind's independent review of the FRP Monopile Technology. Key takeaways are provided below:

- Turbine dynamics, loads, mooring tension, anchor–soil interaction, and centre-pile flexibility are interdependent in the FRP foundation concept. Therefore, it was assessed with a fully integrated simulation model, alongside iterative optimisation to achieve the most weight- and cost-efficient design that meets all performance requirements.

- Mooring lines must remain in axial tension under all load cases throughout the asset's life, avoiding slack to maintain restoring action and provide the required centre-pile support. This requires continuous monitoring of cable loads during iterative design, guided by the centre-pile's horizontal deflection at the mooring interface.

- The FRP substructure and foundation concept is evaluated through a FEED-level benchmark against monopile (MP) and jacket foundations at a representative deep water North Sea site (-75 m LAT and harsh offshore conditions). Results indicate ~60% material savings versus MP and ~25% versus jacket solutions. The FRP concept also shows significantly reduced sensitivity to turbine standstill, lowering a key operational risk in offshore wind farms. While promising, challenges remain, including potential long-term losses in cable pretension.

The deployment of the FRP substructure & foundation concept at an industry scale is, however, challenged by a number of factors. Firstly, the deep-water sites and support structure sizes necessitate the largest installation vessels in the current-generation fleet, of which only a few exist. Secondly, the impact of potential soil creep and cable relaxation should be clarified in further detail to add confidence to the FRP concept.

1. The Deep-Water Challenge for Offshore Wind

A large portion of the global wind resources is located in areas with water depths exceeding 60 m. At these water depths, the most common substructure & foundation concepts of Monopile (MP) and Jacket are near their cost-effective limit, and it is relevant to explore alternative foundation concepts to harness wind energy at deep water sites.

Floating foundation technologies, targeting sites with mid- to very deep water depths, have been discussed for many years, but at the time of writing, the large-scale development of floating wind technology is still hindered by relatively high costs. A critical gap is currently present in the build-out of offshore wind, and cost-efficient foundation alternatives for mid- to deep-water sites are needed.

In response to the identified gap in the offshore wind market, Entrion Wind have introduced the Fully-Restrained Platform (FRP) foundation concept. It combines mooring line elements typically found in floating offshore technologies with the classical Monopile (MP) concept. The concept aims to provide a cost-efficient application of the MP technology at increased water depths. The technical deployment range of the FRP concept is estimated to be between 60 and 100 meters of water depth. In more shallow waters, classical foundation concepts are expected to be more cost-efficient than the FRP technology, whereas sites with water depths exceeding approximately 100 meters are reserved for other novel (e.g. floating) foundation concepts. According to [FRPUK], this corresponds to approximately 25% of the seabed area within the identified key market of the UK. The details of the FRP concept are presented in Section 2.

C2Wind has independently reviewed the FRP concept, and a detailed description of the methods and results of this review is provided in the present report. It addresses the potential of the FRP concept through highly detailed performance studies, benchmarking the FRP concept against commonly applied substructure & foundation concepts. The performance benchmarks are evaluated to a detail- and certainty level typically associated with Front-End-Engineering-Design (FEED) studies, involving fully Integrated Load Analyses (ILA), multiple foundation design iterations, based on detailed metocean conditional inputs.

The concept review report is structured in accordance with the following scheme:

- Section 2: General introduction to the FRP concept, incl. previous applications and concept outlook,
- Section 3: Introduction to C2Wind's FRP design philosophy, incl. assumptions and design performance metrics,
- Section 4: Detailed discussion of the FRP benchmark case study results comparing multiple foundation concepts,
- Section 5: Summary of the FRP concept review, including remaining challenges.

1.1 FRP Benchmark Study Introduction

The benchmark study of the FRP substructure & foundation concept compares the FRP performance to the substructure & foundation alternatives of the classical bottom-fixed Monopile (MP) and jacket concepts. Thus, the FRP performance benchmark considers:

- Pin-piled jacket,
- Bottom-fixed monopile,
- Fully-restrained platform monopile.

For the evaluation, a deep-water site with a seafloor elevation of -75 mLAT is considered. The metocean conditions assumed for the concept evaluations represent a generic North Sea site with challenging conditions. Geotechnical soil conditions, providing a likely representation of a North Sea site, are assumed for all studies of the FRP benchmark performance evaluation.

The FRP benchmark performance study evaluates the Ultimate-, Accidental-, Fatigue-, and Serviceability Limit States. All substructure & foundation concepts are designed and evaluated using C2Wind's state-of-the-art analysis framework, coupling the individual in-house developed tools of C2FLEX, C2MONDE, C2JACK, and C2TOWER, for load, MP, jacket, and tower design & verification, respectively.

For the benchmark study, a Wind Turbine Generator (WTG) with specifications matching the current generation is considered for all foundation concepts. That is, a rotor diameter of 236 m and an associated power output of 15 MW are considered in all base case studies.

The results of the FRP concept performance benchmark study are given in Section 4, providing normalised result comparisons across all three foundation concepts for load effects, tonnages, and standstill sensitivity.

Please note that the present report does not include a detailed presentation or validation of the mooring line attachment components, ensuring the centre-pile and mooring line interface, as the focus is placed on overall system performance and benchmarking instead of single components. This focus is chosen as the design of individual components may be suboptimized without jeopardising the validity of the present report.

Further, no detailed validation of the bolted flange connections has been included in the benchmark performance study. However, the low extreme- and fatigue load levels observed for the FRP substructure & foundation concept strongly indicate that bolted L-flange connections are feasible for use in the FRP concept, based on C2Wind's previous experience with detailed flange validation for comparable designs. However, for the MP substructure & foundation concept, the bolted L-flange is assessed to be near its maximum feasibility limit, based on the observed load levels.

2. Introducing the Fully-Restrained Platform Monopile Concept

The FRP substructure & foundation concept is introduced in the following, including an in-depth description of the concept and its operational principle, the immediate benefits, historical application of restrained support structures, as well as a brief concept outlook.

2.1 Concept Description

The FRP concept is designed to extend the applicability of the Monopile (MP) based foundation solution into water depths previously infeasible for this technology. Using restraining mooring lines, the application of the well-known MP foundation concept at increased water depths is enabled, providing an attractive foundation candidate for the build-out of offshore wind in mid- to deep water ranges.

2.1.1 Primary Components

The primary components of the FRP substructure & foundation concept are sketched in Figure 2-1 and Figure 2-2.

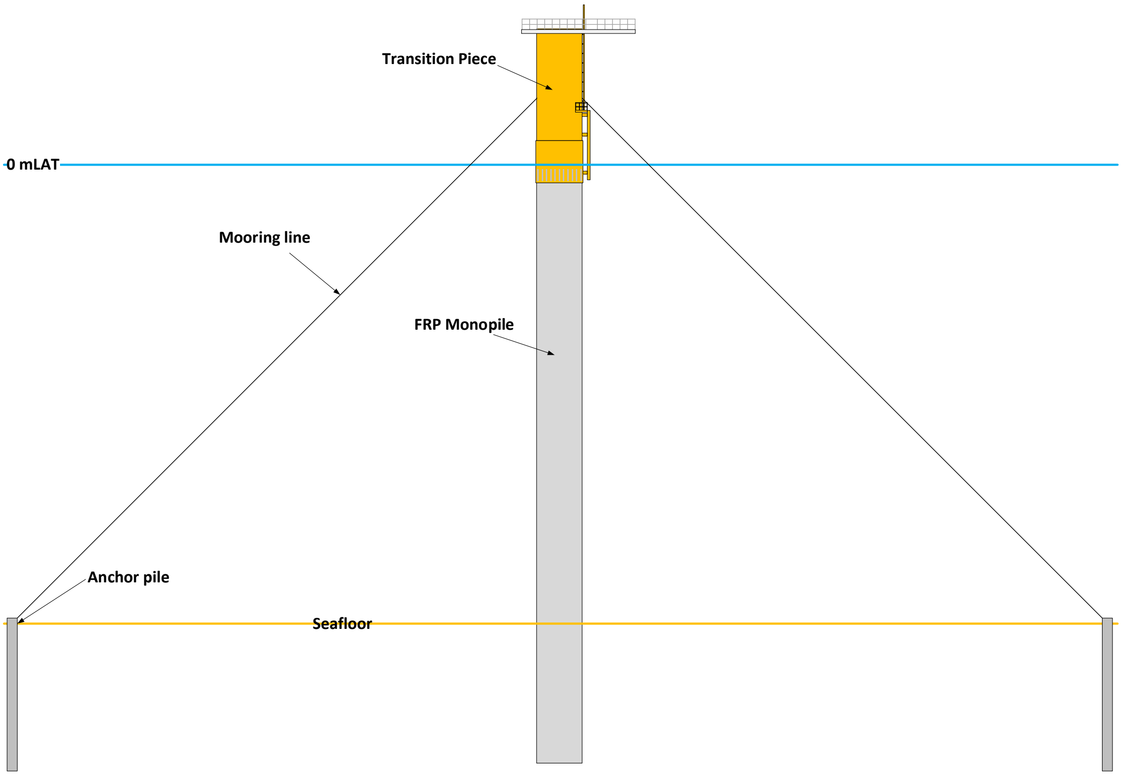

Figure 2-1: Illustration of the FRP substructure & foundation concept evaluated in the present report. A more detailed view of the Transition Piece and mooring line interface can be seen in Figure 2-2.

The following primary structural elements are used in the substructure & foundation concept:

- Transition Piece,
- FRP centre-pile,
- Pretensioned mooring lines,
- Anchor piles.

Using a number of anchoring piles and mooring lines, the slender centre-pile is supported by pretensioned mooring lines attached to the centre-pile at a predetermined elevation above the sea surface. The interface between the centre-pile and the mooring lines is secured through a mooring line attachment component found in the transition piece. Each mooring line is connected to an anchor pile using a pinned connection, ensuring that the mooring line carries loads primarily as pure tension, with negligible bending and/or shear at the anchor interface. Both centre-pile and anchor piles are driven into the seabed using an impact hammer or more novel methods like vibro-driven pile installation. A detailed view of the transition piece is given in Figure 2-2.

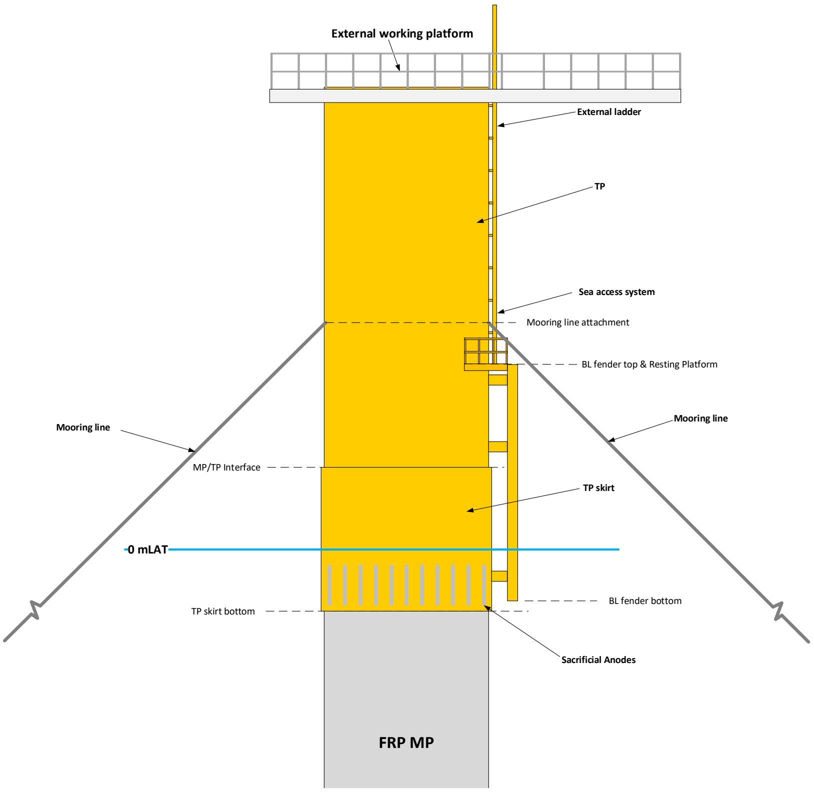

Figure 2-2: Illustration of the transition piece and mooring line interface of the FRP concept substructure & foundation.

The FRP substructure & foundation concept uses a number of mooring lines, arranged in a symmetrical pattern around the centre-pile. However, to attain some redundancy of the restraining system in the case of cable failure, it is common practice to use a cable configuration featuring at least two individual mooring lines for each anchor pile. Additionally, a multi-cable configuration of the mooring line system may reduce the size of the individual cables, which could make the concept more cost-efficient.

The Transition Piece (TP) is bolted to the MP, and the WTG tower is attached to the TP using a bolted L-flange connection. The TP includes a skirt overlapping the MP. Corrosion protection is ensured using sacrificial anodes in combination with the use of duplex coating systems.

2.1.2 Hybrid Approach

The FRP substructure & foundation concept mixes the known technology of the bottom-fixed MP with a mooring line system most commonly associated with floating applications. As a result, design and validation of this hybrid concept rely on a mixed set of standards and guidelines, supporting both classical substructure & foundation concepts and mooring line elements found in novel floating foundation technologies. Relevant design standards and guidelines for the design and validation of an FRP substructure & foundation concept are detailed in Section 3.1.

2.1.3 Operating Principle

In the FRP substructure & foundation concept, the bottom-fixed centre-pile is supported by a number of mooring lines at a predefined interface elevation. Each mooring line is anchored to the seafloor using anchor piles, installed symmetrically at a predefined radial distance around the centre-pile. Through pretensioning of the mooring lines, the horizontal stiffness of the foundation system is significantly improved. The mooring line system efficiently prevents dynamic excitations of the support structure, resulting in significant ultimate- and fatigue load reductions. Lateral and overturning loads induced by wind, wave, and current actions on the support structure are resisted through a combined response of monopile bending stiffness and axial cable forces.

Under lateral loading, the FRP centre-pile undergoes global bending and rotation at the seabed level, resulting in different elongations of the mooring lines. The mooring lines on the leeward side experience increased axial tension, providing a restoring force that counteracts FRP monopile rotation and reduces bending moments in the centre-pile. Conversely, windward cables experience a reduction in axial force but remain in tension due to the imposed pretension. This load redistribution mechanism leads to the coupled system dynamics of the FRP substructure & foundation concept, in which overturning moments are partially resisted by axial forces in the mooring lines rather than solely by monopile global bending and soil reactions.

The load distribution throughout the substructure & foundation concept is significantly altered by the use of pretensioned mooring lines, allowing for a more slender centre-pile supporting reduced bending load effects from the mooring line attachment elevation to the seabed, when compared to an unsupported MP substructure & foundation concept.

The FRP substructure & foundation concept is designed to ensure that all mooring lines remain in a state of positive axial tension under all governing load combinations. That is, a predefined pretension is applied to the mooring lines during installation and must be maintained throughout the lifetime of the assets to ensure the continuous engagement of the restraining-cable system. The application of mooring-line pretension eliminates slack in the cables and prevents the scenario of load reversals under cyclic environmental- and operational loading. Maintaining a minimum axial tension in all mooring lines ensures a beneficial contribution to the overall system dynamics from the onset of lateral displacement and rotation of the centre-pile, thus providing a predictable and linear structural response within the serviceability- and ultimate limit state envelopes.

Selecting an appropriate pretension level ensures that the global structural behaviour of the restraining system may be represented using equivalent members, modelling using linear elastic beam theory. That is, the pretensioned mooring lines act as equivalent tension-only members in which axial forces in the cables contribute to lateral stiffness and overturning resistance.

If the axial force in any mooring line is predicted to approach zero for any given load combination, nonlinear geometrical effects should be taken into account, and a more advanced modelling approach is required. Maintaining sufficient axial cable tension of all mooring lines for any load combination is thus fundamental to ensure an effective functionality of the FRP substructure & foundation concept as well as modelling accuracy. As a result, the minimum axial cable tension of the mooring lines across all load combinations is identified as a primary design driver of the FRP concept.

2.1.4 Immediate Benefits

The FRP substructure & foundation concept presents itself as a cost-efficient foundation candidate, well-positioned to support the build-out of offshore wind in development zones with increased water depths, where classical MP and jacket foundation concepts, as well as floating foundations, have failed to provide cost-efficient solutions. Building on well-known principles from the classical MP foundation concepts, the FRP substructure & foundation concept may benefit from already implemented industry-standard fabrication, transport, and installation methods, which is a significant benefit of the concept, and a non-negligible factor as to why a cost-efficient foundation solution may be offered for the mid- to deep water sites within a foreseeable time horizon.

C2Wind considers the FRP substructure & foundation concept a cost-efficient foundation candidate, capable of supporting the current- and next generation of offshore Wind Turbine Generators (WTG)s for water depths in the mid- to deep range of 60 m to more than 100 m. Without any true competition from alternative foundation concepts for this water depth application range, and considering the small number of solution providers of the mooring line arrangement, the cost associated with initial application is, however, likely to supersede those most commonly seen for the application of classical foundation concepts. Furthermore, the installation of pile support structures approaching a length of 100+ m may prove a significant challenge considering the capabilities of the current-generation installation vessels.

2.2 Historical Concept Application

Cable-stayed support structures have been used in the past across both the oil and gas, as well as the wind industry, as exemplified in the following.

The FRP concept is to some extent considered a derivative from previous use of restrained support structures within the oil and gas industry. On multiple occasions, large water depths have necessitated restraining cables to ensure structural stability of the platforms and supporting structure. One of the earliest applications of a restrained platform concept was the Lena Guyed Tower platform, installed in the Gulf of Mexico in 1983 and decommissioned in 2020. For the Lena Guyed Tower platform, 20 mooring lines ensured the stability of the platform at the installation position, featuring a water depth of 1,000 ft (~305 m), cf. Figure 2-3.

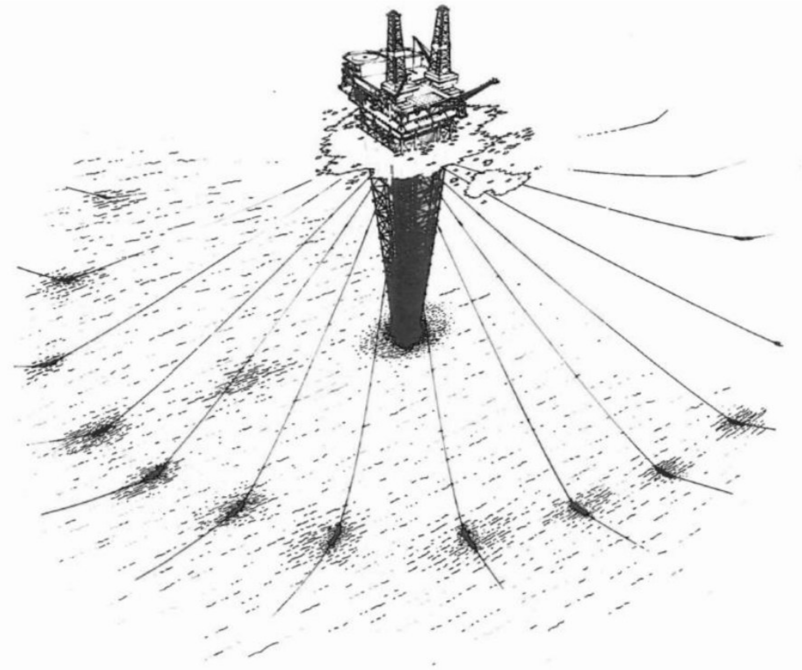

Figure 2-3: Lena Guyed Tower platform installed in 1983 in 1,000 ft of water, utilising mooring lines to ensure the stability of the platform. Reproduced from Figure 2 of [LENA].

For the Lena platform, pretensioning of the guyed wires was achieved by the use of clump weights attached to the end of each mooring line. During its installation, the Lena platform was considered vulnerable to storm conditions until the initial four mooring lines were installed and pretensioned, as a result of insufficient structural stability in harsh environmental conditions in the non-restrained configuration of the initial installation phase. This could indicate that the use of cable-stayed support structures in an offshore environment is highly dependent on meticulous installation planning and that installation windows for these substructure & foundation concepts may be reduced when compared to more traditional foundation concepts. As a result of these observations for the installation of the Lena Guyed Tower, a design load case representing this scenario is proposed as part of the Design Load Cases (DLC) introduced in Section 3.5.1.

In the wind industry, the use of restrained support structures has also been seen, as most recently demonstrated in the cable-stayed WTG tower technology applied in the onshore wind farm of Viinamäki, Finland. Here, five Vestas V150-4.2 MW turbines with a record-setting hub height of 175 m have been installed with cable-stayed towers as seen in Figure 2-4.

Figure 2-4: Cable-stayed tower for Vestas V150-4.2 MW as installed and operated in the Viinamäki wind farm in Finland. Reproduced from [WFBOP].

Somewhat similar to the FRP substructure & foundation concept, enabling the use of an existing foundation technology at increased water depths, the aim of the cable-stayed WTG tower concept is to reach increased hub heights with a greater wind potential, relying on industry-standard technology. It is noted that the cable-stayed wind turbine towers are not widely used in the onshore wind industry, potentially indicating low margins, a limited market, or both.

2.3 Concept Outlook

As the FRP substructure & foundation concept can be considered an evolution of the classical MP concept, it is clear that, despite being a newly developed concept, it may benefit from economies of scale and widespread industry knowledge established through decades of experience, gained through the deployment of MP foundations. Utilising well-established and globally spread fabrication facilities presents a major upside to the FRP concept when compared to other foundation concepts for deep-water sides, including floating foundations. This does, however, mean that a lower learning rate, typically measured as the cost reduction for a doubling of produced capacity, should be considered for the FRP concept as compared to other deep-water foundation concepts, largely given by the lower initial production cost gained from the use of a well-established fabrication industry.

The potential of the FRP concept has been addressed for the United Kingdom (UK) key market, cf. [FRPUK]. Given the high number of development areas with water depths surpassing the current cost-efficient limit of the MP and jacket substructure & foundation concepts, combined with an attractive wind climate, the FRP concept seems particularly suitable for the UK market. Additionally, the restructuring of the Contracts for Difference (CfD) of recent UK allocation rounds has further increased the interest in wind development in deeper waters, through a strengthened outlook for the affected project. In [FRPUK], an addressable market volume exceeding 10 GW by 2040 is identified across approximately 220 areas, identified as potential candidates for the build-out of offshore wind in the UK. It is noted that more than half of the evaluated projects are located in deep water areas with water depths exceeding 80 m. As reported in [FRPUK], multiple projects have already included the FRP technology in their submitted consent documentation, indicating a justified interest from the market.

Critical infrastructure supporting the build-out of offshore wind is tailored to classical substructure & foundation concepts like the MP and jacket concepts. Thus, the development of offshore wind at deep-water sites could potentially challenge the capabilities of the most common transport and installation vessel in operation today. Securing investments in next-generation installation vessels relies on firm market potential before investments, to the scale required to support large-scale deployment of the FRP concept, can be justified. Getting developer consent and establishing credible market potential to secure the required investments in critical support infrastructure is identified as a major remaining challenge in the large-scale roll-out of the FRP concept within offshore wind.

3. Engineering Excellence: Design Philosophy

The methodologies and assumptions suggested for the design and validation of an FRP substructure & foundation are introduced in the following. Further, key design performance metrics suggested for the qualitative assessment of the system performance are identified.

3.1 Design Standards

The FRP substructure & foundation concept is not covered by a dedicated design standard or a single codified framework covering all design aspects. Instead, the concept combines characteristics of both bottom-fixed and mooring systems of floating offshore wind structures as covered in [IEC613] and [DNV0126], and [DNV0119], respectively.

As a result, the evaluation of an FRP substructure & foundation concept requires a hybrid approach, combining relevant design principles originating from multiple standards. An overview of the applicable design standards is given below:

- [IEC613]: IEC-61400-3-1 – Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines,
- [DNV0126]: DNV-ST-0126 – Support structures for wind turbines,
- [DNV0119]: DNV-ST-0119 – Floating wind turbines,
- [DNVC212]: DNV-RP-C212 – Offshore soil mechanics and geotechnical engineering,
- [DNVC203]: DNV-RP-C203 – Fatigue design of offshore steel structures,
- [EN1993]: EN 1993-1-6 – Design of steel structures – Strength and stability of shell structures,
- [DNVC401]: DNV-OS-C401 – Fabrication and testing of offshore structures.

3.2 Design Assumptions

A simplified modelling of the pretensioned mooring line arrangement can be used for the analysis of the FRP substructure & foundation concept. Within their pretensioned domain, the mooring lines may be idealised as axial elements with a linear force-displacement relation, and their stiffness contribution to the overall global response may be represented using equivalent axial stiffness terms.

This modelling assumption is validated as illustrated in the example of Figure 3-1, in which the centre-pile deformations from a complex Finite Element (FE) representation of the full mooring line arrangement are compared to the deformation results of a simplified FE model, applying the equivalent axial stiffness modelling of the pretensioned mooring line arrangement using linearised horizontal springs.

As seen in the example of Figure 3-1, identical results are found, justifying the suggested approach for the modelling of the pretensioned mooring line arrangement. However, it is noted that the equivalent axial stiffness modelling of the mooring lines is not capable of accurately representing cable slack scenarios, calling for close monitoring of mooring line tension for all design load combinations.

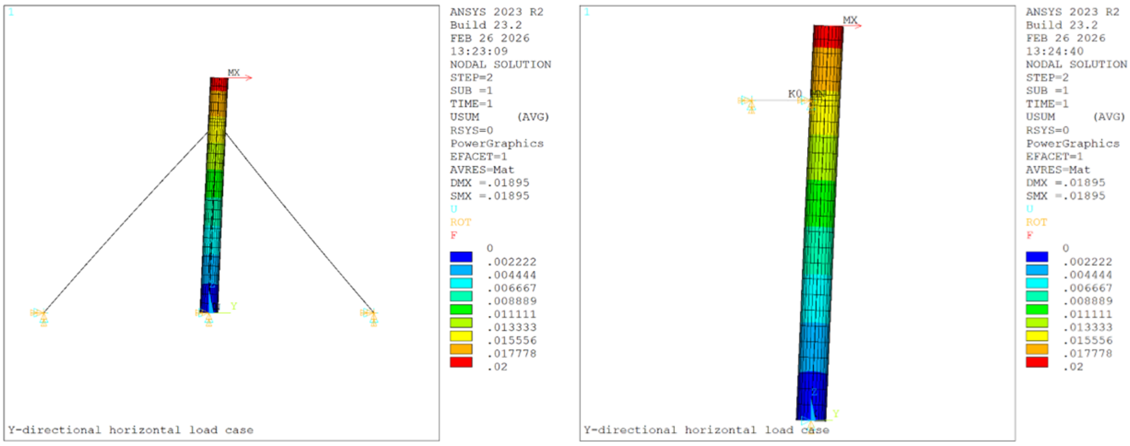

Figure 3-1: Validation example comparing the deformation result of the FRP centre-pile of a detailed FE model, including full representation of the pretensioned mooring line arrangement vs. the results of an FE model applying the suggested equivalent axial stiffness representation of the pretensioned mooring lines.

A cable-stayed support structure like the FRP substructure & foundation concept is likely to be affected by long-term pretension losses. Long-term pretension loss may be caused by a number of phenomena, such as cable relaxation, soil creep, and long-term anchor pile settlement. It is recommended that such highly detailed analyses are reserved for a detailed design study, as they pose requirements for highly detailed design inputs, typically not well captured for initial FEED studies. It is noted that a detailed investigation of the long-term pretension loss and the phenomena leading to this has not been accounted for in the present concept evaluation, but it is underlined that they must not be neglected in advanced project stages. Pretension losses related to potential soil creep may be countered in the design phase by increasing the lengths of the anchor piles or by continued tension monitoring and re-tensioning of mooring lines in the operational life cycle stage.

The presence of platforms, boat landing, and other secondary steel items and appurtenances should be accounted for in the evaluation of an FRP substructure & foundation concept. This may be achieved using simplified representations of external appurtenances, including mass contributions, in order to attract wave loading, ensuring representative hydrodynamic load effects are captured. This includes hydrodynamic load modelling on the mooring line arrangement.

Additionally, the mooring line arrangement is assumed to be placed above sea level to accommodate the use of the commonly applied MP and Transition Piece (TP) concepts for the centre-pile in combination with an interface module in the TP. Besides allowing for the use of well-known technologies, the placement of the mooring line interface module above sea level will benefit installation, inspection, and service & maintenance.

Soil performance has a direct impact on the key design driving parameter of axial cable tension of the mooring lines in the FRP concept. This may include the phenomenon of soil layer creep, which may only be determined through detailed geotechnical surveys and laboratory assessments of on-site samples, often not associated with the detail level of soil inputs used in early project stages. This may suggest an increased geotechnical focus and effort for development zones, considering the use of FRP support structures. For the performance benchmark study, a high-fidelity geotechnical model, describing soil creep with great detail, is not considered, but given the potential design criticality, this may need to change for future FRP concept assessments. In case significant pretension losses can be attributed to the soil creep phenomenon, anchor pile lengths may be increased as a countermeasure.

3.3 Design Constraints

When designing a support structure of the FRP substructure & foundation type, the most optimal trade-off between centre-pile flexibility and mooring line arrangement stiffness is sought. This iterative design process should, however, be constrained by a predetermined maximum allowable cable size in order to yield feasible support structure configurations. Further, the common practice of size and weight restrictions of individual MP, TP, pile cans, and cable sizes to suit fabrication and supply chain is recommended.

3.4 Design Philosophy

Design load effects, dynamic behaviour of the foundation, and mooring line arrangement stiffness are interdependent parameters of an FRP. Thus, an iterative design process, as illustrated in Figure 3-2, is recommended for an FRP substructure & foundation assessment, and fully integrated load analyses must be applied as part of the evaluation.

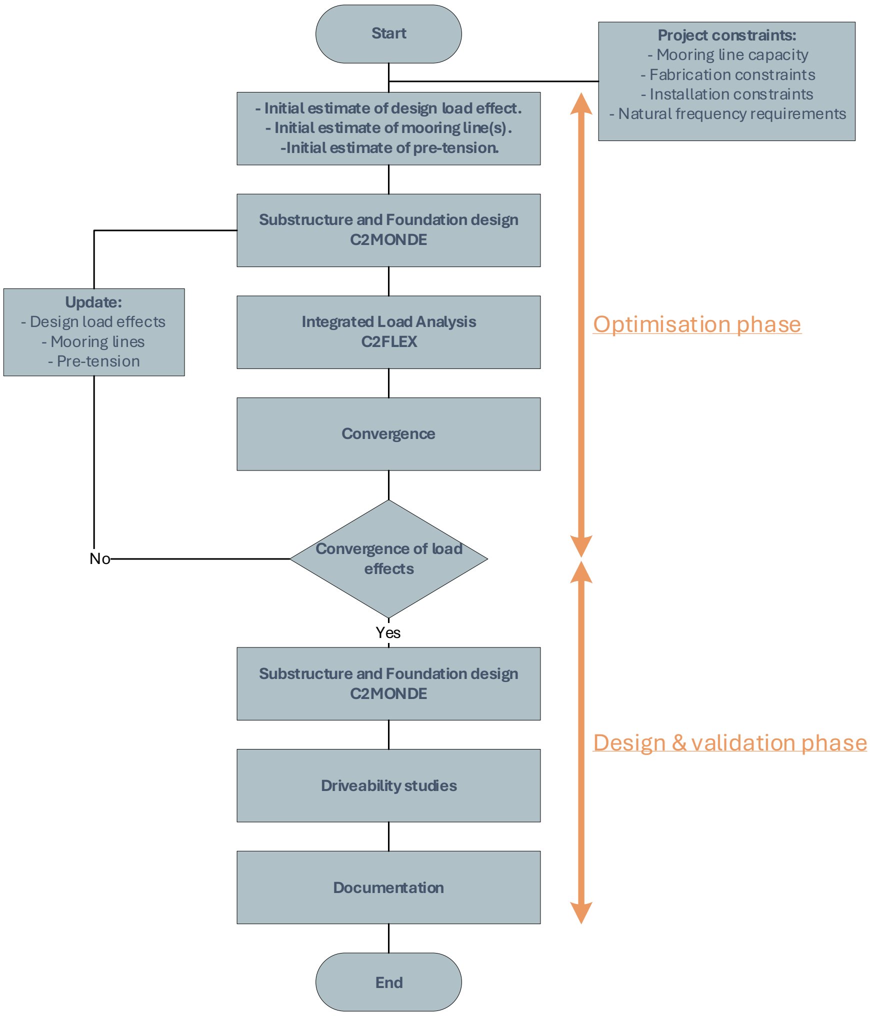

Figure 3-2: Flow chart describing the iterative design process suggested for the design & validation of an FRP substructure & foundation concept.

With reference to Figure 3-2, the proposed design process has been divided into the two main phases of *Optimisation* and *Design & validation*.

In the initial optimisation phase, an iterative process is recommended for the evaluation of the interaction between centre-pile flexibility, mooring line pretension & axial stiffness, and soil response, in order to determine an optimal configuration capable of satisfying the design requirements. In this process, the design performance metrics, introduced in detail in Section 3.4.1, are meticulously monitored to ensure feasible performance of the FRP substructure & foundation concept. An appropriate pretension level of the mooring lines is established to ensure continuous axial engagement of all mooring lines across all design load combinations. The optimisation phase could be based on the ultimate- and fatigue limit states, whereas the detailed assessment of the serviceability- and the accidental-, and installation limit states may be reserved for the design & validation phase discussed next.

In the subsequent design & validation phase, the final verification of the FRP centre-pile and the anchor piles should be performed. This includes a final ILA verification to confirm the compatibility between the FRP substructure & foundation and the WTG, to ensure that any stiffness updates of the final design iteration do not significantly influence the turbine load envelopes or dynamic behaviour of the combined system. Naturally, a final assessment of the key performance metrics and design requirements is to be performed and reported. Further, relevant accidental- or serviceability limit states could be evaluated as part of the design & validation phase if not addressed in the initial optimisation phase. It is recommended that an assessment of the pile driveability is performed as part of the design & validation phase as well.

3.4.1 Design Performance Metrics

Sufficient structural integrity must be demonstrated for all design situations covered by the limit states of ULS and FLS, as part of the initial Optimisation phase, supplemented by ALS and SLS for the detailed Design & validation phase. The demonstration of sufficient structural capacity should follow the methodologies outlined in the codified design standard framework outlined in Section 3.1. This includes the verification of various failure modes, including checks of primary steel, soil capacity, and natural frequency. For the verification of the mooring line arrangement, a comparison between the maximum axial cable tension and the Minimum Breaking Load (MBL) is required to secure the structural integrity of the mooring lines when subjected to extreme load combinations associated with ULS and ALS.

As discussed in Section 2.1.3, the pretension of the mooring lines is fundamental for the functionality of the FRP substructure & foundation concept, and it is identified as a key design performance metric as a result. To secure the restoring forces and resistance to lateral- and overturning load effects, the mooring lines must remain in a state of axial tension for all load combinations across all design limit states. That is, the combined effects from environmental & operational loading, centre-pile deflection, plastic deformation of soil and pile anchors, as well as installation tolerances, must never result in a state of slack in the mooring line cables. Thus, a slack prevention criterion is identified as a key performance metric, which should be monitored for any load combination across all evaluated DLCs. The mooring line tension load is affected by the centre-pile flexibility through the horizontal displacement at the mooring line interface elevation. That is, a flexible FRP centre-pile will displace more than a stiffer centre-pile, affecting the axial tension of the mooring lines for various load combinations. For any given mooring line configuration, an allowable limit for the horizontal deformation at the interface elevation may be defined. As part of the iterative design optimisation process, the horizontal deformation at the interface elevation should be used as a design driving constraint, ensuring that the resulting centre-pile configuration is compatible with the predefined mooring line configuration. Following this approach, the horizontal deflection of the mooring line interface may be used as a driving parameter to either stiffen or soften the FRP centre-pile to achieve a feasible FRP configuration. The horizontal deformation of the centre-pile at the mooring line interface elevation thus becomes a highly important design performance parameter, ensuring that the FRP substructure & foundation concept is feasible and designed to operate within its allowable limits.

3.5 Integrated Load Analysis (ILA)

The inherent interdependency between load effects, mooring line configuration, and centre-pile flexibility dictates the use of a fully integrated ILA approach in the design & verification of an FRP substructure & foundation concept. For an accurate representation of an FRP-supported offshore wind turbine, the following areas must be well-described in the ILA simulation model:

- Aerodynamic loading from the rotor and control system,
- Soil-structure interaction,
- Axial tension/stiffness contribution provided by the mooring lines,
- Hydrodynamic wave and current excitation.

For the FRP performance benchmark study of Section 4, C2Wind's ILA framework, designed around the aeroelastic load modelling tool of C2FLEX, is utilised. C2FLEX is a computer software designed to model the dynamic behaviour of horizontal-axis wind turbines operating in specified wind conditions, including simulated turbulent wind and waves. The software operates in the time domain and produces time series of simulated loads and deflections.

The FRP substructure & foundation concept is modelled in C2FLEX using the in-house developed add-on tool of C2FlexFund, capable of simulating stiffness and wave load effects for a structural model based on beam elements. C2FlexFund interfaces with C2FLEX in the time domain, enabling a fully coupled aeroelastic simulation model of the combined WTG and substructure & foundation system.

An example view of the turbine simulation model from C2FLEX is given in Figure 3-3, whereas an illustration of the FRP concept from C2FlexFund is given in Figure 3-4. In the simulation model used for the ILA, the soil-structure interaction, for both the centre-pile and the anchor piles, can be represented using mudline super elements or the Modified Apparent Fixity (MAF) model.

Figure 3-3: Illustration of a C2FLEX Simulation. The waves can be seen from a 30° direction compared to the turbine yaw direction.

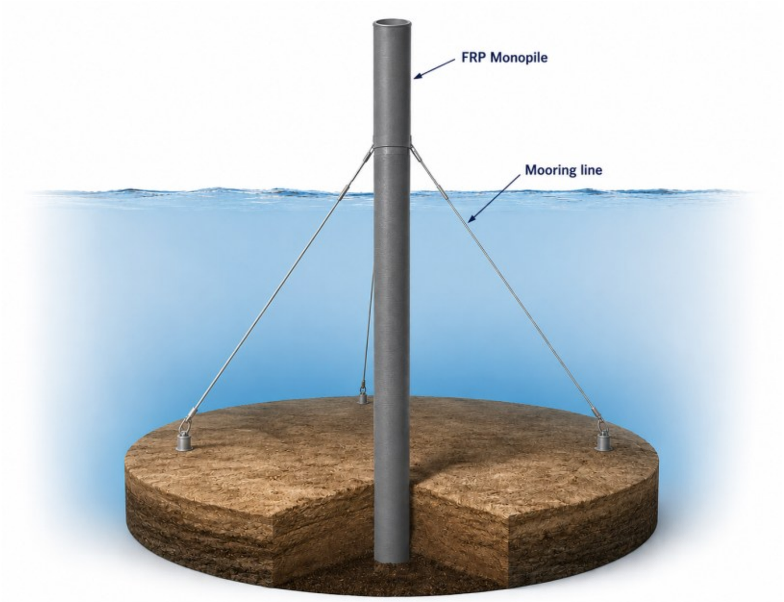

Figure 3-4: Visualisation of an FRP substructure & foundation concept. The sub-soil part of the anchor piles is modelled using mudline super elements, whereas the sub-soil part of the FRP centre-pile is modelled using a Modified Apparent Fixity (MAF) element.

3.5.1 Design Situations and Design Load Cases

To evaluate the performance of an FRP substructure & foundation concept, the following limit states should be assessed:

➢ Ultimate Limit State (ULS)	- Defining the maximum load-carrying resistance of the structure.
➢ Fatigue Limit State (FLS)	- Defining the resistance against fatigue failure caused by cyclic loading.
➢ Accidental Limit State (ALS)	- Defining the maximum load-carrying resistance of the structure for rare accidental loads, accounting for a potentially damaged structure.
➢ Serviceability Limit State (SLS)	- Defining tolerance criteria covering normal use cases.
➢ Installation checks (INS)	- Verification of pile installation scenarios.

The above-listed design situations should be evaluated through the simulation of various Design Load Cases (DLC)s collected from [IEC613] and [DNV0119], applicable to the hybrid FRP substructure & foundation concept. The DLCs cover both operational- and parked turbine configurations, for both normal- and extreme site conditions, including fault, shutdown, and installation events. A summary of the DLCs applicable for a preliminary performance assessment of a support structure of the FRP substructure & foundation type is given in Table 3-1.

With reference to the observed vulnerability of the Lena guyed tower platform during the installation phase, cf. Section 2.2, an installation scenario without restraining mooring lines, is proposed as part of the DLCs for the design & validation of an FRP support structure.

DLC	Limit state	Description
		In-place scenario
1.2 [IEC613]	FLS/ULS	Power production with continuous turbine operation, simulated with consideration of full directional wind-wave misalignment.
1.4 [IEC613]	ULS	Power production with directional change.
2.2 [IEC613]	ULS	Power production with pitch fault modelling, including shutdown.
2.3 [IEC613]	ULS	Power production under extreme operating gust conditions, including shutdown and grid disconnection simulation.
6.1 [IEC613]	ULS	Parked turbine configuration subjected to 50-year environmental conditions, including grid loss and yaw error modelling.
6.4 [IEC613]	FLS/ULS	Parked (standstill or idling) outside the operational wind speed range of the WTG.
7.2 [IEC613]	FLS/ULS	Parked with fault condition modelling.
F 1.2 [DNV0119]	ALS	Power production simulating normal turbine operation for an ALS scenario representing breakage of a single mooring line.
F 2.2 [DNV0119]	ALS	Idling turbine configuration subjected to 1-year extreme environmental conditions for an ALS scenario representing breakage of a single mooring line.
		Installation scenario
8.2 [IEC613]	ULS	Unsupported FRP centre-pile, pre-installation and tensioning of the mooring line arrangement, and pre-installation of WTG tower, subjected to 1-year extreme environmental conditions.

Table 3-1: Summary of DLCs to be considered for the evaluation of a concept support structure of the FRP-type.

Through the evaluation of the DLCs of Table 3-1, the preliminary foundation performance may be assessed using the design performance metrics identified in Section 3.4.1. For a more complete evaluation of the FRP concept, the preliminary assessment could be supplemented by various installation, accidental, and tolerance checks, as this will further strengthen confidence in the FRP substructure & foundation performance.

A special-case design situation is defined for the evaluation of an FRP substructure & foundation concept to demonstrate sufficient redundancy and robustness of the FRP concept and mooring line arrangement in the case of a cable failure. That is, the ALS case of a 1-year extreme sea state is considered for the partly damaged FRP structure, for which a single mooring line is assumed broken. Following the cable breakage, 1-year environmental conditions are applied in the most onerous load direction, and the horizontal deflection of the centre-pile and the axial tension of the mooring lines are monitored to ensure that no cable slack is observed, even for the partially damaged structural configuration. As a result of the shift in the force equilibrium of the mooring line arrangement, it is vital to investigate both overloading of the remaining cable on the damaged side, as well as the potential risk of cable slack for the opposite cables.

Appropriate partial factors for both material and loads, used in the various limit state assessments, can be collected from the applicable design standards, i.e. [IEC6141], [DNV0119], and [DNV0126]. It is noted that a partial material factor for soil as high as 1.7 should be used for the ULS assessment of the anchor piles of the FRP substructure & foundation concept as per [DNV0119], as load redistribution from one anchor pile to another is not possible for this concept.

3.6 Global Structural Analysis Model

FRP centre-pile and anchor piles should be evaluated using a high-fidelity structural analysis model, applying detailed soil-structure modelling using non-linear soil-reaction springs and accurate structural modelling, e.g. using FE methodologies. For the FRP performance benchmark study of Section 4, the detailed design & verification of the anchor piles and centre-pile rely on the in-house developed structural analysis tool of C2MONDE. C2MONDE is C2Wind's design software for analysis of the overall WTG structure and structural design, verification, and optimisation of monopile-type substructure & foundation designs, including anchor piles.

The C2MONDE analysis model consists of a 2D FE model representing the components of MP, TP, and tower using beam elements, applied for all basic analyses. The soil-structure interaction is accounted for using discrete, non-linear soil-reaction springs. For advanced analyses, as per various code checks, C2MONDE relies on a number of supporting modules covering structural steel checks, pile-driveability, etc. Further, an additional contribution to the overturning bending moment is considered for ULS/ALS to account for the self-weight contribution originating from an out-of-vertical in-place configuration of the support structure, combining an assumed allowable installation tolerance with an accumulated permanent inclination for operation. Further, the additional vertical load originating from the pretensioned mooring line arrangement must be considered in the global structural analysis model, as the buckling capacity, natural frequency, and soil integrity may all be affected.

To ensure sufficient structural buckling capacity of the FRP centre-pile, the additional hydraulic pressure corresponding to an extreme wave passage should be accounted for as part of the structural capacity checks.

The fully coupled design and load iterations are ensured through a smooth interface between C2FLEX and C2MONDE, as illustrated in Figure 3-5.

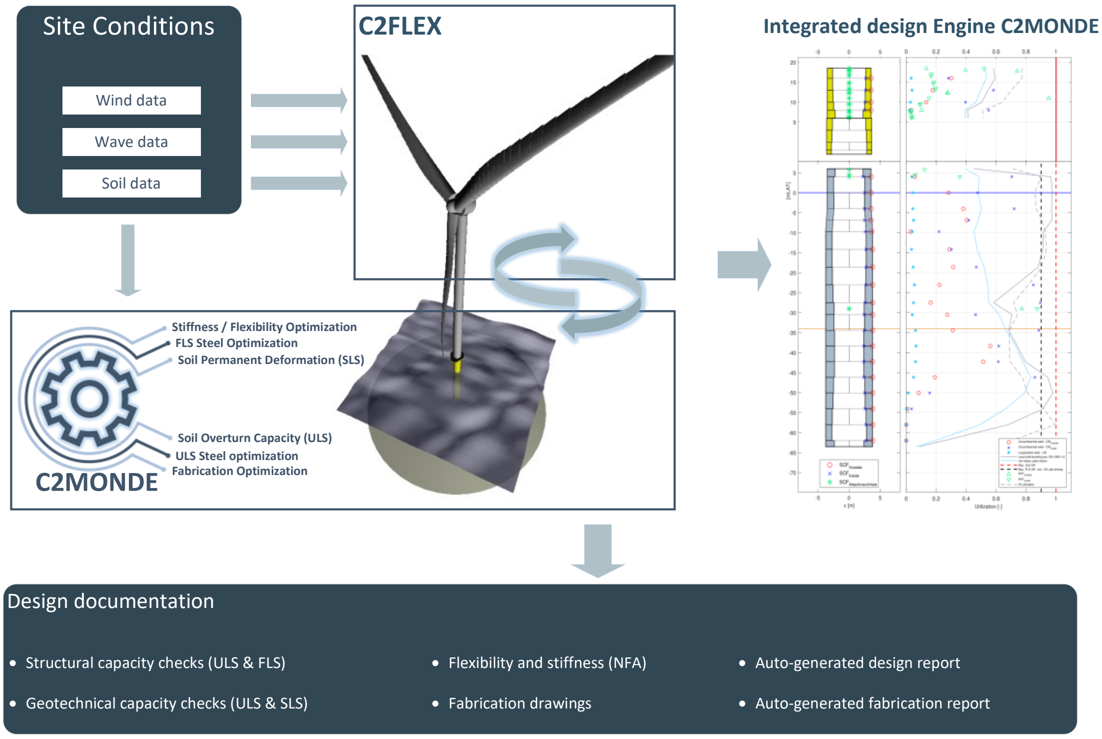

Figure 3-5: Design and load iteration methodology applied in the FRP substructure & foundation performance benchmark study using the coupled simulation framework of C2FLEX and C2MONDE.

Using C2MONDE, the DLCs of Section 3.5.1 are evaluated following the codified framework of [DNV0126]. Through the application of an integrated optimisation design module, weight- and cost-optimised pile structures are derived and subsequently validated using representative load effects. The feasibility of the centre-pile configuration is continuously monitored using the design performance metrics identified in Section 3.5.1.

4. FRP Concept Performance Benchmark

The performance of the FRP substructure & foundation concept is evaluated through a detailed benchmark study, comparing the performance of the FRP concept to the competing foundation concepts of a classical MP and a jacket concept. Direct comparisons are primarily given for the FRP vs. the MP-type support structure, but a jacket-type support structure is evaluated as well for completeness.

All benchmark studies are based on identical site conditions and follow the design philosophy outlined in Section 3. The foundation concepts are designed and evaluated using C2Wind's in-house state-of-the-art design framework containing the tools of C2FLEX, C2MONDE, C2JACK, and C2TOWER.

4.1 Assumptions

The FRP benchmark performance study is based on a deep-water site, assuming a seafloor elevation of -75 mLAT:

- **Seafloor elevation, -75 mLAT.**

Considering that the application range of an FRP concept may exceed -100 mLAT, the water depth of the benchmark study is considered a mid-range application scenario for the FRP concept. Harsh site conditions, representing a generic North Sea site, are assumed for all concept support structure evaluations.

It is expected that the classical substructure & foundation types of MP and jacket will be outperformed by the FRP concept, considering the feasibility limits observed in previous deep-water application studies for both classical foundation concepts. The performance overhead of the FRP concept, however, remains to be clarified through the benchmark study to investigate if the performance margin is sufficient to attract developers despite being a novel technology for offshore wind applications.

For deep-water sites, as the one assumed for the presented benchmark study, floating foundation concepts could be considered direct competitors to the FRP substructure & foundation concept. However, floating foundations have not been addressed as part of the present performance benchmark study as a result of the remaining cost-efficiency challenges of this technology.

A 30-year operational lifetime is assumed for the benchmark performance study, supplemented by 1.5 years of combined commissioning and decommissioning. Additionally, a 10% standstill is assumed for the performance benchmark study, summing to a combined standstill duration of 3 years:

- **Assuming a lifetime of 30 years, including 10% standstill. Supplemented by 1.5 years of combined commissioning and decommissioning.**

Mooring lines for the FRP performance benchmark study are selected using reference product catalogues and cable design parameters from established cable suppliers.

The performance benchmark case study is based on the application of a current-generation turbine featuring a rotor diameter of 236 m and an approximate power output of 15 MW:

- **Generic WTG with rotor Ø236m with 15 MW power output.**

All wind turbine support structures, including mooring line arrangement, are classified as a Normal Safety Class in accordance with [DNV0119]. This classification reflects the unmanned nature of the assets during normal operation and the limited environmental consequences in the event of failure, which is instead dominated by economic consequences. This classification reflects common practice within the offshore wind industry and ensures an appropriate reliability level.

4.2 Scenarios Excluded from Performance Scope

Various scenarios covering the storage-, transport-, and installation product lifecycle stages of the support structures have not been addressed as part of the performance benchmark study. This includes detailed evaluations of ship impact scenarios, which have not been addressed as part of the ALS evaluation in this study. However, the mooring line arrangement may be vulnerable to ship impact, and this could have an impact on the FRP substructure & foundation design. Thus, it is highly recommended to include detailed assessments of ship impact scenarios as part of the next steps in the FRP concept evaluation.

For the mooring line arrangement, no detailed evaluation of the mooring line interface module has been included in the performance benchmark study, as this study is intended as a generally applicable assessment of the FRP performance, not related to a single mooring line interface solution. Note that fatigue checks of the mooring lines have not been included in the present evaluation. Instead, it is ensured that the mooring lines only operate within the dynamic axial tension domain and that load reversals are avoided using the slack performance criterion of Section 3.4.1.

A detailed assessment of secondary long-term effects of the mooring lines, including thermal expansion, mooring line & soil creep, and local dynamic amplification (flutter), is not evaluated as part of the performance benchmark study. However, the capacity of the soil layers has been reduced by the use of creep factors in the absence of sufficiently detailed geotechnical inputs. As the aforementioned phenomena may have a direct impact on a critical design parameter of an FRP concept, these should be investigated in detail as part of the next steps.

4.3 Result Comparison

The results of the FRP performance benchmark studies are summarised using comparison plots of load effect envelopes, support structure tonnages, and standstill sensitivities. Note, all plots and results are normalised using the FRP substructure & foundation results to support ease of reading.

4.3.1 Load effects

A comparison of the normalised load effects for the FRP-, MP-, and the jacket substructure & foundation concepts is given in Table 4-1 and Table 4-2 for ULS and FLS, respectively. Note, all load effects are normalised using the load levels of the FRP substructure & foundation concept.

Elevation	ULS load effects		
	Normalised overturning moment, M_{res} [-]	Normalised horizontal shear force, V_{res} [-]	Normalised torsion, T [-]
FRP substructure & foundation concept			
Tower interface	1.0	1.0	1.0
Seafloor	1.0	1.0	1.0
MP substructure & foundation concept			
Tower interface	1.0	1.1	1.0
Seafloor	3.4	2.2	1.0
Jacket substructure & foundation concept			
Tower interface$^{1)}$	1.1	1.0	1.0
Seafloor	-	-	-
1) The tower interface elevation of the jacket support structure is higher than for both the MP and the FRP concepts.			

Table 4-1: ULS load effects across the three evaluated foundation concepts, normalised using the FRP substructure & foundation load levels.

Elevation	FLS load effects, $m = 5$ & $N_{\mathrm{ref}} = 1E7$	
	Normalised damage equivalent bending moment, M_{eq}	Normalised damage equivalent shear force, V_{eq}
FRP substructure & foundation concept		
Tower interface	1.0	1.0
Seafloor	1.0	1.0
MP substructure & foundation concept		
Tower interface	1.7	1.7
Seafloor	3.9	2.0
Jacket substructure & foundation concept		
Tower interface	0.6	1.0
Seafloor	-	-

Table 4-2: FLS load effects across the three evaluated foundation concepts, normalised using the FRP substructure & foundation load levels.

The ULS load levels of Table 4-1 for the FRP- and the MP substructure & foundation concepts reveal how the ULS loads at the TP/Tower interface elevation are comparable. The load levels observed at the seabed, however, demonstrate the fundamental difference in the way loads are supported between the FRP- and the MP support structure concepts. At the seabed elevation, overturning moment loads 3.4 times larger are found for the unsupported MP concept in comparison to the FRP, and shear forces are seen to increase by a factor of 2.2 for the MP concept.

The FLS load effects of Table 4-2 demonstrate a similar tendency, as the normalised damage equivalent overturning moment for the classical MP support structure is 3.9 times higher than the comparable damage equivalent overturning moment for the FRP concept at the seafloor elevation. Further, the damage equivalent shear loads are increased by a factor of 2.0 at the seafloor elevation.

It is observed how both the damage equivalent overturning moment and the damage equivalent shear force are increased by a factor of 1.7 at the tower interface elevation for the classical MP concept as compared to the FRP substructure & foundation concept. This is a clear indication of a significantly different dynamic structural behaviour of the FRP-supported wind turbine model as compared to the MP-supported wind turbine, attracting reduced fatigue loads as a result of the altered dynamic amplification.

The normalised load effects of Table 4-1 and Table 4-2 are visualised through the centre-pile and the MP in Figure 4-1 and Figure 4-2. As demonstrated in the figures, the load distribution through the substructure & foundation changes fundamentally when restraining mooring lines are included in the support structure. Comparable ULS load effects are found for the tower bottom elevation, as these originate from operational DLCs. This is especially seen for the overturning ULS moments of Figure 4-1, in which the bending moment load effect at the mooring line interface elevation of the FRP concept is comparable to the load level at the seafloor, which is unique for this foundation type.

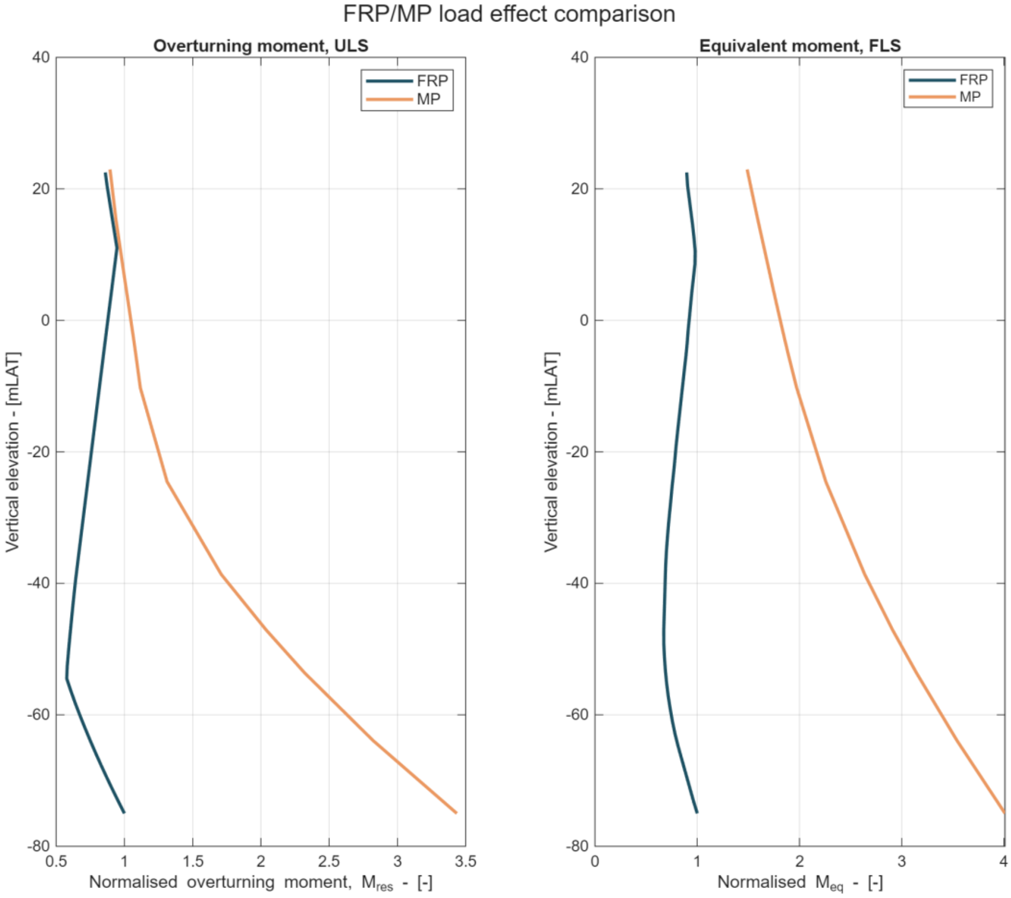

Figure 4-1: Normalised comparison of the FRP and MP bending moment load effects derived from the ILA of the two substructure & foundation concepts for the benchmark case study, showing the FRP concept load effects in blue and the MP load effects in orange.

As observed from Figure 4-1, significant load reductions are seen for the FRP substructure & foundation concept for both ULS and FLS at the seafloor elevation. Further, it is noted how the load path of the bending moment is significantly altered for the FRP substructure & foundation concept, as a result of the horizontal support provided by the pretensioned mooring lines and the associated load redistribution.

From the right panel of Figure 4-1, the offset of 1.7 from Table 4-2 is observed at the tower interface elevation between the FRP- and the MP foundation concept load effects, indicating how the overall system dynamics are improved for the FRP substructure & foundation concept, reducing the general FLS load effects as a result.

The FRP concept does induce higher shear and normal loads in the centre-pile at the mooring line attachment interface elevation, when compared to the classical MP substructure & foundation concept, cf. Figure 4-2. However, it is noted that the general shear force load level is found to decrease for the FRP concept in the direct comparison with the classical MP substructure & foundation concept, as horizontal load effects are supported by the mooring line arrangement.

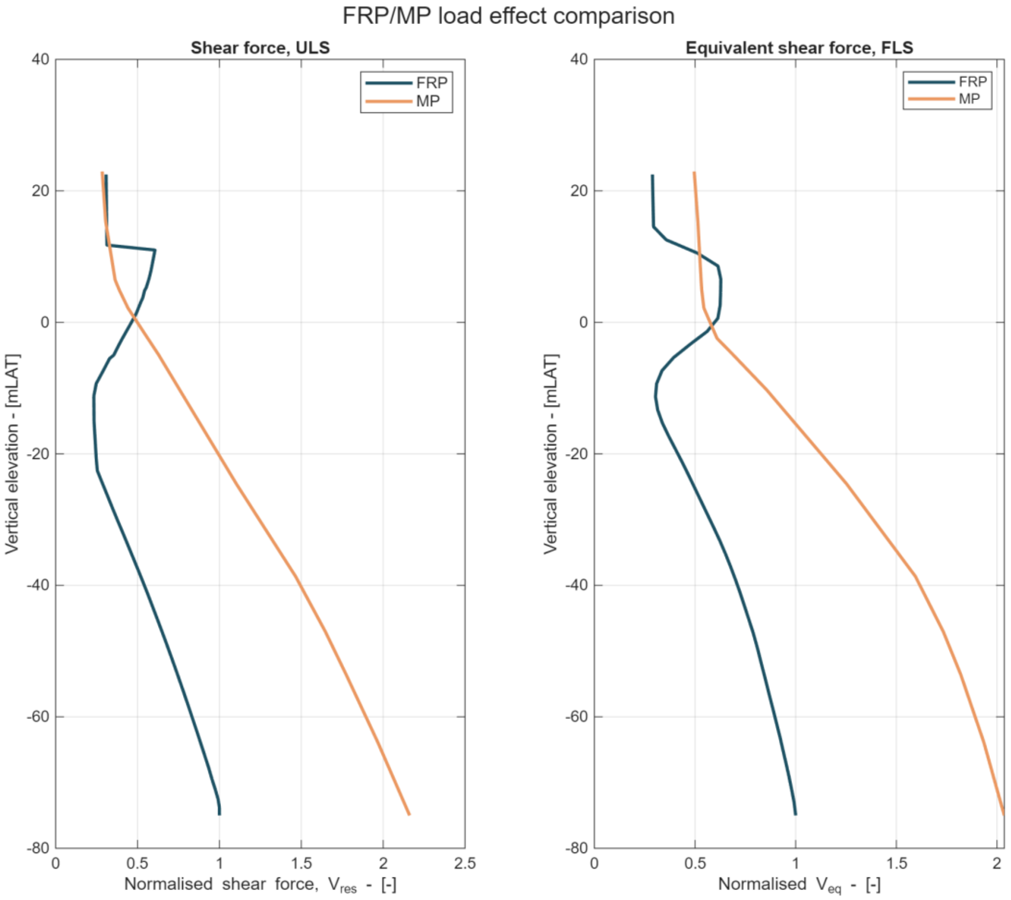

Figure 4-2: Normalised comparison of the FRP and MP shear load effects derived from the ILA of the two substructure & foundation concepts for the benchmark case study, showing the FRP concept load effects in blue and the MP load effects in orange.

In Section 4.3.2, a high-level comparison of the substructure & foundation tonnages is given across the three benchmark substructure & foundation concepts, indicating the potential of the FRP substructure & foundation concept through the reported material usage reduction.

4.3.2 Tonnages

The resulting tonnages of the FRP-, MP-, and jacket substructure & foundation concepts of the benchmark case study are compared in Figure 4-3. It is noted that the resulting tonnages are normalised using the FRP concept results to ease the direct comparison.

The reported tonnages are shown for the primary steel components of *'WTG Tower', 'Transition Piece', 'Substructure',* and *'Anchor piles'*. For the FRP concept, the mooring line mass of the benchmark case study is reported as part of the '*Substructure*' component of the FRP concept.

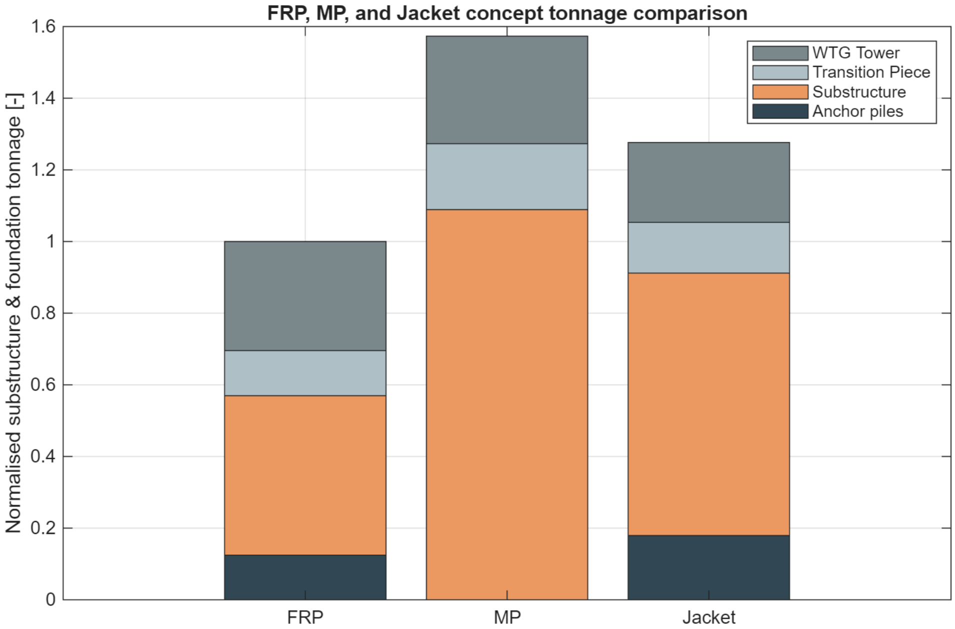

Figure 4-3: Normalised mass presented as colour-coded subcomponent masses. Normalised using the concluded mass of the FRP foundation concept.

The lowest material usage for the combined support structure was found for the FRP substructure & foundation concept, as demonstrated by the results of Figure 4-3. An approximately 60% higher combined tonnage is reported for the primary steel elements of the classical MP substructure & foundation concept, whereas approximately 25% higher material usage is found for the jacket-type substructure & foundation. Considering the significantly different fabrication cost, especially for the jacket-type concept, surpassing those of both the FRP and the MP concepts, these reported numbers cannot be directly translated into foundation costs, although the tonnages strongly indicate that the FRP substructure & foundation concept is by far the most cost-efficient solution, from a fabrication perspective, for the site of the performance benchmark study. As a side note, it is argued that the MP substructure & foundation concept concluded in the benchmark study requires cans with very large wall thickness, making this design highly challenging from a fabrication perspective. Thus, typical steel unit cost figures for MP designs do not apply to the unsupported MP, evaluated as part of the benchmark performance study.

It is noted that the WTG tower of the FRP substructure & foundation concept is governed by a frequency constraint for the combined support structure, and that it is not fully utilised from a design load perspective. This indicates a potential for further material reductions for the FRP support structure, some of which may be realised through close dialogue with the turbine supplier, purchase of additional WTG technologies affecting the allowable frequency range, or alternative stiffening of other areas of the combined FRP substructure & foundation concept. Without consideration of the frequency constraint, a material reduction of approximately ~25% is calculated for the FRP tower.

The concluded penetration depth of the FRP substructure & foundation concept is found to be governed by the installation scenario, representing an unsupported centre-pile configuration without WTG, subjected to 1-year extreme conditions, substantiating the importance of non-operational scenarios in early-stage FRP design studies.

The concluded configuration of the mooring line cables for the benchmark FRP concept yielded an outer diameter of the sheathed spiral strand of Ø155 mm and a specified pretension level of 540 tonnes, equal to 5,303 kN. Achieving a maximum horizontal displacement of the centre-pile at the mooring line interface elevation of 28 cm for FLS/ULS and 39 cm for the special-case ALS scenario ensured a constant state of tension in the mooring line cables across all load combinations, thus complying with the design-driving slack prevention criterion of Section 3.4.1.

4.3.3 Standstill Sensitivity

The sensitivity to standstill represents a significant upside for the FRP substructure & foundation concept, when compared to the classical MP foundation concept, as demonstrated in Figure 4-4. In Figure 4-4, the relative damage contribution from turbine operations and turbine standstill is seen for the FRP- and the classical MP substructure & foundation concepts. As stated in Section 4.1, a 10% standstill, corresponding to a combined duration of 3 years of standstill, is assumed. Note that the standstill sensitivity for the jacket-type substructure & foundation concept of the benchmark study is not included in the comparison of Figure 4-4, as this support structure technology demonstrates very little sensitivity to turbine standstill.

The results of Figure 4-4 demonstrate a fundamental challenge for the use of the classical, unsupported MP substructure & foundation technology in deep waters. Here, the MP is found to be highly sensitive to standstill, and the relative damage contribution from standstill load cases exceeds the accumulated damage of operational load cases despite representing only a 10% duration of the lifetime. This indicates that the use of the classical monopile-type support structure technology in deep waters is highly dependent on the additional damping contribution from a well-performing tower damper system. For the FRP substructure & foundation, however, the relative damage contribution from standstill is significantly reduced as a result of the altered system dynamics. This demonstrates that the risk of jeopardising the lifetime of the assets from standstill is significantly reduced when a substructure & foundation concept of the FRP-type is utilised instead of a classical MP foundation concept.

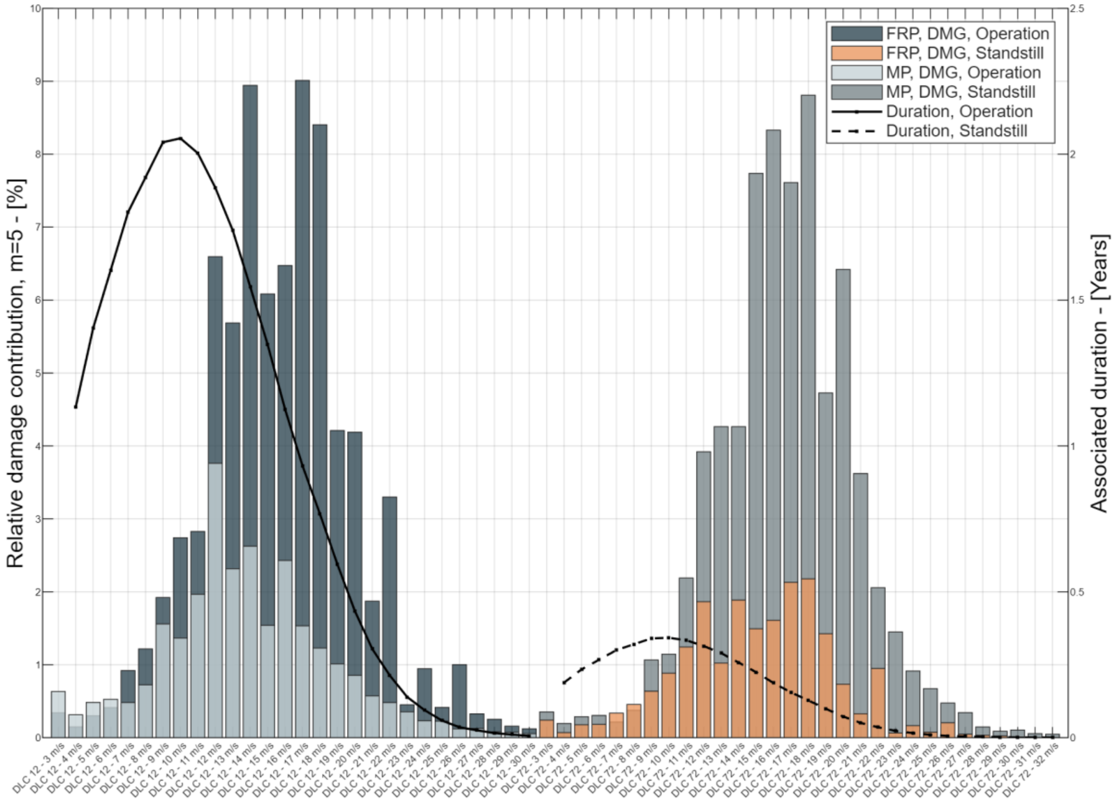

Figure 4-4: Relative damage contribution and associated duration for simulated FLS DLCs as part of the performed ILAs for the FRP and MP foundation concepts, categorised into the two configurations of *operational* and *standstill*. The black lines represent the operational- and standstill durations, whereas the bar charts represent the relative damage contribution from individual DLCs.

4.3.4 Mooring Line System Redundancy

The DLCs of *F 1.2* and *F 2.2* of Table 3-1 are used to demonstrate the redundancy of the mooring line arrangement for both operational- and parked turbine configurations in combination with extreme environmental conditions. The assessment of these ALS scenarios demonstrated the robustness of the FRP substructure & foundation concept, as the slack prevention criterion of Section 3.4.1 was achieved, even for the damaged configuration featuring a single-cable failure, while simultaneously demonstrating the required structural integrity.

5. The Future of Deep-Water Offshore Wind Foundations

Through the benchmark study and the included result comparison, the FRP concept is found to outperform the classical foundation concepts of bottom-fixed monopile and a jacket substructure supported by pin-piles. It is noted that the site selected for the case study was expected to favour the FRP foundation concept, as previous case studies have demonstrated that the MP and Jacket foundation concepts are close to their practical- and economical application limits at comparable water depths.

The FRP is considered a cost-effective supplement to the classical and widely used foundation concepts of MP and Jacket structures, enabling offshore wind farm development at deeper sites, previously challenged by high foundation cost and overall low profitability. Whilst it has proven challenging to develop cost-competitive floating foundation concepts, able to attract offshore wind developers, the FRP stands out as an economically feasible foundation concept, targeting an identified market gap for offshore wind development in mid- to deep waters.

Further, significant fatigue load reductions, when compared to a classical bottom-fixed MP foundation, were demonstrated for the FRP concept. This will have a positive impact on both the support structure cost and/or the lifetime of the assets, providing a significant positive benefit to the project's return of investment.

5.1 FRP Concept Challenges

Despite the results of the performance benchmark study indicating a promising potential of the FRP substructure & foundation concept for the offshore wind industry, a number of challenges and concept risks remain unaddressed at the time of writing.

Long-term loss of the mooring line pretension may pose a challenge to the FRP concept. Given the fundamental importance of maintaining sufficient axial tension in the mooring lines throughout the lifetime of the assets, continuous monitoring of the axial cable tension in combination with the ability to re-tension the wire system is likely required. It is noted that multiple proven solutions for the continued monitoring and potential re-tensioning of the wire system, in an offshore environment, are readily available in the industry. A detailed evaluation of the long-term pretension losses within the mooring line arrangement, accounting for installation tolerance chains, plastic deformation of soil, and soil creep & cable relaxation phenomena, is recommended as part of the next steps in assessing the feasibility of the FRP concept. To mitigate the risk associated with the long-term loss of mooring line pretension, it is recommended to apply a conservative approach in any early-stage design studies until this topic has been thoroughly examined through in-depth studies. Note that minor elongation of the anchor piles and initial over-tensioning of the mooring lines are low-cost solutions to counter the long-term loss of pretension and lower the associated risk.

The installation of FRP foundations in deep-water sites could prove costly, considering the limited number of capable installation vessels currently in operation. Further investments in next-generation installation vessels, bringing down the cost of deep water installation, depend on accurate market potential identification, justifying these investments. Detailed investigations of the market potential for the FRP technology for the UK have been performed, as reported in [FRPUK], but whether the market potential is sufficient to attract new investments in the supporting infrastructure remains unclear. However, it is noted that the increased water depths observed for deep-water development zones are considered for the next generation of installation vessels. Besides the northernmost development zones in the UK, less harsh extreme sea conditions, compared to those applied in the benchmark performance study, should be expected for the UK market, which may have an effect on the FRP substructure & foundation technology potential.

As a logical continuation of the historical trend in the wind turbine industry, it is only natural to expect that even larger WTGs will be offered to the market in the future. The FRP technology is considered configurable and scalable to support the size increase projected for the next generation of offshore WTGs, being achieved either through scaling of the existing concepts or reconfigurations of the mooring line arrangement, centre-pile, and anchor piles of the FRP concept. Furthermore, FRP mooring line technology is expected to benefit from advancements in mooring line systems driven by the development of future floating offshore wind solutions.

For an FRP substructure & foundation concept, the soil behaviour has a direct effect on the critical design driving parameter of axial cable tension. Further, complex phenomena like soil creep, which are often not well represented in the geotechnical inputs utilised in early project phases, might become critical inputs for an FRP support structure FEED. Thus, high-fidelity geotechnical inputs, derived from detailed on-site surveys and laboratory testing, might be required even in early-stage FRP design studies, whereas high-fidelity geotechnical surveys are often reserved for the detailed design stages of projects utilising classical MP- or jacket-type foundation concepts.

Addressing these and other identified challenges of the FRP concept, being either engineering-, operational-, or commercial, forms the logical next steps of the FRP concept qualification process, heading towards large-scale deployment. Thus, upcoming qualification studies of the FRP concept should evaluate the identified topics with increased detail and confidence levels as a continuation of the work presented in this report, with the objective of further reducing the risk profile for the deployment of the FRP technology. Such studies could include advanced modelling, physical testing, and demonstration through scaled pilot testing. Furthermore, it is recommended that operational monitoring & inspection methodologies of the FRP substructure & foundation concept are clarified with a great detail level as part of the next steps in the FRP qualification process, to increase confidence in the long-term operational performance of the FRP technology.

Despite the identified challenges of the FRP concept, the potential of this technology, as demonstrated through the benchmark study through steel tonnage reductions, improved fatigue performance, reduced sensitivity to standstill, and a sizeable addressable market, indicates that the FRP technology presents a commercially attractive and technically feasible foundation concept for the build-out of offshore wind in the targeted water depth application range.

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